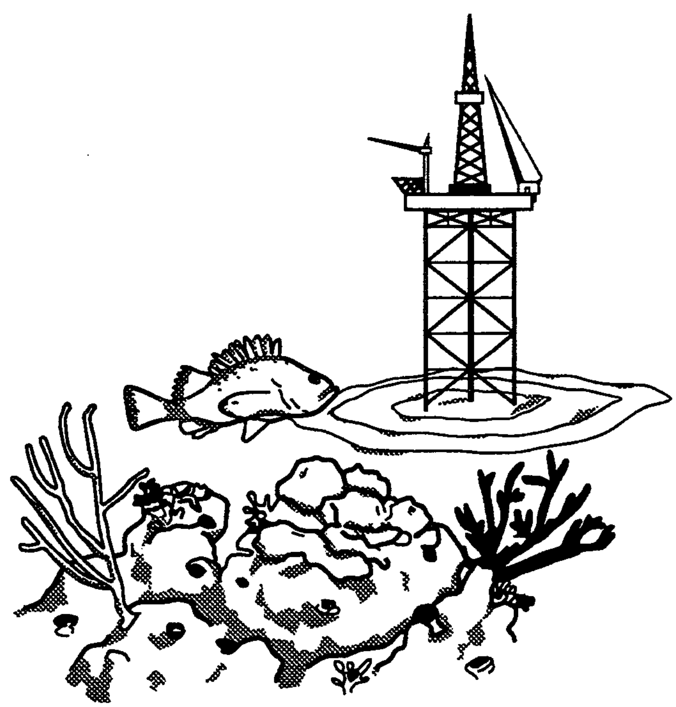
OCS Study
MMS 95-0049

# Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III

## Final Report



U.S. Department of the Interior
Minerals Management Service
Pacific OCS Region

OCS STUDY
MMS 95-0049

# MONITORING ASSESSMENT OF LONG-TERM CHANGES IN BIOLOGICAL COMMUNITIES IN THE SANTA MARIA BASIN: PHASE III

FINAL REPORT

November 1995

Submitted by

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## DISCLAIMER

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# ABBREVIATIONS, ACRONYMS, AND CONVERSIONS

The following is a list of abbreviations and acronyms used in the report. A table of metric equivalents is included to allow conversions from metric to U.S. units.

| | |
|---|---|
| Advanced Very High Resolution Radiometer | AVHRR |
| aluminum | Al |
| analysis of covariance | ANCOVA |
| analysis of variance | ANOVA |
| arsenic | As |
| barium | Ba |
| beryllium | Be |
| cadmium | Cd |
| centimeter | cm |
| chlorite and smectite | C/S |
| chromium | Cr |
| chrysene | C |
| circa | ca. |
| coefficient of variation | CV |
| cold vapor atomic absorption spectrophotometer | CVAAS |
| copper | Cu |
| cubic centimeter | $cm^3$ |
| cycles per day | cpd |
| Data Management System | DMS |
| degrees Celsius (Centigrade) | °C |
| Department of the Interior | DOI |
| dibenzothiophenes | D |
| dry weight | dry wt |
| empirical orthogonal function | EOF |
| Environmental Protection Agency | EPA |
| feet | ft |
| flame atomic absorption spectrophotometer | FAAS |
| flame ionization detector-gas chromatography | FID-GC |
| fluorenes | F |
| gallons per day | gpd |
| gas chromatography/mass spectrometry-selected ion monitoring | GC/MS-SIM |
| General Oceanics | GO |
| global positioning satellite | GPS |
| gram | g |

# ABBREVIATIONS, ACRONYMS, AND CONVERSIONS

**(cont'd.)**

| | |
|---|---|
| grams per cubic centimeter | g/cc |
| grams per square meter per day | $g/m^2/day$ |
| graphite furnace atomic absorption spectrophotometer | GFAAS |
| greater than | > |
| greater than or equal to | ≥ |
| higher n-alkanes | HALK |
| Hour Low Pass | HLP |
| illite and smectite | I/S |
| inch | in |
| instrumental neutron activation analysis | INAA |
| iron | Fe |
| kilogram | kg |
| kilometer | km |
| laboratory control sample | LCS |
| lead | Pb |
| less than | < |
| less than or equal to | ≤ |
| liter | L |
| lower n-alkanes | LALK |
| mean | $\bar{x}$ |
| MEC Analytical Systems, Inc. | MEC |
| mercury | Hg |
| meter | m |
| methylene chloride | DCM |
| micro | μ |
| microgram | μg |
| micrograms/gram | μg/g |
| micrograms/kilogram | μg/kg |
| micrograms/liter | μg/L |
| micrometer | μm |
| milligram | mg |
| milligrams/gram | mg/g |
| milligrams/kilogram | mg/kg |
| milligrams/liter | mg/L |
| milliliter | mL |
| millimeter | mm |
| million gallons per day | MGD |
| Minerals Management Service | MMS |
| nanogram | ng |

| | |
|---|---|
| nanograms/gram | ng/g |
| naphthalene | N |
| National Biological Service | NBS |
| National Data Buoy Center | NDBC |
| National Oceanic and Atmospheric Administration | NOAA |
| National Weather Service | NWS |
| nickel | Ni |
| optical backscatter sensor | OBS |
| Outer Continental Shelf | OCS |
| phenanthrenes+anthracenes | P |
| physical measurements array | PMA |
| phytane | Ph |
| polycyclic aromatic hydrocarbon | PAH |
| pound | lb |
| pounds per day | lb/day |
| practical salinity units | psu |
| principal component analysis | PCA |
| pristane | Pr |
| relative percent difference | RPD |
| remotely operated vehicle | ROV |
| quality assurance/quality control | QA/QC |
| Ryan-Einot-Gabriel-Welch Quotient | REGWQ |
| San Diego State University | SDSU |
| Science Applications International Corporation | SAIC |
| Scripps Institution of Oceanography | SIO |
| sea surface temperature | SST |
| second | sec |
| seconds squared | $sec^2$ |
| sediment measurement rod | SMR |
| sediment trap | ST |
| silver | Ag |
| Smart Acoustic Current Meter | SACM |
| species | sp |
| species (more than one) | spp |
| square centimeter | $cm^2$ |
| square kilometer | $km^2$ |
| square meter | $m^2$ |
| standard | std |
| Standard Operating Procedure | SOP |

# ABBREVIATIONS, ACRONYMS, AND CONVERSIONS

(cont'd.)

| | |
|---|---|
| Statistic Analysis System | SAS |
| suspended material concentration | SMC |
| temperature | T |
| Texas A&M University/Geochemical and Environmental Research Group | TAMU/GERG |
| total hydrocarbons | THC |
| total n-alkanes | TALK |
| total organic carbon | TOC |
| University of California Santa Barbara | UCSB |
| University of Connecticut | UCONN |
| unresolved complex mixture | UCM |
| vanadium | V |
| weight | wt |
| Western Instrument Corporation | WIC |
| wet weight | wet wt |
| X-ray diffraction | XRD |
| zinc | Zn |

| Metric System With U.S. Equivalents | |
|---|---|
| **Metric Unit** | **U.S. Equivalent** |
| **Length** | |
| millimeter (mm) | 0.04 inches |
| centimeter (cm) | 0.39 inches |
| meter (m) | 39.37 inches/3.28 feet |
| kilometer (km) | 0.62 miles |
| **Area** | |
| square centimeter ($cm^2$) | 0.155 square inches |
| square meter ($m^2$) | 1.196 square yards |
| square kilometer ($km^2$) | 0.3861 square miles |
| **Weight** | |
| milligram (mg) | 0.015 grains |
| gram (g) | 0.035 ounces |
| kilogram (kg) | 2.2046 pounds |
| metric ton (MT) | 1.1 tons |
| **Speed** | |
| centimeter/second | 0.0194 knots |
| **Volume** | |
| cubic centimeter ($cm^3$) | 0.061 cubic inches |
| cubic meter ($m^3$) | 1.31 cubic yards |
| **Capacity, Cubic** | |
| milliliter (ml) | 0.06 cubic inches |
| liter (l) | 61.02 cubic inches |
| kiloliter (kl) | 1.31 cubic yards |

# Exec. Summary

# EXECUTIVE SUMMARY

## 1.0 INTRODUCTION

The Department of the Interior (DOI), Minerals Management Service/National Biological Service has been performing long-term studies in the Santa Maria Basin, offshore southern California, since 1983 to determine potential impacts to the benthic environment from oil and gas production and development activities. The present study, entitled "Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III", was conducted by Science Applications International Corporation (SAIC; San Diego, CA) from 1991–1995, under Contract No. 14-35-0001-30584. Other key team members included MEC Analytical Systems, Inc., University of California Santa Barbara, University of Connecticut, and consultants Ms. Suzanne Benech, Dr. Joseph Connell, Dr. Paul Dayton, Dr. Mick Keough, and Dr. Jerrold Zar. Quality Review Board members were Drs. Donald Boesch, James Brooks, Roger Green, Judith McDowell Capuzzo, and Clinton Winant.

The initial, Phase I, program focused on defining baseline environmental conditions and providing recommendations of long-term study sites for hard-bottom communities in the southern Santa Maria Basin (SAIC 1986). Phase II (Steinhauer and Imamura 1990; Hyland et al. 1994) initiated monitoring of physical, chemical, and biological processes at nine selected study areas in the vicinity of Platforms Hidalgo, Harvest, and Hermosa during predrilling, during-drilling, and post-drilling periods. The Phase III study extended long-term monitoring at these sites, but focused additionally on physical and chemical processes that can affect natural and discharge-related changes in the biological communities.

Specific objectives of the Phase III program were to:

- Develop a better understanding of the environmental fate and effects of chronic, low-level discharges of drilling wastes and their potential for long-term and/or cumulative impacts to hard-bottom communities; and

- Improve knowledge of the processes controlling changes in the communities.

Specific tasks to fulfill these objectives included continuation of Phase II studies on ocean currents, waves, and tides; sediment grain size and chemical contaminants; particle fluxes; and photographic documentation of the distribution and abundance of hard-bottom communities (Table ES-1). New tasks for Phase III focused on in situ larval settling experiments; laboratory

Table ES-1. Summary of DOI Phase III Objectives and Methods.

| | Physical Oceanography | Sediment Physical and Chemical Properties | Particle Fluxes and Sediment Resuspension | Hard-Bottom Communities | Larval Settling Experiments | Laboratory Toxicity Tests |
|---|---|---|---|---|---|---|
| **Study Objectives** | • Continue Phase II characterizations of regional oceanographic conditions.<br>• Assess coherence scale of currents using variable location secondary mooring. | • Continue Phase II characterizations of sediment properties including grain size, chemistry, and mineralogy. | • Characterize sediment transport and resuspension events.<br>• Model dispersion of drilling mud discharges. | • Continue Phase II characterizations of hard-bottom communities in the vicinity of Platform Hidalgo. | • Document platform effects on larval settlement and growth. | •Assess potential toxic effects of drilling muds on representative species from the study area. |
| **Field Methods** | • Current meter moorings, physical measurements arrays (PMAs), wave/tide gauges, and satellite imagery. | • Sediment samples collected using Van Veen grab samplers and box corers. | • Data collected using sediment traps and optical backscatter probes on the PMAs. | • ROV used to collect 35- and 70-mm photoquadrat and color video data in high- and low-relief areas at shallow and deep depths. | • Settling plates exposed to natural bacterial films in the field prior to experiments.<br>• Filmed plates exposed in situ to manipulated red abalone larvae (short-term) and to natural larval settlers (short- and long-term) at deep high- and low-relief sites near and far from platforms. | • Drilling mud samples collected from platforms. |
| **Laboratory Methods** | • Data from current meters and PMAs downloaded and analyzed statistically; composite satellite images produced by computer. | • Analysis of grain size, mineralogy, and sediment chemistry, including trace metals and hydrocarbons. | • Platform discharge data obtained from EPA.<br>• Flux rates calculated.<br>• Current meter and platform discharge data used to model transport and dispersion of drilling mud particles. | • Abundance (percent cover) and distribution of epifaunal taxa and fish estimated from photographic and video data. Statistical methods included clustering, correlation/ regression, and ANCOVA. | • Settled larvae identified and enumerated. | • Toxicity tests performed on red abalone larvae and adult brown cup corals (*Paracyathus*). |

toxicity tests; near-bottom current measurements; assessment of the distance over which regional currents are similar; sediment resuspension; and additional measurements of particle fluxes at high- and low-relief heights (Table ES-1). The overall Phase III study design included assessments of (1) post-Phase II drilling impacts, and (2) drilling and post-drilling impacts during Phase III.

## 2.0 METHODS

The Phase III program was conducted from October 1991 through November 1995. Thirteen field surveys focused on nine hard-bottom sites near Platform Hidalgo, with additional sediment collections and larval settling experiments performed near Platforms Harvest and Hermosa (Figure ES-1). Survey depths ranged from approximately 90–215 m.

Six general tasks were conducted for the program, ranging from physical oceanography and characterizations of chemical contaminants in sediments and suspended sediments to documentation of changes in biological communities, larval settlement patterns, and laboratory toxicity tests (Table ES-1).

## 2.1 PHYSICAL OCEANOGRAPHY

Physical oceanographic studies included current meter measurements at the same (primary) mooring location near Platform Hidalgo that was used during Phase II, as well as at a secondary, variable-location mooring that was moved quarterly to biannually within a few to several kilometers from the platform. The primary mooring used three Smart Acoustic Current Meters (SACM) at depths of 14, 53, and 125 m, and back-up General Oceanic (GO) Mk2 meters at 1 m below the main instruments. The mooring also had a Sea Data wave/tide recorder attached to a secondary anchor. The secondary mooring normally was outfitted with GO meters (representing the only extra meters that were available) that varied in number (2–3) and depth depending on the mooring location. The moorings, including the bottom anchor weights, were recovered for periodic servicing and data recovery using an acoustic release system.

Supporting satellite data for the current meter deployment periods were obtained from the NOAA-11 Polar Orbiting Satellite Advanced Very High Resolution Radiometer (AVHRR). Weekly composite images subsequently were prepared from these data.

Specially designed Physical Measurements Arrays (PMA), initially consisting of a hemispherical (igloo-shaped) steel frame, into which an S4 current meter, two optical backscatter sensors (OBS), and sediment traps were secured, were used to document near-bottom currents, sediment resuspension events, and particle fluxes, respectively, for the first two years of the program. Concerns about interference from the frame with current measurements subsequently resulted in

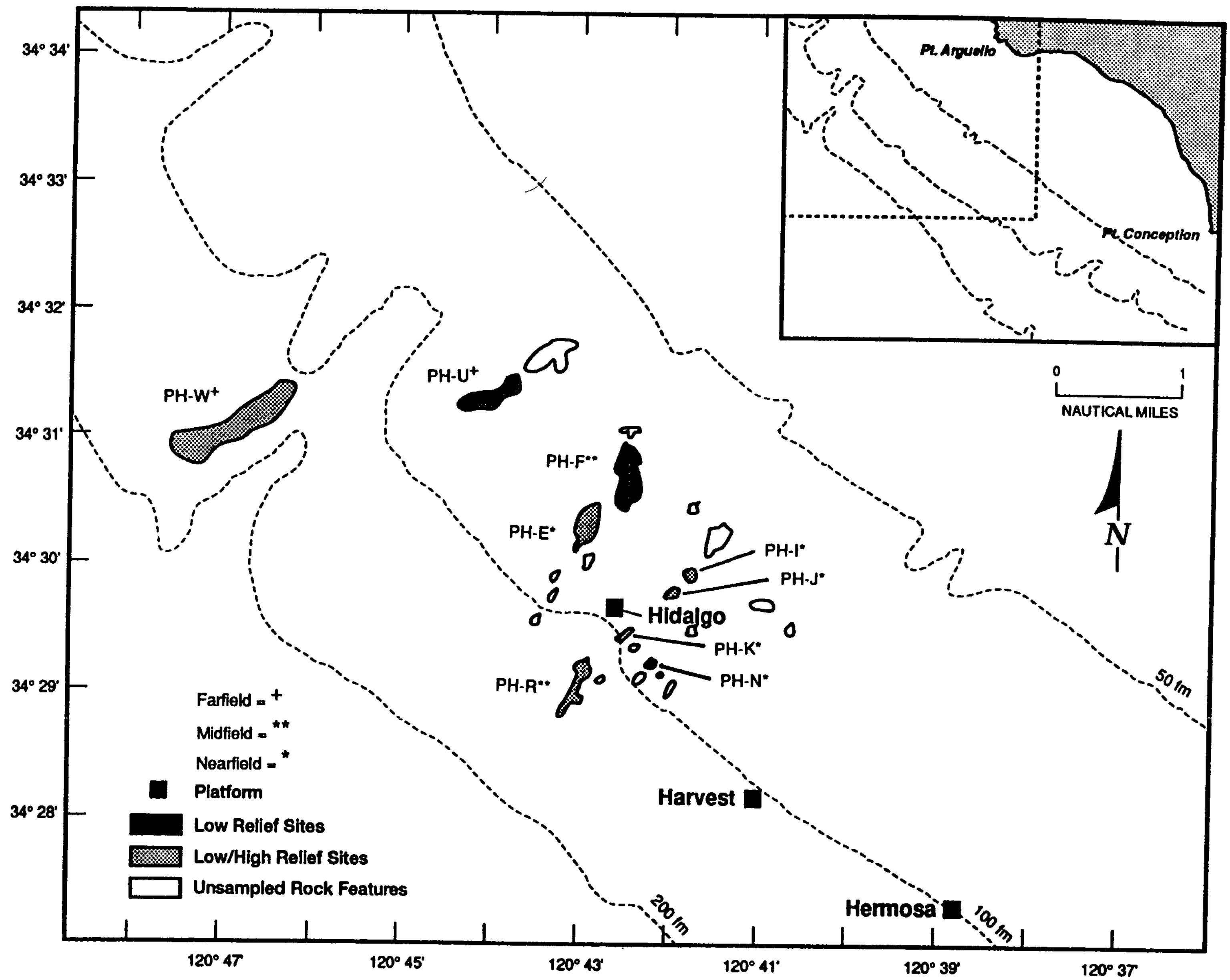


Figure ES-1. General Location of DOI Phase I, Phase II, and Phase III Studies in the Pt. Conception to Pt. Arguello Region.

The only hard-bottom features shown are those in the vicinity of Platform Hidalgo, representing the primary biological study sites for Phase II and Phase III.

a redesign of the PMA to an in-line configuration for the third year. One PMA each was located at approximately 200 m depth at a nearfield and a farfield location relative to Platform Hidalgo. Particle fluxes and sediment resuspension are discussed additionally in Section 2.3.

## 2.2 SEDIMENT PHYSICAL AND CHEMICAL PROPERTIES

Surface sediments were sampled for physical (grain size and mineralogy) and chemical (total organic carbon, trace metals, and hydrocarbons) analyses using a 0.1 $m^2$ Van Veen grab. The samples were collected from nine stations adjacent to the hard-bottom features that were monitored for biological community changes (Figure ES-1). Surface and subsurface (10–12 cm) sediment samples also were collected using a 0.015 $m^2$ box corer at a radial array of stations near Platforms Hidalgo, Harvest, and Hermosa. Representative samples of drilling muds, cuttings, and produced water were obtained from the platform operators for comparisons with the sediment and particle flux and modeling data (Section 2.3). A sample of a petroleum product (diluent) from the Guadalupe oil field also was obtained from the California Department of Fish and Game for comparison with sediment and particle samples from the Phase III study area.

Grain size analyses were performed by first separating gravel and sand particles from the samples using decreasing sieve sizes, followed by pipette analysis to determine the silt-clay fractions. Data were expressed as percentages of gravel, sand, silt, and clay. Mineralogy analyses were conducted by smearing < 4 micron size particles on microscopic slides, followed sequentially by air drying, glycolation, heat treatment, and X-ray diffraction analysis. Total organic carbon content was determined using an infrared spectroscopy method.

Trace metal chemical analyses (except barium) consisted of a strong acid (nitric and hydrofluoric) digestion, followed by flame atomic absorption spectrophotometry (AAS) for aluminum and chromium; graphite furnace AAS for arsenic, silver, cadmium, copper, lead, nickel, and zinc; and cold vapor AAS for mercury. Barium (Ba) concentrations were measured by irradiation with a Triga Reactor and instrumental neutron activation analysis.

Hydrocarbon analyses involved Soxhlet extraction of the samples followed by chromatographic separation using silica gel. Final extracts for saturated n-alkanes and selected isoprenoids and polycyclic aromatic hydrocarbons (PAHs) were then concentrated and analyzed by flame ionization detector-gas chromatography (FID-GC) and gas chromatography/mass spectroscopy-selected ion monitoring (GC/MS-SIM), respectively. Analyses of selected samples for saturated biomarkers (terpanes and steranes) also were performed using GC/MS-SIM.

Statistical analyses included linear regression, t-tests, and analysis of variance to evaluate spatial and temporal trends and relationships between the physical and chemical variables. Further, patterns of excess Ba (as an important surrogate of drilling mud discharges) in sediments was calculated from the platform radial array data by subtracting the background from the measured concentrations, and then interpolating the results over the nearfield region of the platforms.

## 2.3 PARTICLE FLUXES AND SEDIMENT RESUSPENSION

Suspended particles were collected from sediment traps, each of which had four, 1 m high collection tubes, located near each of the nine Van Veen sediment sample and hard-bottom sites. The traps were bottom-oriented and recovered using an ROV. Samples from the traps were analyzed for trace metals, hydrocarbons, total organic carbon, and grain size using the same methods as noted in Section 2.2. Statistical analyses of these data also were performed using methods similar to those described for sediment samples. Additionally, principal component analysis was used to compare selected hydrocarbon components (PAHs, sterane, and terpane biomarkers) from diluent and crude oil samples with concentrations in sediment trap samples.

A particle tracking model was used to predict the thickness of drilling material discharges on the bottom and the size of the area over which it is distributed. The Phase III model separately tracked three size classes of particles (coarse sand, coarse silt, and clay-silt) using current data from multiple mooring locations, as compared to modeling using only one size class and a single mooring during Phase II. Data for compositions of the three size classes were based on analyses of drilling mud samples from the platforms. Based on the available current meter data, the accuracy of the dispersion and deposition estimates decreases with distances from the moorings of 10–20 and 5–10 kilometers in the along- and cross-isobath directions, respectively.

## 2.4 HARD-BOTTOM COMMUNITIES

A remotely operated vehicle (ROV) was used to collect photographic and video data of the biological communities inhabiting high- and low-relief features at the nine hard-bottom sites. Photoquadrats representing a 1 $m^2$ surface area were taken randomly using a 70-mm or 35-mm camera that was oriented using dual lasers on the ROV to standardize the offset distance from the feature (and thereby the surface area). In high-relief areas the camera was oriented in a forward-looking direction, while a downward-looking angle was used for low relief. The study planned for the collection of 60 photoquadrats in each relief category at each site. However, after the photoquadrats were reviewed to exclude poor quality (e.g., low water clarity) slides a total of 476, 815, and 744 photographs were used for analysis from surveys in 1991, 1992, and 1994, respectively. The color video camera, used to document broader-scale community features than typically are possible using photoquadrat data alone, was angled at approximately 45 degrees from the bottom.

Laboratory analysis of the photoquadrats was done by projecting color slides at life size (1 $m^2$) onto a 50 dot, point contact grid. The species or substrate type that was contacted by each dot was then recorded on coding sheets to provide percent cover estimates. Counts of all taxa in each slide also were recorded, regardless of whether they were contacted by a dot. Video analysis included species presence-absence determinations along non-overlapping band transects.

The transects represented approximately 20 one-minute video segments of the different relief categories within each study site.

Statistical analysis included multivariate cluster analysis to distinguish community types, correlation of abundance with physical and chemical variables to evaluate potential cause and effect relationships, linear regression to evaluate trends in abundance over time, and analysis of covariance to determine changes in abundance with distance from Platform Hidalgo. Power analyses also were performed to determine the statistical ability to detect significant decreases in percent cover for dominant taxa.

## 2.5 LARVAL SETTLING EXPERIMENTS

Two types of in situ larval settling experiments, focusing on manipulated red abalone (*Haliotis rufescens*) and natural colonizers, were performed at one nearfield and one farfield site adjacent to each of the three platforms during predrilling and during/post-drilling time periods. Prior to each experiment, plexiglass settling plates were exposed in the field at each site to allow natural microbial films to become established. Reciprocal transplants of the filmed plates between the sites were then performed to determine the potential effect on settlement. For the experiments, filmed plates were attached to specially designed hemispherical steel frames (igloos) and deployed to the sea bottom (approximately 200 m depth). Plates were attached to the igloos at both high- and low-relief heights. Recovery of the igloos normally was accomplished using an acoustic release/pop-up buoy system. The red abalone studies were conducted by injecting precompetent (ready to settle) larvae into holding chambers attached to the igloos. After three days deployment on the bottom the red abalone experiments were recovered and the number of settled larvae was determined. For the natural settlement experiment, larvae that settled naturally on the plates were identified and quantified over exposure periods extending from 3 to 1,000 days.

Statistical analysis of the red abalone data was performed using a fixed effect analysis of variance procedure to determine potential drilling-related impacts. Analysis of variance also was used for the natural settlement studies to address waterborne and relief height effects relative to the drilling period.

## 2.6 LABORATORY TOXICITY TESTS

Toxicity tests on red abalone (gametes, zygotes, and larvae) and brown cup coral (*Paracyathus stearnsii*) adults were conducted using a series of drilling mud dilutions from 0.002 to 20,000 mg/L. Final experiments focused on concentrations greater than 200 mg/L because preliminary laboratory experiments indicated no toxicity effects at concentrations less than 200 mg/L. The red abalone tests assessed fertilization success; zygote development; and survivorship, settlement, and viability of larvae. The settlement experiments included evaluations of the potential interference of drilling mud with a natural inducer of settlement, specifically, coralline algae crusts that are known to induce red abalone larvae to settle. For the brown cup coral experiments the endpoints were survivorship and tissue loss of adults.

Statistical analyses used toxicity data expressed as percent fertilization, survivorship, etc. compared to a control. Types of tests included regression analysis and, for the cup corals, analysis of covariance.

# 3.0 RESULTS AND CONCLUSIONS

Results and conclusions from the Phase III monitoring program are summarized in Table ES-2 and detailed in Sections 3.1–3.3.

## 3.1 PHYSICAL PROCESSES

The study area is located in a dynamic physical oceanographic regime that is subject to strong waves and currents associated with various cross-over regions of the California Current System and exposure to Pacific storms. Because of this, the water column is well mixed to approximately 100 m bottom depths and can result in resuspension of sediments that are transported along and across the shelf. Sediment transport events below these depths also can be substantial; however, they do not appear to be caused by surface winds and waves, and likely are due to cross-shelf movement of material from shallower regions. Rainfall runoff from land is one likely source. The significantly greater rainfall and river discharge volumes, as well as presumed sediment transport, during Phase III as compared to drought conditions during Phase II may have contributed to some of the differences in the biological communities (e.g., decreasing trends in abundance for some species; see Section 3.3) noted between phases.

Current measurements from the primary and secondary moorings indicated that flows were predominantly upcoast during summer and winter and downcoast during spring; however, there was substantial variability in the timing and intensity of these patterns among phases and years. Eddies and meanders contributed to this variability and likely influenced the small scale (from a few to several kilometers) of similarity in currents between the primary and secondary locations.

Large spatial and temporal variability was also reflected in the timing and size of near-bottom sediment transport events, although as noted above transport in deeper locations was not related to local wind and wave events. Near-bottom concentrations of suspended particles typically were low (e.g., 1–5 mg/L) but aperiodic events were associated with suspended particle concentrations up to several orders of magnitude higher. Consistent with these general trends, data from

Table ES-2. Summary of DOI Phase III Results and Conclusions.

| | Physical Oceanography | Sediment Physical and Chemical Properties | Particle Fluxes and Sediment Resuspension | Hard-Bottom Communities | Larval Settling Experiments | Laboratory Toxicity Tests |
|---|---|---|---|---|---|---|
| **Results and Conclusions** | • Current flows primarily upcoast during summer through winter and downcoast in spring, but substantial local variability due to eddies and meanders.<br>• Currents generally coherent over only small scales (e.g., a few kilometers). | • Residual Phase II contaminants only consisted of slightly elevated barium (Ba) in bottom sediments.<br>• Pre-Phase III drilling trend of low molecular weight PAHs determined to be partly consistent with land-based diluent spill 50 km to the north.<br>• Phase III drilling discharges only evident as slight increases in Ba from sediment traps near Platform Hidalgo. | • Dynamic coastal system including strong mixing of water column and resuspension of sediments, perhaps to 100 m.<br>• At 200 m depths, very limited resuspension from meteorological events and surface waves.<br>• Resuspension at 200 m study depths apparently derived from shallower, in-shore areas and storm runoff.<br>• Runoff from storms substantially higher in Phase III than Phase II.<br>• Near-bottom (suspended sediment) concentrations generally low (1-5 mg/L).<br>• Sediment fluxes 25-60% higher at low- versus high-relief sites, and approximately twice as high at shallow compared to deep stations. | • Epifauna were similar in Phase II and Phase III. Cnidarians, echinoderms, and sponges most common phyla.<br>• 286 combined Phase II and Phase III taxa.<br>• Many taxa exhibit preferences for shallow versus deep and high- versus low-relief habitats; but numerous large, motile taxa are ubiquitous.<br>• More taxa and in higher abundance are found in deep and high-relief habitats.<br>• Decreasing trends in abundance were observed for many common taxa from Phase II to Phase III, although there were no consistent, platform-related patterns. | • Natural biogenic films increased larval settlement.<br>• Natural settling rates were low, with high spatial and temporal variability.<br>• Common taxa included one bivalve species, bryozoans, hydroids, serpulid worms, and komokoiaceans.<br>• No drilling-related effects were evident from natural settlement experiments.<br>• However, significant platform effects were detected from the red abalone studies. | • Decreased ability of red abalone larvae to respond to a natural settlement inducer; but no effects to fertilization mechanism, early development, or survivorship.<br>• Significant increase in mortality of brown cup corals. |

Table ES-2. Continued.

| | Physical Oceanography | Sediment Physical and Chemical Properties | Particle Fluxes and Sediment Resuspension | Hard-Bottom Communities | Larval Settling Experiments | Laboratory Toxicity Tests |
|---|---|---|---|---|---|---|
| **Results and Conclusions (continued)** | | | • No evidence of drilling period increases in near-bottom suspended particles.<br>• Particle tracking model indicated very thin average bottom accumulation (1.5-7.5 microns) distributed over very large area (100-550 $km^2$). | • ANCOVA tests of percent cover and distance from the platform for 20 common taxa identified 18 positive and 17 negative effects.<br>• However, Chi-square contingency analyses of the combined ANCOVA data indicate that there is no significant difference in these results from random chance.<br>• Only 2 of the 4 taxa identified from Phase II as showing potential platform-related effects were characterized by similar patterns during Phase III.<br>• There was low statistical power to detect significant decreases in percent cover of even dominant taxa (only 14 of 57 combinations of taxa and relief height had a power of $\geq 50\%$). | | |

sediment traps indicated that particle fluxes were higher at shallow compared to deep stations. Further, the sediment traps at different relief heights on the PMAs indicated that fluxes were approximately 25–65% higher at low- compared to high-relief heights. These types of differences also may be reflected in some of the differences noted in the biological communities (Section 3.3).

Results from the particle tracking model were reflective of the dynamic current regime in the study area, as well as the relatively shallow discharge depth (35 m, equating to at least 100 m above the bottom) and relatively small discharge volumes. These calculations predicted only very thin layers of accumulation on the bottom (average of 1.5–7.5 microns), representing a very large footprint area for fine-grained materials (approximately 100–550 square kilometers). Thus, it appears unlikely based on these conclusions that particulate contaminants from the platform discharges (also see Section 3.2) would cause significant impacts to hard-bottom communities.

## 3.2 CHEMICAL PROCESSES

Analysis of sediment and sediment trap (suspended particle) data indicated that the only residual Phase II drilling effects, prior to the onset of Phase III discharges, were slightly elevated Ba concentrations in bottom sediments, primarily near the platforms. No increases above background concentrations were evident for other metals or petroleum hydrocarbons, although non-drilling related increases in low molecular weight PAHs were noted at a few stations during the October 1991 survey. These latter increases were potentially attributable to a land-based spill of a petroleum product (diluent) from a site located approximately 50 km north, in addition to natural seep and anthropogenic combustion products.

The only Phase III drilling period effects were slight increases in Ba in suspended particles at three sites near Platform Hidalgo. Residual Ba from Phase II discharges near the three platforms also were evident at concentrations up to an order of magnitude above background. This general lack of effects for other contaminants is consistent with their low concentrations in the discharges, the solubility of lower molecular weight PAHs, large natural variability of background hydrocarbon concentrations, low discharge volumes (only 10% of the Phase II discharges), and apparently high dispersion of this material by dynamic oceanographic conditions (Section 3.1).

## 3.3 BIOLOGICAL PROCESSES

### 3.3.1 Biological Community

The combined data from Phases II and III indicated a diverse hard-bottom epifaunal community having at least 286 taxa dominated by cnidarians (cup corals, colonial corals, sea fans, anemones, and hydroids), echinoderms (particularly feather stars, seastars, and brittlestars), and sponges. Primary and secondary determinants of community composition are water depth and substrate relief height, respectively. Taxa characteristic of shallow depth sites (105–119 m) included several species of cup coral and seastars, while deeper sites (160–212 m) were typified by other corals and seastars in addition to various sponges, anemones, and basketstars. Species that occurred broadly over the full depth range included brittlestars, large anemones (*Metridium*), feather stars, and tunicates (sea squirts). High-relief (> 1 m) taxa were characterized by filter and particle feeders such as sponges, basketstars, and some corals; low-relief (0–1 m) organisms included ophiuroids, and some anemones, cup corals, and seastars. It is theorized that many of these patterns are influenced by relative tolerances for particles fluxes and sediment movement (shallow and low-relief habitats are subjected to higher loading), although direct evidence for these relationships are not presently available.

The rank order of dominance of most hard-bottom taxa was relatively stable over time as compared to periods of Phase II and Phase III drilling discharges and distance from Platform Hidalgo. However, analysis (linear regression) of temporal trends for common taxa indicated that 35% exhibited decreasing abundance (percent cover), although there was no consistent, platform-related pattern for any one taxon. Other statistical analyses (analysis of covariance and Chi-square contingency analysis) to test for changes in abundance with distance relative to the platform indicated that the combined positive and negative trends may be due to chance alone. Therefore, there did not appear to be any statistically significant, large-scale impacts from the discharges. These conclusions are undoubtedly influenced by apparently large natural variability in the hard-bottom communities and the low statistical power to detect changes using present, random photoquadrat techniques. The statistical power to detect significant ($\alpha = 0.05$) decreases in mean percent cover for 15 dominant taxa was 50% or greater for only 14 out of 57 combinations of the taxa and three habitats (deep high- and low-relief and shallow low-relief). Increases in the number of photoquadrats per habitat and site would improve the power somewhat, but it is recommended that future studies also incorporate sampling at fixed in addition to randomly selected stations.

These conclusions are consistent with the lack of any apparent large-scale physical/chemical impacts from the particulate components of the discharges (Sections 3.1 and 3.2). However, the trends in decreasing abundance noted for some taxa may represent more subtle, long-term effects. The platform-related mechanism(s) for such effects, if they occurred, are presently unknown but are not obviously related to particulate discharges or, based on substantial initial dilution and mixing of aqueous discharges, with produced water. Nonetheless, the monitoring studies to date have not focused directly on dissolved contaminants associated with the discharges, although other field studies (e.g., Krause 1995) have concluded that impacts to larvae can result from exposure to produced water.

### 3.3.2 In Situ Larval Experiments

Results from the in situ experiments indicated that natural microbial filming of the larval settling plates was important to achieve optimal settlement, regardless of the type of experiment. Manipulated red abalone larvae were associated with significant decreases in settlement at nearfield stations during Phase III drilling periods. However, natural settlement was not significantly affected by the discharges. Common taxa from the natural settling experiments included a bivalve, two bryozoans, two hydroids, a colonial protozoan, and a tube worm. Preferences by some taxa were evident for high- versus low-relief settling heights; these results provide a important example of early settlement patterns that may produce later community differences. Very low natural settlement (only 9 of approximately 50 taxa occurred on even 5% of all plates) undoubtedly limited the ability of these experiments to detect potential impacts. This emphasizes the importance of controlled field experiments, such as represented by the red abalone studies, in assessing impacts to larval communities.

### 3.3.3 Laboratory Toxicity Experiments

Laboratory experiments on two hard-bottom species indicated that the fertilization mechanism and early development stages of red abalone were not affected by exposures to used drilling muds. In contrast, the ability of larvae to respond to a natural inducer of settlement (coralline algae crusts) was significantly reduced. Further, adult brown cup corals also were significantly impacted due to progressive tissue loss and mortality following exposure to the drilling muds. These types of effects may suggest a mechanism for impacts to hard-bottom communities through reductions in recruitment of some larvae and direct impacts to some adults. However, as noted above the specific cause of the effects is still unknown, suggesting that additional studies may be appropriate on, for example, effects from dissolved chemical contaminants.

## 4.0 OVERALL CONCLUSIONS

Conclusions from the Phase II and III studies did not indicate severe, large-scale impacts to the hard-bottom communities from platform drilling discharges, although possible effects to larvae could influence some long-term trends in abundance and species composition. The larval studies in particular provided deep-water data from a unique set of in situ experiments. However, any effects that may have occurred to larvae or adults appeared to be subtle and limited to nearfield (within approximately one kilometer) regions of the platform. Low statistical power to detect significant decreases in the abundance of dominant hard-bottom taxa was influenced by the combination of high natural variability and the reliance on random photoquadrat field methods. Use of both fixed location and random sampling should improve the ability to detect change. The drilling-related mechanisms that may cause impacts to larvae and adults are not obviously caused by the particulate fractions of the discharges. However, based on other field and laboratory studies, effects from dissolved fractions may be important to address.

The long-term studies represented by the combined Phase I – Phase III programs provide a growing but as yet incomplete picture of the full life-cycle and potential effects from oil and gas production and development activities in the Santa Maria Basin. Presentation of the majority of the Phase III results and conclusions in the form of manuscripts for publication represents the high interest of DOI in making these continuing studies broadly available in the primary literature.

# Chapter 1

# INTRODUCTION

## 1.1 OVERVIEW

This report presents the background, results, and conclusions of the U.S. Department of the Interior (DOI), National Biological Service (NBS)/Minerals Management Service (MMS) program on "Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III." The program was conducted by Science Applications International Corporation (SAIC) between 1991 and 1995 under Contract No. 14-35-0001-30584. Primary subcontractor support was provided by MEC Analytical Systems, Inc. (MEC), the University of California Santa Barbara (UCSB), the University of Connecticut (UCONN), Texas A&M University/Geochemical and Environmental Research Group (TAMU/GERG), Oceaneering International, and Western Instrument Corporation (WIC). Additional consultant support was provided by Ms. Suzanne Benech (Benech Biological and Associates), Dr. Joe Connell (UCSB), Dr. Paul Dayton [Scripps Institution of Oceanography (SIO)], Dr. Mick Keough (University of Melbourne), Dr. Jon Witman (Northeastern University), and Dr. Jerrold Zar (Northern Illinois University). The Quality Review Board was comprised of Dr. James Brooks (TAMU), Dr. Donald Boesch (University of Maryland), Dr. Roger Green (University of Western Ontario), Dr. Judith McDowell Cappuzzo (Woods Hole Oceanographic Institute), and Dr. Clinton Winant (SIO).

The principal results and conclusions are presented as a series of manuscripts. Each manuscript is included in an appendix (Appendices B-D) to this report in a format that is consistent with the peer-reviewed journal to which it will be submitted for publication. As such, each appendix is self-contained, providing detailed methods, results, conclusions, and references by study task. In contrast, the first four chapters of the report address the general Phase III program as follows: overview, including technical items, hypotheses, and study area description (Chapter 1); synopsis of methods (Chapter 2); integration of study results as presented in the appendices (Chapter 3); and recommendations (Chapter 4). Appendix A, addressing the physical oceanographic and modeling tasks is the only section that is not planned for publication due to the overall descriptive nature of this study segment.

The Phase III program extends the period of research and monitoring initiated in the Santa Maria Basin, California, during the MMS Phase I (SAIC 1986) and Phase II (Steinhauer and Imamura 1990) programs. The Phase I program included baseline studies and recommendations of long-term study sites for hard-bottom communities in the Pt. Conception to Pt. Arguello region

(Figure 1.1-1) (SAIC 1986). Phase I sites included hard-bottom features in the vicinity of Platforms Harvest, Hermosa, and Hidalgo (Figure 1.1-1). The Phase II program initiated monitoring studies at nine hard-bottom sites near Platform Hidalgo (Figure 1.1-1), focusing on potential impacts to epifaunal communities from platform discharges of drilling muds (Steinhauer and Imamura 1990). The Phase II study included predrilling, during-drilling, and postdrilling periods, with the last drilling activity from Platform Hidalgo occurring in January 1989 (Table 1.1-1). Drilling from Platform Irene occurred from 1986 through October 1989; however, its location over 10 km to the north of the study area suggested that these discharges had minimal, if any, additional effects near Platform Hidalgo (Steinhauer and Imamura 1990). Other components of the Phase II program included soft-bottom studies (infauna and sediment chemistry) focusing on the region of the then-planned Platform Julius. This platform was to be located off Pt. Sal, approximately 40 km north of Pt. Arguello. However, installation was delayed indefinitely, precluding meaningful studies in this specific area by MMS for the Phase III program.

The Phase III field program, initiated in October 1991 and concluding in January 1995, represented the continuation of monitoring in the Phase II study region near Platforms Harvest, Hermosa, and Hidalgo (Figure 1.1-1). However, based on the extensive Phase II monitoring data at the hard-bottom sites near Platform Hidalgo, this platform was the continued focus of Phase III studies. The overall Phase III study design included assessments of continued (since Phase II) "post"-drilling and "during"-drilling impacts.

Drilling discharges during Phase III occurred only from Platforms Hermosa and Hidalgo and were substantially lower (e.g., factor of two to one order of magnitude) than during Phase II (Table 1.1-1). Other differences included much higher rainfall and runoff (and presumably, natural sediment transport) during Phase III (Section 1.4), and potential effects near the beginning of Phase III from a spill of hydrocarbon-based diluent that was discharged from a site approximately 50 km to the north (Appendix B).

## 1.2 PURPOSE AND GOALS

The overall purpose of the Phase I, II, and III monitoring programs was to conduct long-term studies on the cumulative effects of offshore drilling and production activities on the marine environment. Knowledge of the physical, chemical, and biological processes in the study region is necessary to distinguish background changes and inherent variability from oil- and gas-related impacts.

Impacts to hard-bottom communities, particularly epifauna, are of interest because of the greater sensitivity of many of these species to increased particulate loads and the generally uncommon occurrence of hard-bottom compared to soft-bottom habitats in the study region (SAIC 1986; Lissner et al. 1991). Impacts to epifauna can include smothering from sediment movement and accumulation, and fouling of filter-feeding structures (Lissner et al. 1991). Other potential

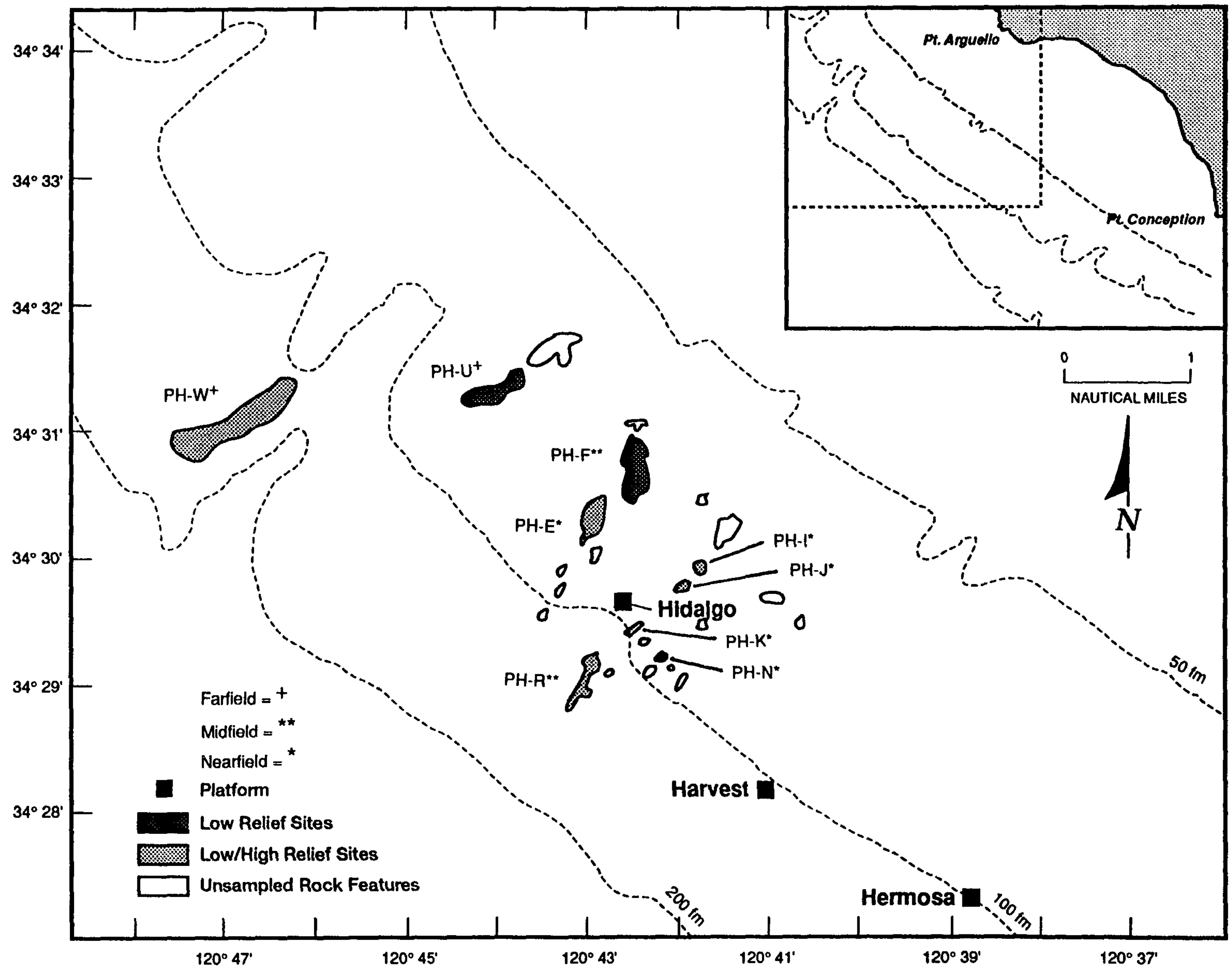


Figure 1.1-1. General Location of DOI Phase I, Phase II, and Phase III Studies in the Pt. Conception to Pt. Arguello Region.

The only hard-bottom features shown are those in the vicinity of Platform Hidalgo, representing the primary biological study sites for Phase II and Phase III.

Table 1.1-1. Summary of Drilling Activities in the General Phase II (Steinhauer and Imamura 1990) and Phase III Study Region.

| Platform | Drilling Period | Mud Discharged ($m^3$) | Barite Discharged (kg) | Cuttings Discharged ($m^3$) |
|---|---|---|---|---|
| **Harvest** | | | | |
| **Phase II** | 11/86–05/88 | 16,340 | 1,844,136 | DI |
| **Phase III** | ND | ND | ND | ND |
| **Hermosa** | | | | |
| **Phase II** | 01/87–09/88 | 16,373 | 1,470,955 | 3,114 |
| **Phase III** | 09/93–11/93 | 822 | 84,321 | 136 |
| **Hidalgo** | | | | |
| **Phase II** | 11/87–01/89 | 7,963 | 1,805,000 | 2,294 |
| **Phase III** | 11/93–05/94 | 3,850 | 770,000 | 739 |
| **Irene** | | | | |
| **Phase II** | 04/86–10/89 | 12,967 | 612,455 | 4,585 |
| **Phase III** | ND | ND | ND | ND |

DI=Data incomplete; ND=No discharge

impacts, such as toxicity to larvae and adults and larval-settling effects (Boesch and Rabalais 1987), are not well documented for hard-bottom organisms and are the subject of some Phase III studies described in this chapter and in Appendix C.

The Phase I monitoring program included an extensive reconnaissance (predrilling) study of soft-bottom and hard-bottom communities of the Santa Maria Basin and western Santa Barbara Channel, and associated physical/chemical parameters. This study provided an important basis of site selection for the Phase II program. The Phase II monitoring program resulted in extensive data on physical, chemical, and biological conditions during predrilling, during-drilling, and postdrilling periods. However, impacts to the hard-bottom communities were not demonstrated conclusively, and only preliminary linkages to physical and chemical processes were suggested (Steinhauer and Imamura 1990). The Phase III studies focused additionally on natural and anthropogenic (drilling-related) factors and processes that may influence spatial and temporal variability in hard-bottom communities near Platform Hidalgo.

Overall Phase III goals were twofold:

(1) To increase understanding of the environmental fate and effects of chronic, low-level inputs of drilling wastes and their potential for sublethal, long-term, and/or cumulative impacts to hard-bottom communities; and

(2) To improve knowledge of the fundamental processes controlling natural variability in the communities. This knowledge is critical because it distinguishes biotic changes associated with natural variability compared to those associated with drilling discharges.

To maintain comparability and continuity with the Phase II program, many of the Phase III study methods were consistent with the previous program. Study methods in common included those used to measure ocean currents; particle fluxes and sediment resuspension, as measured by sediment traps; sediment chemistry; and monitoring of hard-bottom epifauna. However, as noted in Chapter 2, modifications were made to some methods to better address specific questions without affecting data comparability between the phases. Several new studies also were added to the Phase III program—optical backscattering probes and current meters located in the benthic boundary layer, and extensive larval settling experiments (including natural settlers and laboratory-reared red abalone)—to evaluate physical and biological processes that influence the hard-bottom communities.

## 1.3 TECHNICAL ITEMS AND HYPOTHESES

The Phase III program included six technical items, specified by DOI to monitor spatial and temporal trends in the study region. A hierarchically designed, conceptual model was generated to express how these technical tasks are organized and interrelated (Figure 1.3-1). At the highest

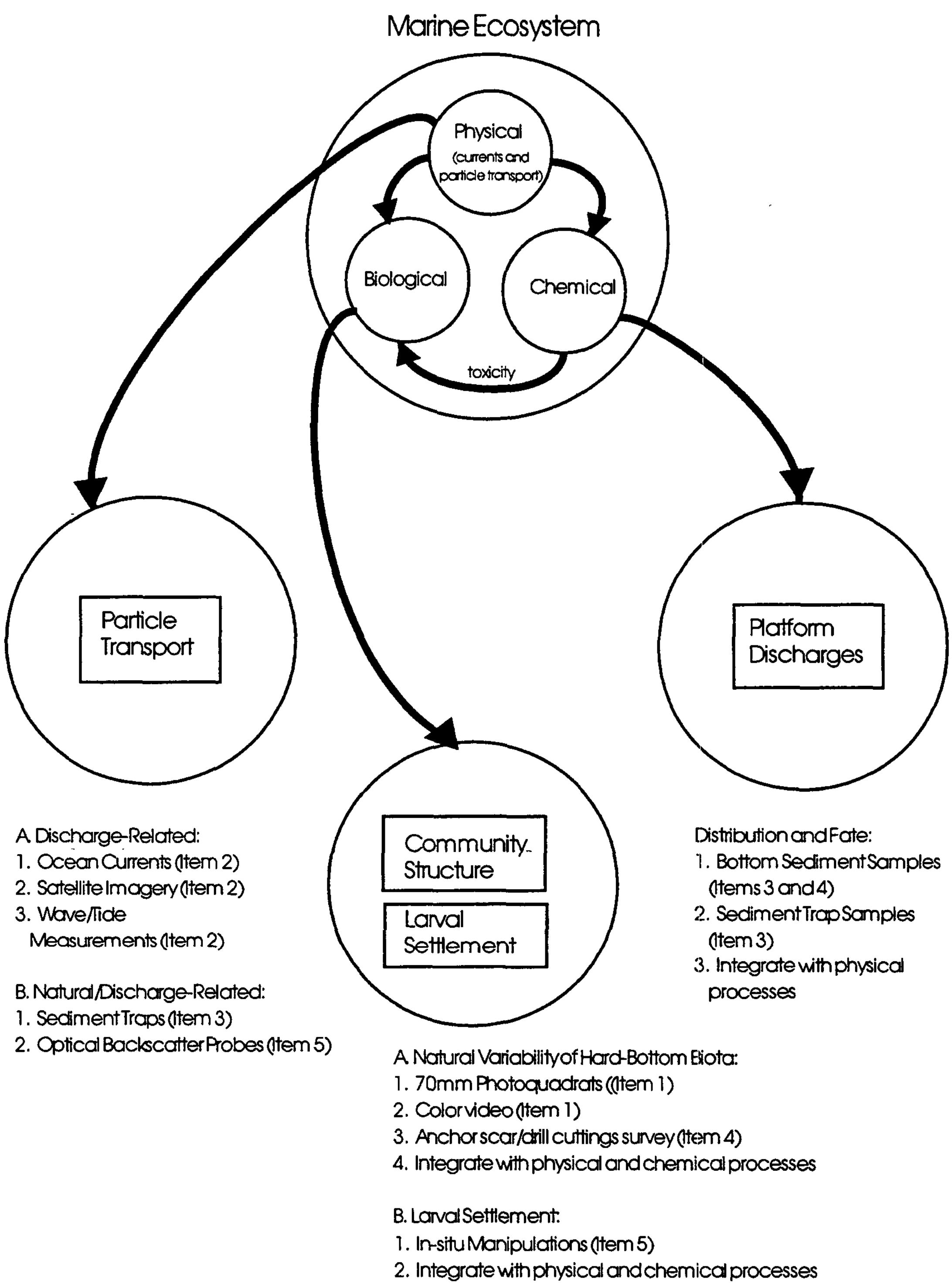


Figure 1.3-1. Hierarchical, Conceptual Model of a Marine Ecosystem Consisting of Physical, Biological, and Chemical Subsystems: DOI Phase III.

Black arrows represent the degree of influence of one subsystem on another. Insets provide detail of each subsystem with the primary variables of interest "boxed" in each subsystem. Below the individual subsystems are analytical details of how the variables were measured by different technical items.

level is the marine ecosystem, which is subdivided into three process-oriented subsystems: physical, chemical, and biological. These three subsystems represent the basic study elements of the Phase III design. Ecosystems often are conceptualized as hierarchical systems of biological processes that are strongly affected by physical and chemical forces (O'Neill et al. 1986). This is depicted in Figure 1.3-1 where the physical and chemical subsystems have a substantial influence on the biological subsystem but there is relatively little assumed influence of the biota on the other subsystems. The scale of effects to biota, which can range from small patches of centimeters to meters in area to regional or landscape scales of tens to hundreds of square kilometers, are also important to evaluate (Fahrig and Freemark 1995). Note also that physical processes can strongly affect the chemical subsystem (Figure1.3-1). Each of these subsystems can be isolated from the conceptual model to study its structure, and to identify and quantify which components are important.

Within the physical subsystem, particle transport, as influenced by currents, is a primary variable of interest. Of particular concern is distinguishing between particle transport properties associated with drilling activities and those associated with natural background events. As depicted in Figure 1.3-1, a primary goal of the physical measurements tasks was to determine how they affect the biotic and chemical subsystems in the study area. Three technical tasks (Items 2, 3, and 4) focused on physical processes. Item 2 involved obtaining data on local physical oceanographic conditions via current meters, satellite imagery, and wave/tide measurements. These data provided critical information on water mass movements and transport potential, and were used to interpret sediment-related results obtained under Item 3, including data on bottom sediments and suspended material. Item 4 involved additional sediment sampling near Platforms Hidalgo, Harvest, and Hermosa, and a remotely operated vehicle (ROV) reconnaissance survey of anchor scar and drill-cutting impacts to biological communities. Item 4 also included computer modeling to estimate the deposition patterns of material discharged from the platforms.

A primary variable in the chemical subsystem is platform discharges (Figure 1.3-1). However, other sources such as the diluent spill noted above also may be important. Item 3 (also see physical subsystem) involved collection of data on platform discharges, bottom sediments, and suspended material. Item 4 was designed to characterize short- and long-term sediment fluxes and chemical concentrations in the benthic boundary layer. By integrating this information with the data collected on physical oceanographic conditions (Item 2), suspended particle contaminant fluxes can be calculated, as well as contaminant accumulation in bottom sediments. This combination of physical and chemical data is essential to address the potential effects of contaminated sediments and suspended material on the biological subsystem.

Two primary variables of interest in the biological subsystem are epifaunal community structure and larval-settlement dynamics (Figure 1.3-1). Item 1, using 70-mm and 35-mm photoquadrat and color video surveys from an ROV, provided detailed information on the variability of hard-bottom epifauna in the study area. Combining the community structure data with the synoptically collected physical and chemical data allowed assessment of (1) relationships between community structure and environmental factors; and (2) hypothesis generation regarding these relationships. Item 5 employed in situ manipulative experiments to investigate the effects of drilling muds on larval settlement. A series of these unique experiments was used to monitor larval settlement, growth, and survivorship; the results are integrated with physical and chemical data (currents and particle concentrations). Finally, Item 6 addressed toxicity of drilling muds to selected species (red abalone and the cup coral *Paracyanthus stearnsii*) in the laboratory.

A schematic summary of the Phase III study elements is presented in Figure 1.3-2.

Each of the technical items (1–6) outlined above has associated general hypotheses. These hypotheses are listed below based on their relationship to the physical, chemical, and biological subsystems summarized in Figure 1.3-1, as opposed to being listed in numerical order, although it is recognized that some hypotheses are applicable across the artificially constructed subsystem boundaries.

I. Physical and Chemical Hypotheses

Item 2 $Ho_1$ : There is no difference between physical oceanographic conditions measured during Phase III compared to Phase II and other regional studies.

Item 2 $Ho_2$: There is no difference between currents measured by a primary mooring at a fixed site and currents measured by a secondary mooring positioned at variable locations relative to the primary mooring.

Item 3 $Ho_1$: There is no difference between concentrations of barium and other chemical contaminants measured during Phase III, including pre-, during-, and postdrilling periods, compared to Phase II background conditions.

Item 4 $Ho_1$: There is no difference between boundary-layer currents and particle fluxes, including pre-, during-, and postdrilling periods, at nearfield and farfield locations relative to Platform Hidalgo or between particle fluxes measured at high- versus low-relief heights during Phase III.

Item 4 $Ho_2$: There is no difference based on particle transport modeling in the dispersion of drilling muds relative to Platforms Hermosa and Hidalgo during Phase III.

II. Biological Hypotheses

Item 1 $Ho_1$: There is no difference between biological communities observed during Phase II and Phase III, including pre-, during-, and postdrilling periods, at nearfield and farfield sites relative to Platform Hidalgo, or at high- versus low-relief heights and at shallow versus deep bottom depths.

Item 5 $Ho_1$: There is no difference between larval settlement and recruitment, including pre-, during-, and postdrilling periods, at nearfield and farfield sites relative to Platforms Hidalgo, Harvest, and Hermosa, and at high- versus low-relief heights during Phase III.

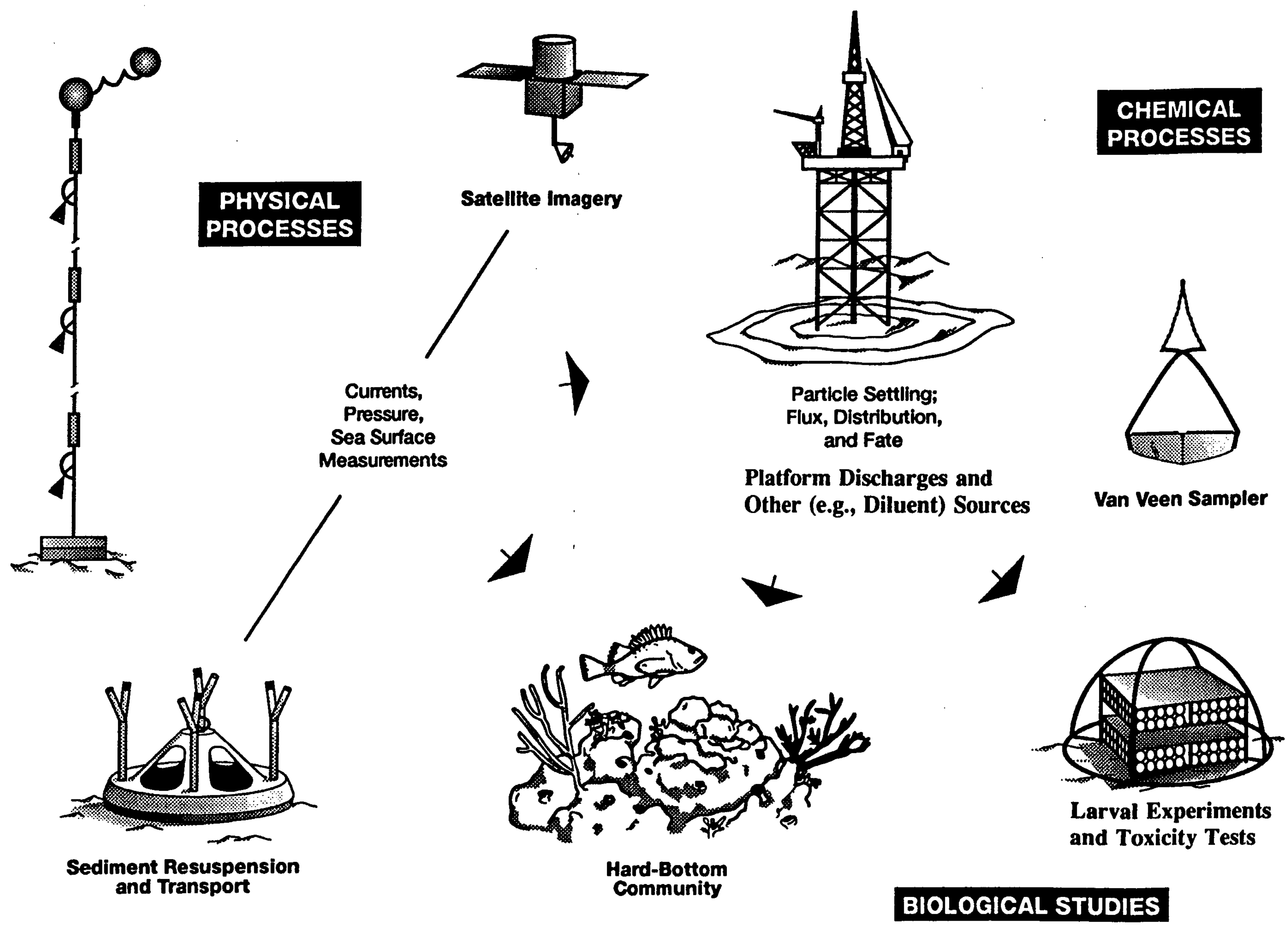


Figure 1.3-2. Interrelationship of Study Components: DOI Phase III.

Item 6 $Ho_1$: There is no difference in laboratory toxicity test results between organisms exposed to various concentrations of drilling muds compared to controls.

## 1.4 DESCRIPTION OF STUDY AREA

The study area consists of a portion of the continental shelf, extending from shore to approximately 110 m depth, and the continental slope off southern California, between Pt. Conception and Pt. Arguello (Figure 1.1-1). The coastal axis and bathymetric contours in the region are oriented approximately southeast-to-northwest. Bottom study depths range from approximately 90 to 215 m.

The oceanographic conditions of the region are dominated by the California Current System, an eastern boundary current of the North Pacific Gyre (summarized in Steinhauer and Imamura 1990). The California Current is predominantly southward-flowing, extending from the surface to approximately 200 m, and moving from along the seaward edge of the continental shelf to as much as 1,000 km from shore (Blumberg et al. 1984; Chelton et al. 1982).

Mean current flow in the Pt. Conception to Pt. Arguello region is generally parallel to the coastline and the bathymetric contours (Chelton et al. 1982). However, despite the long-term, generalized patterns exhibited by the California Current System, the local current structure can be quite variable, consisting of numerous transient features including eddies, swirls, filaments, and jets (Mooers and Robinson 1984). These patterns also are influenced strongly by interannual variations associated with drought conditions, such as those that persisted in California from approximately 1985 through at least early 1991, and El Niño events that occurred in 1992 through 1994 (United States Geological Survey 1988–1993, 1994 in press). El Niño events, in particular, can cause a reduction in seasonal (usually March to June) upwelling of nutrient-rich water that normally causes a significant increase in primary production in the study region (Dugdale and Wilkerson 1989; Chelton et al. 1982).

The United States Geological Survey (USGS) data, referenced above, include flow volumes from several rivers and creeks that discharge into the DOI study region. These data are available for the Phase II and most of the Phase III study period, and allow direct comparisons of the relatively low and high discharge volumes, respectively, associated with these two phases (Figure 1.4-1). River flow data indicate an approximate twofold to tenfold increase in volumes during Phase III, corresponding to water years (October of one year through September of the following year) 1991 through 1994 and up to December (1994) of water year 1995, compared to Phase II, which corresponded to water years 1987 through 1990.

Data on sediment loads associated with these river discharge volumes are not available for the same time period. However, Drake et al. (1971) estimated conservative sediment loads associated with single, strong rainstorms in the general region of approximately 3 x $10^6$ metric tons per storm. Further, analyses of local geologic landforms suggest that up to 30% of the sediment bed

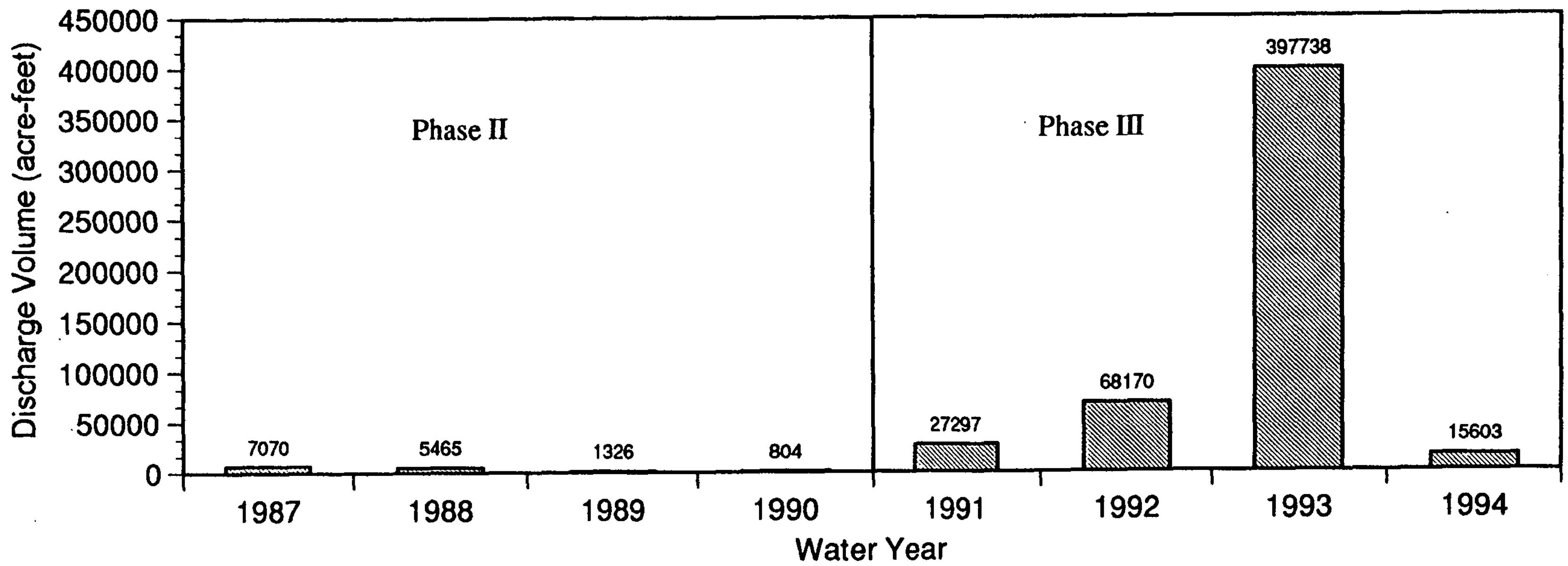


Figure 1.4-1. Summary of Discharge Volumes from the Santa Ynez, San Antonio, and Santa Maria Rivers During Phase II (water years 1987-1990) and Phase III (water years 1991-1994).

A water year extends from the end of September of one year to the end of September of the next (listed) year. Source: USGS 1988-1993, 1994 unpublished data. Santa Maria River records are not available (discontinued USGS station) for water years 1993 and 1994.

load can comprise sands, which typically settle out in the nearshore region (Taylor 1978). This means that approximately 70% of the "original" (Drake et al. 1971) bed load, primarily comprising a mixture of clays and silts, may be transported further offshore into the general DOI study region. If it is assumed (based on continental shelf/margin dynamics) that approximately 50% of this remaining sediment is then transported out of the study region (i.e., is unavailable for local deposition), the final volume of sediment subject to deposition near the study sites may comprise approximately one-third of the original bed load volume, or about $1 \times 10^6$ metric tons.

Using this bed load value for a typical heavy storm year (e.g., water year 1992), and an average of 10 storms per year, up to $10 \times 10^6$ metric tons of sediment may be deposited on the continental shelf area (~ 200 $km^2$) including the study sites. Assuming the sediment is predominantly quartz minerals (Drake et al. 1971), a specific density of 2.65 $g/cm^3$ (Cornelius et al. 1985) can be used to convert the yearly sediment load to a volume of approximately $3.8 \times 10^{12}$ $cm^3$.

Therefore, using the following relationship: depth of sediment coverage (deposition) = sediment discharge volume ($3.8 \times 10^{12}$ $cm^3$)/area of study region (200 $km^2$), a uniform layer of sediment deposited over the study sites would be approximately 2 cm thick.

This thickness is only a rough order-of-magnitude estimate and does not account for local differences, including currents and low- to high-relief, hard-bottom features (Denny 1988), which may cause uneven (thicker or thinner) sediment deposition. The "100-year" storm events that characterized the California region during the winter of 1994–1995 (not shown in Figure 1.4-1 since data for water year 1995, extending from October 1994 – end September 1995, are not yet available) undoubtedly were associated with even higher sediment discharges and deposition on the continental shelf. Nonetheless, large differences in rainfall and associated sediment loads from runoff likely result in significant differences in sediment deposition over the study region. This in turn may affect the quality and quantity of benthic habitats, including hard-bottom features characterized by organisms that may be sensitive to burial and increased sediment loads (e.g., Lissner et al. 1991).

As noted above, the distribution of nearshore and offshore sediments is influenced strongly by discharges of silts, clays, and sandy materials from rivers and streams, primarily to the north of Pt. Arguello, and littoral transport of sands from the north and south of the study area (SAIC 1986). Sediment types in the study area range from approximately 35–85% fines and 15–65% sand, with no predominant trends with depth or distance offshore (Steinhauer and Imamura 1990). Hard-bottom features, ranging in vertical relief from a few centimeters to over ten meters, are scattered throughout the study region (Figure 1.1-1) but are relatively uncommon (SAIC 1986).

Some riverine discharges, representing natural sources of the minerals barite and chromite (barium sulfate and oxides of bivalent chromium, respectively), contribute to the sedimentary loads of these materials to the study area (SAIC 1986). However, in addition to natural sources, barium, in particular, is a major component of drilling-mud discharges, and chromium was used historically as an additive by the oil and gas industry.

Other natural chemical sources in the study region include hydrocarbon seeps (e.g., Reed and Kaplan 1977; Simoneit and Kaplan 1980). Evidence of submarine oil seeps in the Santa Maria Basin includes macroscopic tar particles observed in bottom sediment samples from Phase II (Steinhauer and Imamura 1990) and observations of bacterial mats (*Beggiatoa* spp.) associated with seeps and gas bubbles at some hard-bottom sites (BBA/ROS 1986; Lissner et al., pers. obs., October 1992).

The primary sources of anthropogenic inputs to the study region are associated with historical oil- and gas-drilling activities from Platforms Harvest, Hermosa, and Hidalgo (Steinhauer and Imamura 1990). Historical discharges associated with production operations from these platforms are summarized in Table 1.1-1. Further, releases of several million gallons of a hydrocarbon-based diluent occurred over a period of years from an oil and gas production facility in Guadalupe, CA, (approximately 50 km north of Pt. Arguello), representing contaminants from land-based sources that flowed into the coastal environment. Other anthropogenic sources can include atmospheric deposition, tanker/shipping discharges and spills (e.g., PAC BARONESS), and wastewater discharges from platforms and vessels. The coastal area in this region is relatively undeveloped, contributing to the generally undisturbed nature of the environment.

Biological communities of the study region are very diverse, particularly in intertidal to shallow subtidal areas, in association with their occurrence in a transition zone between two biogeographic provinces: the Oregonian to the north of Pt. Conception and the Californian to the south (Newman 1979). Biological organisms at study area depths (approximately 100–200 m) also are abundant and diverse. However, the communities are very similar to other regions of the California shelf and slope (BBA/ROS 1986; SAIC and MEC 1989; Lissner et al. 1991).

Hard-bottom epifauna, the biotic focus of the Phase III program, are influenced strongly in their distribution and abundance by depth and substrate relief (SAIC 1986; SAIC and MEC 1989; Steinhauer and Imamura 1990; Hardin et al. 1994). Sediment movement, potentially resulting in burial or exposure of some organisms, can have significant effects on the local distribution and abundance of populations (Lissner et al. 1991). These effects are most pronounced in areas of low relief (e.g., $\leq$ 0.5 m), although many of the characteristic species appear to be adapted to these sediment dynamics (Lissner et al. 1991).

Common species in the hard-bottom areas, as summarized by SAIC (1986) and Steinhauer and Imamura (1990), include the anemones *Stomphia didemon* and *Amphianthus californicus*, and the corals *Desmophyllum dianthus* (formerly *crista-galli*) and *Lophelia pertusa* (formerly *californica*) in areas of high relief. Common species in areas of low relief include the corals *Caryophyllia* spp. and *Paracyathus stearnsii,* the crinoid *Florometra serratissima,* and the ophiuroid *Ophiacantha diplasia*. Other common species found in a variety of relief types include the anemone *Metridium giganteum* (formerly *senile*), numerous species of rockfish (*Sebastes* spp.), the asteroids *Stylasterias forreri* and *Mediaster aequalis,* and numerous "mat-like" organisms such as hydroids, ectoprocts, zoanthids, and komokoiacean protozoans.

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# Chapter 2

# MATERIALS AND METHODS

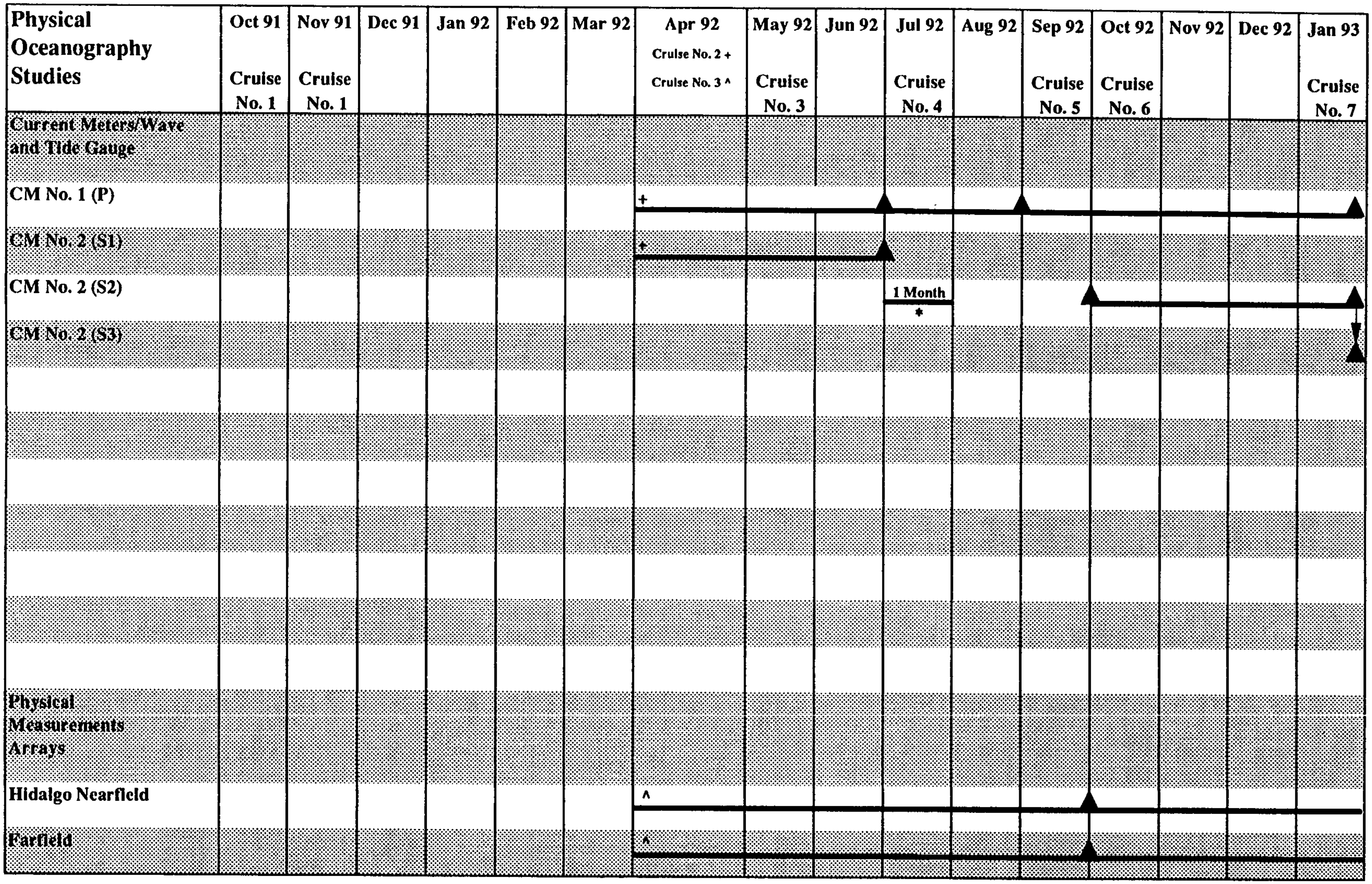
This chapter provides an overview of the Phase III materials and methods. An overview of field surveys—including descriptions of vessels, navigation, and sampling activities—which were conducted from October 1991 through January 1995, is presented in Section 2.1. General laboratory and data analysis methods for studies of physical, chemical, and biological processes are described in Sections 2.2, 2.3, and 2.4, respectively, with detailed methods presented in Appendices A through D.

## 2.1 OVERVIEW OF FIELD SURVEYS

Field surveys corresponding to thirteen separate cruises were conducted in the following time periods: October–November 1991 (Cruise No. 1), April 1992 (Cruise No. 2), April–May 1992 (Cruise No. 3), July 1992 (Cruise No. 4), September 1992 (Cruise No. 5), October 1992 (Cruise No. 6), January 1993 (Cruise No. 7), August 1993 (Cruise No. 8), September 1993 (Cruise No. 9), December 1993 (Cruise No. 10), January 1994 (Cruise No. 11), July 1994 (Cruise No. 12), and January 1995 (Cruise No. 13). Summaries of the methods and types of samples collected on the cruises are presented in Figures 2.1-1 and 2.1-2. Station locations are shown in Figures 2.1-3 through 2.1-6.

Studies of physical processes included current meter measurements at the same primary mooring location used during Phase II, as well as at a second, variable-location mooring within a few to several kilometers of the primary site. Wave/tide gauge measurements also were made at the primary mooring. Satellite images were collected of the general study region. Wind data were collected from the National Oceanographic and Atmospheric Administration (NOAA) meteorological buoys located in the general study region. Sediment flux and resuspension was monitored with bottom-located sediment traps (STs) in addition to STs and optical backscattering probes mounted on specially designed physical measurements arrays (PMAs). These arrays, including a near-bottom current meter, provided physical effects data for comparison with results from in situ larval experiments (see below). Finally, specially designed sediment measurement rods (SMRs) were deployed to assess evidence of any large-scale sediment movement or accumulation. (The current meter and ST data were used for subsequent particle transport modeling tasks.)

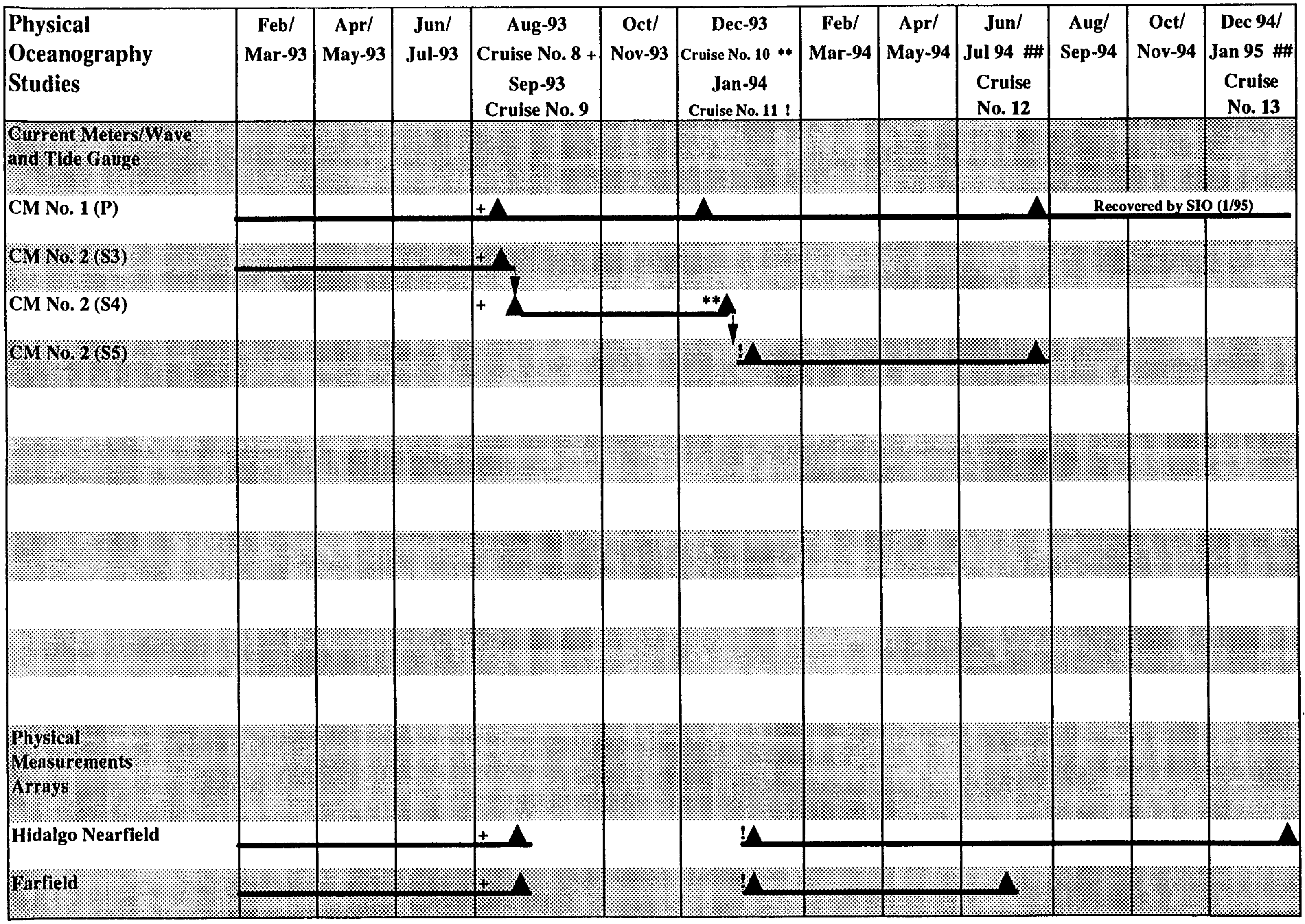
Studies of chemical processes included analyses of trace metals and hydrocarbons from ST samples and bottom sediments collected with Van Veen grab samplers and box corers. Grain




* Intended Length was 3 months; apparent human activity caused premature release of mooring.

▲ Item was recovered, serviced, and redeployed on station.

Figure 2.1-1a. Summary of DOI Phase III Survey Activities and Sampling: Physical Processes.




## Month that the survey occurred.
▲ Item was recovered, serviced, and redeployed on station.

Figure 2.1-1a. Continued.

| Sediment Flux Studies | Oct 91 Cruise No. 1 | Nov 91 Cruise No. 1 | Dec 91 | Jan 92 | Feb 92 | Mar 92 | Apr 92 Cruise No. 2 > Cruise No. 3 | May 92 Cruise No. 3 | Jun 92 | Jul 92 Cruise No. 4 | Aug 92 | Sep 92 Cruise No. 5 | Oct 92 Cruise No. 6 | Nov 92 | Dec 92 | Jan 93 Cruise No. 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sediment Traps 1** | | | | | | | | | | | | | | | | |
| PH-I | | ▲ | | | | | 1 year | | | | | | ▲ | | | |
| PH-F | | ▲ | | | | | 1 year | | | | | | ▲ | | | |
| PH-E | | ▲ | 6 months | | | | 2 > | | 6 months | | | | ▲ | | | |
| PH-U | | ▲ | | | | | 1 year | | | | | | ▲ | | | |
| PH-R | | ▲ | 6 months | | | | ▲ > | | 6 months | | | | ▲ | | | |
| PH-W | | ▲ | 6 months | | | | 2 > | | 6 months | | | | ▲ | | | |
| PH-N | | ▲ | 6 months | | | | ▲ > | | 6 months | | | | ▲ | | | |
| PH-J | | ▲ | 6 months | | | | 2 > | | 6 months | | | | ▲ | | | |
| PH-K | | ▲ | 6 Months | | | | ▲ > | | 6 months | | | | ▲ | | | |
| **Sediment Measurement Rods (2 deployed per station, except as noted)** | | | | | | | | | | | | | | | | |
| PH-I | | | | | | | | | | | | | | | | |
| PH-F | | | | | | | | | | | | | | | | |
| PH-E | | | | | | | | | | | | | | | | |
| PH-U | | | | | | | | | | | | | | | | |
| PH-R | | | | | | | | | | | | | | | | |
| PH-W | | | | | | | | | | | | | | | | |
| PH-N | 3 | | | | | | | | | | | | | | | |
| PH-J | | | | | | | | | | | | | | | | |
| PH-K | | | | | | | | | | | | | | | | |

1 Recovered initially during Cruise No. 1, following a one year period from October 1990 (last Phase II deployment).
2 Duplicate study items were deployed at this station.
3 Triplicate study items were deployed at this station.
▲ Item was recovered, serviced, and deployed on station.

Figure 2.1-1b. Summary of DOI Phase III Survey Activities and Sampling: Physical and Chemical Processes.

| Sediment Flux Studies | Feb/ Mar-93 | Apr/ May-93 | Jun/ Jul-93 | Aug-93 Cruise No. 8 + Sep-93 Cruise No. 9 | Oct/ Nov-93 | Dec-93 Cruise No. 10 ** Jan-94 Cruise No. 11 ! | Feb/ Mar-94 | Apr/ May-94 | Jun/ Jul 94 ## Cruise No. 12 | Aug/ Sep-94 | Oct/ Nov-94 | Dec 94/ Jan 95 ## Cruise No. 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Sediment Traps** | | | | | | | | | | | | |
| PH-I | | 10 months | | + ▲ | | ! ▲' | | | | | | ▲ |
| PH-F | | 10 months | | + ▲ | | ! ▲ | | | | | | ▲ |
| PH-E/ST-LA3 (Cruises 8-13) | | 10 months | | + ▲ | | ! ▲ | | | | | | ▲ |
| PH-U | | 10 months | | + ▲ | | ! ▲ | | | | | | ▲ |
| PH-R | | 10 months | | + ▲ | | ! ▲ | | | | | | ▲ |
| PH-W | | 10 months | | + ▲ | | ! ▲ | | | | | | ▲ |
| PH-N | | 10 months | | + ▲ | | ! ▲ | | | | | | ▲ |
| PH-J/ST-LA6 (Cruises 8-13) | | | | | | | | | | | | |
| PH-K | | | | | | | | | | | | |
| **Sediment Measurement Rods (2 deployed per station, except as noted)** | | | | | | | | | | | | |
| PH-I | | | | | | | | | | | | |
| PH-F | | | | | | | | | | | | |
| PH-E | | | | | | | | | | | | |
| PH-U | | | | | | | | | | | | |
| PH-R | | | | | | | | | | | | |
| PH-W | | | | | | | | | | | | |
| PH-N | | | | | | | | | | | | |
| PH-J | | | | | | | | | | | | |
| PH-K | | | | | | | | | | | | |

**##** Month that survey occurred.
▲ Item was recovered, serviced, and deployed on station.
▲' Item not recovered; new item deployed.

Figure 2.1-1b. Continued.

| Sediment Chemistry Studies | Oct 91 Cruise No. 1 | Nov 91 Cruise No. 1 | Dec 91 | Jan 92 | Feb 92 | Mar 92 | Apr 92 Cruise No. 2 Cruise No. 3 | May 92 Cruise No. 3 | Jun 92 | Jul 92 Cruise No. 4 | Aug 92 | Sep 92 Cruise No. 5 | Oct 92 Cruise No. 6 | Nov 92 | Dec 92 | Jan 93 Cruise No. 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Van Veen Grabs** (Metals and Organics Composites Comprised of 3 Replicates Each) | | | | | | | | | | | | | | | | |
| PH-I | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-J | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-F | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-E | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-U | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-W | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-R | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-N | ▼ | | | | | | | | | | | | ▼ | | | |
| PH-K | ▼ | | | | | | | | | | | | ▼ | | | |
| | | | | | | | | | | | | | | | | |
| **Box Cores** (Number of Trace Metal Stations in Parentheses) | | | | | | | | | | | | | | | | |
| Platform Hidalgo (15) | ▼ | | | | | | | | | | | | | | | |
| Platform Hermosa (9) | ▼ | | | | | | | | | | | | | | | |
| Platform Harvest (9) | ▼ | | | | | | | | | | | | | | | |

▼ Sediment samples were collected at this station.

Figure 2.1-1c. Summary of DOI Phase III Survey Activities and Sampling: Chemical Processes.

| Sediment Chemistry Studies | Feb/ Mar-93 | Apr/ May-93 | Jun/ Jul-93 | Aug-93 Cruise No. 8 + Sep-93 Cruise No. 9 ^ | Oct/ Nov-93 | Dec-93 Cruise No. 10 Jan-94 Cruise No. 11 | Feb/ Mar-94 | Apr/ May-94 | Jun/ Jul 94 ## Cruise No. 12 | Aug/ Sep-94 | Oct/ Nov-94 | Dec 94/ Jan 95 ## Cruise No. 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Van Veen Grabs** (Metals and Organics Composites Comprised of 3 Replicates Each) | | | | | | | | | | | | |
| PH-I | | | | + ▼ | | | | | | | | ▼ |
| PH-J/ST-LA6 (Cruises 8-13) | | | | + ▼ | | | | | | | | ▼ |
| PH-F | | | | + ▼ | | | | | | | | ▼ |
| PH-E/ST-LA3 (Cruises 8-13) | | | | + ▼ | | | | | | | | ▼ |
| PH-U | | | | + ▼ | | | | | | | | ▼ |
| PH-W | | | | + ▼ | | | | | | | | ▼ |
| PH-R | | | | + ▼ | | | | | | | | ▼ |
| PH-N | | | | + ▼ | | | | | | | | ▼ |
| PH-K | | | | + ▼ | | | | | | | | ▼ |
| | | | | | | | | | | | | |
| Box Cores (Number of Trace Metal Stations in Parentheses) | | | | | | | | | | | | |
| Platform Hidalgo (15) | | | | | | | | | | | | ▼ |
| Platform Hermosa (9) | | | | | | | | | | | | ▼ |
| Platform Harvest (5) | | | | | | | | | | | | ▼ |

## Month that survey occurred.
▼ Sediment samples were collected at this station.

Figure 2.1-1c. Continued.

| ROV Biological Survey Studies | Oct 91 Cruise No. 1 | Nov 91 Cruise No. 1 | Dec 91 | Jan 92 | Feb 92 | Mar 92 | Apr 92 Cruise No. 2 Cruise No. 3 | May 92 Cruise No. 3 | Jun 92 | Jul 92 Cruise No. 4 | Aug 92 | Sep 92 Cruise No. 5 | Oct 92 Cruise No. 6 | Nov 92 | Dec 92 | Jan 93 Cruise No. 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Anchor Scar/Cuttings** | | | | | | | | | | | | | | | | |
| Platform Hidalgo | Video | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |
| **Hard Bottom Communities** | | | | | | | | | | | | | | | | |
| PH-I | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-J | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-F | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-E | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-U | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-W | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-R | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-N | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |
| PH-K | Video/70 mm | | | | | | | | | | | | Video/70 mm | | | |

Figure 2.1-1d. Summary of DOI Phase III Survey Activities and Sampling: Biological Processes–ROV Surveys.

| ROV Biological Survey Studies | Feb/ Mar-93 | Apr/ May-93 | Jun/ Jul-93 | Aug-93 Cruise No. 8 Sep-93 Cruise No. | Oct/ Nov-93 | Dec-93 Cruise No. 10 ** Jan-94 Cruise No. 11 ! | Feb/ Mar-94 | Apr/ May-94 | Jun/ Jul 94 ## Cruise No. 12 | Aug/ Sep-94 | Oct/ Nov-94 | Dec 94/ Jan 95 ## Cruise No. 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Anchor Scar/Cuttings** | | | | | | | | | | | | |
| **Platform Hidalgo** | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| **Hard Bottom Communities** | | | | | | | | | | | | |
| PH-I | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-J | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-F | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-E | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-U | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-W | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-R | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-N | | | | | | ! Video/35mm | | | | | | Video/35mm |
| PH-K | | | | | | ! Video/35mm | | | | | | Video/35mm |
| | | | | | | ! Video/35mm | | | | | | Video/35mm |

## Month that survey occurred.

Figure 2.1-1d. Continued.

| Larval Studies | Apr 92<br>Cruise No. 2 +<br>Cruise No. 3 ^ | May 92<br>Cruise<br>No. 3 | Jun 92 | Jul 92<br>Cruise<br>No. 4 | Aug 92 | Sep 92<br>Cruise<br>No. 5 | Oct 92<br>Cruise<br>No. 6 | Nov 92 | Dec 92 | Jan 93<br>Cruise<br>No. 7 | Feb 93 | Mar 93 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Larval Filming Moorings | Larval Settling Plate Filming | | | | | Larval Settling Plate Filming | | | | | | |
| Farfield 1 (a) | + 2 wks | | | | | 3 wks | | | | | | |
| Farfield 1 (b) | + 2 wks | | | | | 3 wks | | | | | | |
| Farfield 2 (a) | + 2 wks | | | | | 3 wks | | | | | | |
| Farfield 2 (b) | + 2 wks | | | | | 3 wks | | | | | | |
| Farfield 3 (a) + (b) | + 2 wks | | | | | 3 wks | | | | | | |
| Hidalgo Nearfield (a) | + 2 wks | | | | | 3 wks | | | | | | |
| Hidalgo Nearfield (b) | + 2 wks | | | | | 3 wks | | | | | | |
| Harvest Nearfield (a) | + 2 wks | | | | | 3 wks | | | | | | |
| Harvest Nearfield (b) | + 2 wks | | | | | 3 wks | | | | | | |
| Hermosa Nearfield (a) | + 2 wks | | | | | 3 wks | | | | | | |
| Hermosa Nearfield (b) | + 2 wks | | | | | 3 wks | | | | | | |
| **Larval Igloo Arrays** | ← Larval Experiment No. 1 → | | | | | ← Larval Experiment No. 2 → | | | | | | |
| Farfield 1 | ^ 3 wks ▲ | | 6 months | | | | ▲ 3 day | | 6 months | | | |
| Farfield 2 | ^ 3 wks ▲ | | 6 Months | | | | ▲ 3 day | | 6 months | | | |
| Farfield 3 | ^ 3 wks ▲ | | 6 months | | | | ▲ 3 day | | 6 months | | | |
| Hidalgo Nearfield | ^ 3 wks ▲ | | 6 Months | | | | ▲ 3 day | | 6 months | | | |
| Harvest Nearfield | ^ 3 wks ▲ | | 6 months | | | | ▲ 3 day | | 6 months | | | |
| Hermosa Nearfield | ^ 3 wks ▲ | | 6 Months | | | | ▲ 3 day | | 6 months | | | |
| **Plankton Recorders** (not operational) | | | | | | | | | | | | |
| Hidalgo Nearfield | | | | | | ▲ | | | | | | |
| Farfield 1 | | | | | | ▲ | | | | | | |

▲ Item was recovered, serviced, and deployed on station.

Figure 2.1-1e. Summary of DOI Phase III Survey Activities and Sampling: Biological Processes–Larval Experiments.

| Larval Studies | Feb/ Mar-93 | Apr/ May-93 | Jun/ Jul-93 | Aug-93 Cruise No. 8 Sep-93 Cruise No. 9 | Oct/ Nov-93 | Dec-93 Cruise No. 10 •• Jan-94 Cruise No. 11 ! | Feb/ Mar-94 | Apr/ May-94 | Jun/ Jul 94 ## Cruise No. 12 | Aug/ Sep-94 | Oct/ Nov-94 | Dec 94/ Jan 95 ## Cruise No. 13 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Larval Filming Moorings** | | | | | | | | | | | | |
| Farfield 1 (a) | | | | | | •• ▲ | | | | | | |
| Farfield 1 (b) | | | | | | •• ▲ | | | | | | |
| Farfield 2 (a) | | | | | | •• ▲ | | | | | | |
| Farfield 2 (b) | | | | | | •• ▲ | | | | | | |
| Farfield 3 (a) + (b) | | | | | | •• ▲ | | | | | | |
| Hidalgo Nearfield (a) | | | | | | •• ▲ | | | | | | |
| Hidalgo Nearfield (b) | | | | | | •• ▲ | | | | | | |
| Harvest Nearfield (a) | | | | | | •• ▲ | | | | | | |
| Harvest Nearfield (b) | | | | | | •• ▲ | | | | | | |
| Hermosa Nearfield (a) | | | | | | •• ▲ | | | | | | |
| Hermosa Nearfield (b) | | | | | | •• ▲ | | | | | | |
| **Larval Igloo Arrays** | | | | | | | | | | | | |
| Farfield 1 | | | | | | ! ▲ | | | | | | ▲ |
| Farfield 2 | | | | | | ! ▲ | | | | | | ▲ |
| Farfield 3 | | | | | | ! ▲ | | | | | | ▲ |
| Hidalgo Nearfield | | | | | | ! ▲ | | | | | | ▲ |
| Harvest Nearfield | | | | | | ! ▲ | | | | | | ▲ |
| Hermosa Nearfield | | | | | | ! ▲ | | | | | | ▲ |
| **Plankton Recorders (not operational)** | | | | | | | | | | | | |
| Hidalgo Nearfield | | | | | | ! ▲ | | | | | | ▲ |
| Farfield 1 | | | | | | ! ▲ | | | | | | ▲ |

▲ Item was recovered, serviced, and deployed on station.
## Month that survey occurred.

Figure 2.1-1e. Continued.

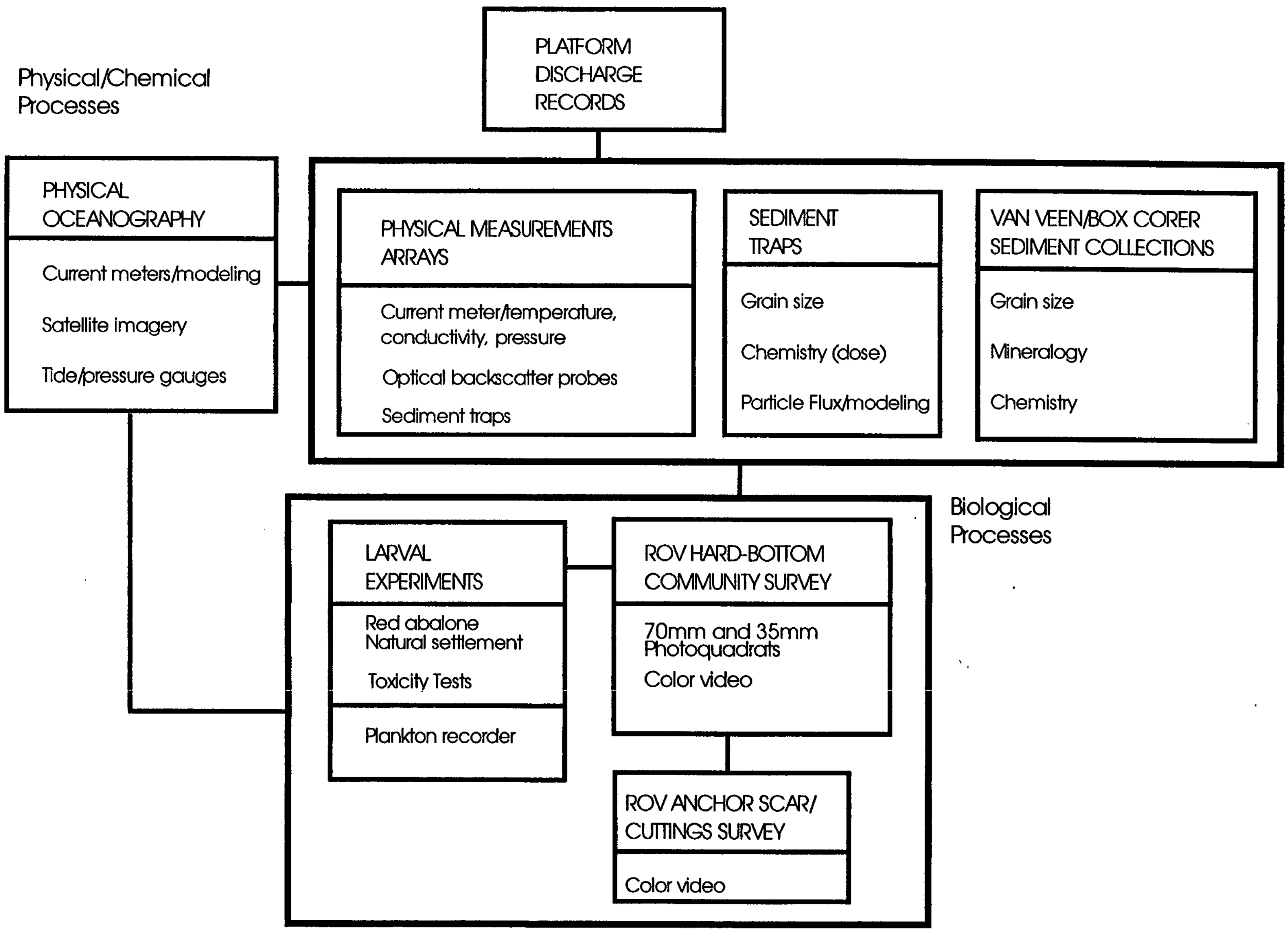



Figure 2.1-2. Interrelationship of Methods and Data Types Collected for DOI Phase III.

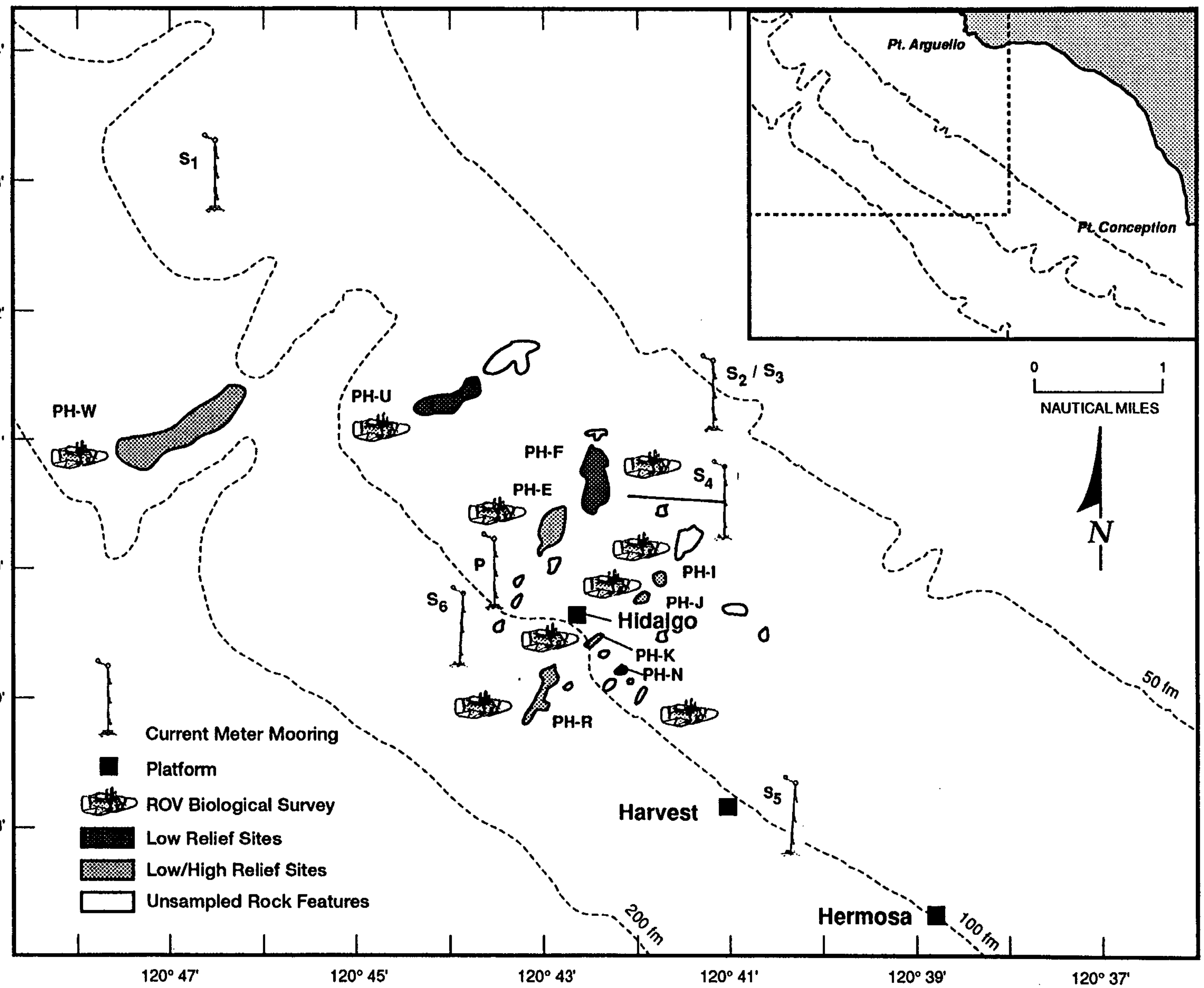



Figure 2.1-3. Approximate Location of Biological Community Study Sites (PH-E through PH-W), Primary Current Meter Mooring (P), Variable-Location Current Meter Moorings (S1-S6), and Platforms, DOI Phase III.

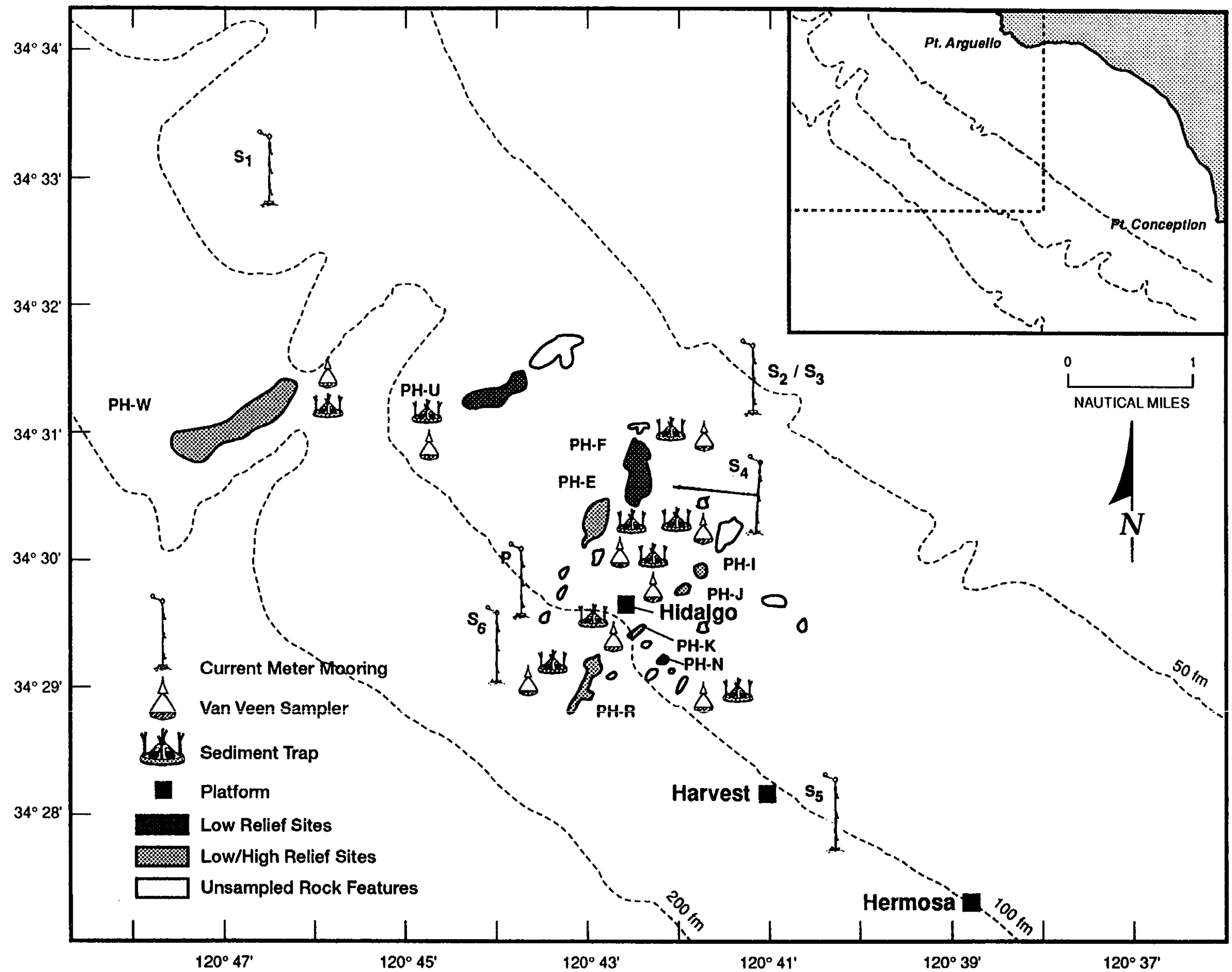



Figure 2.1-4. Approximate Location of Sediment Trap and Van Veen Sample Collection Sites Relative to Hard-Bottom Features (PH-E through PH-W), Primary Current Meter Mooring (P), Variable-Location Current Meter Moorings (S1-S6), and Platforms, DOI Phase III.

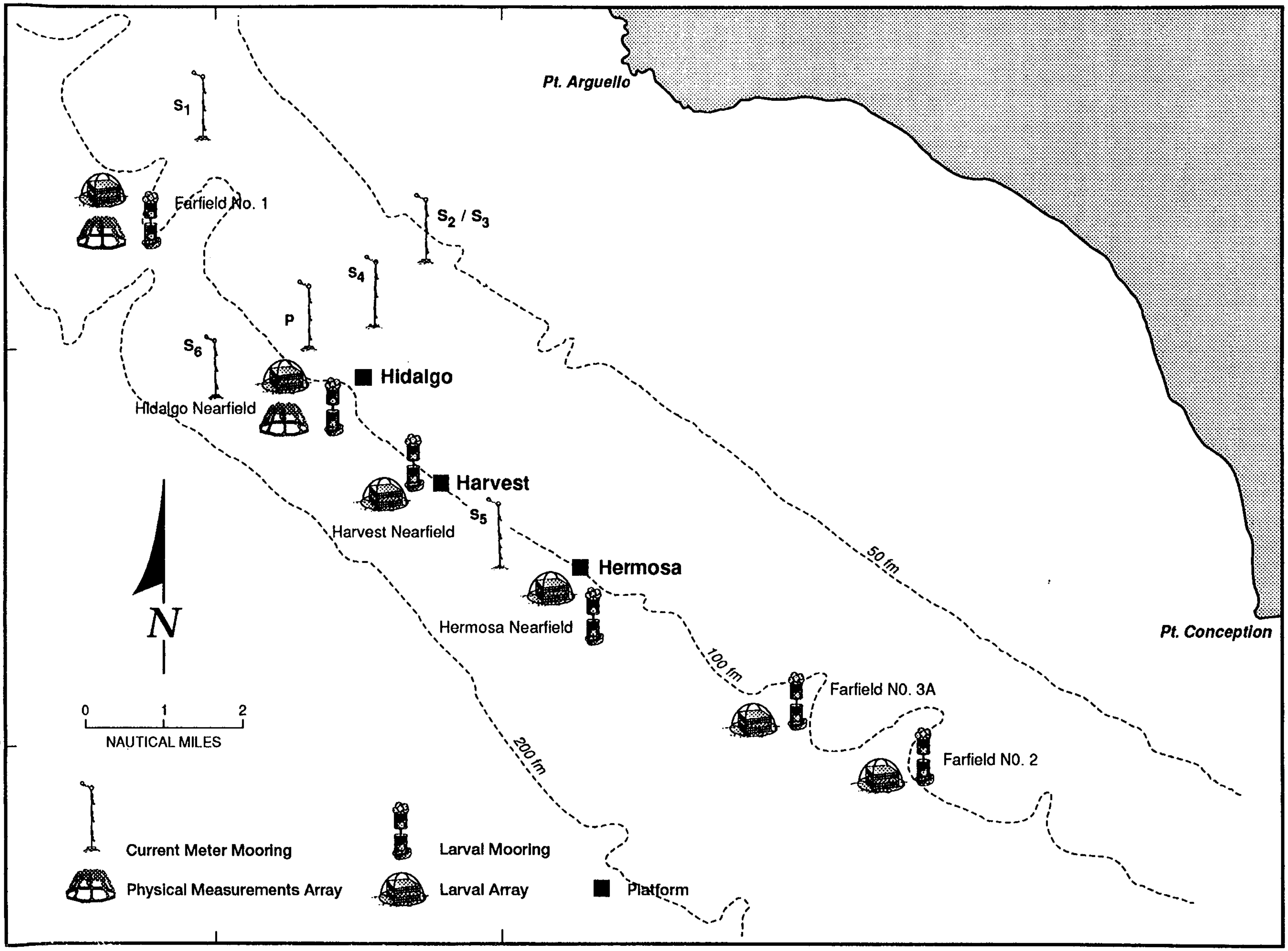



Figure 2.1-5. Approximate Location of Larval (Filming) Mooring, Larval (Igloo) Array, Physical Measurements Arrays, Primary Current Meter Mooring (P), Variable-Location Current Meter Moorings (S1-S6), DOI Phase III.

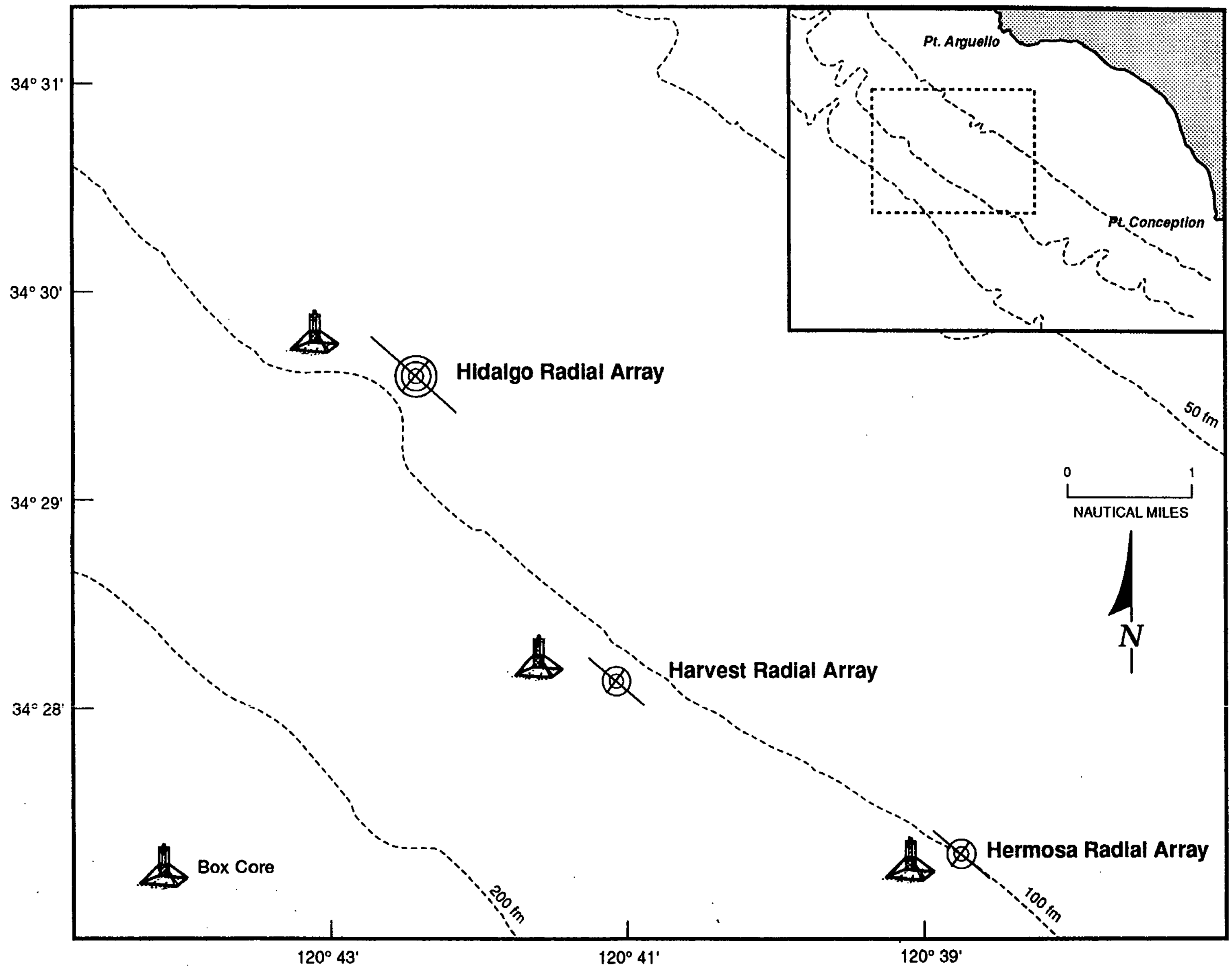



Figure 2.1-6. Approximate Location of Radial Arrays of Box Core Sampling Stations for Platforms Hidalgo, Harvest, and Hermosa, DOI Phase III.

size and mineralogy analyses were performed on some of the sediment samples. Compilation of platform discharge records was performed with data provided by the Environmental Protection Agency (EPA) and MMS.

Studies of biological processes involved the use of a remotely operated vehicle (ROV) to collect 70-mm or 35-mm photographic quadrats (Figure 2.1-1d) and color video data to assess hard-bottom communities in the vicinity of Platform Hidalgo. An ROV reconnaissance survey also was conducted near Platform Hidalgo to assess community effects from platform anchoring and disposal of drill cuttings. Finally, in situ larval settling experiments (natural and manipulated using red abalone larvae) were conducted at one nearfield and one farfield site each associated with Platforms Harvest, Hermosa, and Hidalgo, and laboratory toxicity tests were performed using drilling muds and species characteristic of the study area.

The overall study design focused on the Platform Hidalgo region. Assessments and studies using bottom-located STs, Van Veen grab collections of surface sediments, and SMRs were conducted in the immediate vicinity of nine hard-bottom sites (Figure 2.1-4). Current meter moorings were sited in the same general region (Figure 2.1-3). Additionally, the PMAs and two of the larval experiment sites were located near two of the nine hard-bottom sites, representing one nearfield and one farfield location. The remainder of the study sites were located near Platforms Harvest and Hermosa. These sites included the other four locations for the larval experiments and box core stations arranged in a radial array around all three platforms (Figures 2.1-5 and 2.1-6).

As described above, there was a high degree of spatial integration of data collected in the vicinity of Platform Hidalgo, with some ties to conditions and biological effects associated with Platforms Harvest and Hermosa.

The field studies were performed using five different survey vessels: the U.S. Navy-owned M.V. INDEPENDENCE (Pt. Hueneme, CA) for Cruise Nos. 1, 3, 6, 8 and 13; the M.V. GLORITA provided by GEO 3 (Santa Barbara, CA) for Cruise Nos. 2 and 4; the M.V. RAMBO from Aries Marine (Lafayette, LA) for Cruise No. 11; and the R.V. CAVALIER for Cruise Nos. 5 and 7 and the M.V. WM. A. McGAW for Cruise Nos. 9, 10 and 12, as provided by SAIC (Goleta, CA). The INDEPENDENCE is a 200 ft x 40 ft vessel with a large (40 x 77 ft) rear deck space, deck winches, and an extendable reach crane that assisted in handling of equipment for the ROV and larval experiment tasks (Section 2.4). The vessel also is equipped with bow thrusters and a dynamic positioning system that are critical for maintaining vessel position during rough sea and weather conditions that are typical of the study region. The RAMBO is a 185 ft x 45 ft cable-laying vessel that was substituted due to scheduling constraints for the INDEPENDENCE on one major cruise. Separate mobilization of a crane and winches was required to outfit the vessel for handling the ROV and larval experiments. The GLORITA, the CAVALIER, and the McGAW are 147 ft x 27 ft, 110 ft x 26 ft, and 106 ft x 26 ft vessels, respectively, with appropriate crane and winch capacities for conducting smaller-scale study tasks, such as deployments and recoveries of current meters and larval filming plate moorings.

Survey navigation on the INDEPENDENCE and the RAMBO utilized trisponder-based systems ($\pm$ 3 m accuracy) for all sample collections and deployments, including larval experiment igloos, STs, SMRs, and Van Veen and box corer sample collections. The trisponder system was linked to an O.R.E. Trackpoint system ($\pm$ 3 m accuracy) for all tasks that required the ROV, including biological community surveys, the anchor scar/drill cuttings reconnaissance survey, and ST recoveries. Navigation on the GLORITA, CAVALIER, and McGAW was accomplished using a global positioning satellite (GPS) system ($\pm \sim$ 50 m) calibrated against LORAN measurements.

Brief summaries of accomplishments for each cruise in the Phase III program are provided below.

**Cruise No. 1 (October 31 through November 10, 1991):**

Physical Processes—Twelve STs from the Phase II program were recovered and one ST was redeployed near each of the nine hard-bottom sites from Phase II; SMRs were deployed at each of the nine ST stations; reconnaissance surveys were conducted with the ROV near Platform Hidalgo to assess impacts from drill cuttings, anchor scars, or debris; samples of surface sediments were collected with a Van Veen grab sampler near the nine ST stations; and samples of surface and subsurface sediments were acquired with a box corer at fifteen stations surrounding Platform Hidalgo and nine stations each surrounding Platforms Harvest and Hermosa.

Chemical Processes—Surface sediment and ST samples were collected for trace metal and petroleum hydrocarbon analyses from the twelve ST, nine Van Veen grab, and fifteen + nine + nine box corer stations described for Physical Processes.

Biological Processes—ROV monitoring studies (70-mm photoquadrats and color video) of biological communities were conducted at the nine hard-bottom sites established during Phase II.

**Cruise No. 2 (April 2–4, 1992):**

Physical Processes—Two current meters were deployed to assess the scale of coherency of currents. One of the locations was at a site used historically near Platform Hidalgo during Phase II; the second location was several kilometers upcoast.

Biological Processes—"Warm season" larval experiments were initiated by deploying settling plates to monitor the growth of natural microbial films (i.e., plate conditioning). The deployments were at one near-platform and one reference site each, associated with Platforms Harvest, Hermosa, and Hidalgo (six sites total). The plates were collected during Cruise No. 3.

**Cruise No. 3 (April 16–22 and May 13–15, 1992, corresponding to Legs 1 and 2, respectively):**

Physical Processes—Three of nine STs were recovered and redeployed during Leg 1 and three additional STs were deployed during Leg 2. Adverse weather conditions prevented recovery and redeployment of the six remaining STs. One PMA each was deployed at one near-platform (nearfield) and one reference site (farfield) associated with Platform Hidalgo. Each PMA was outfitted with a current meter; water temperature, conductivity, and pressure sensors; optical backscatter probes; and STs.

Chemical Processes—ST samples were collected for trace metal and petroleum hydrocarbon analyses from the three ST stations described for Physical Processes.

Biological Processes—All settling plate moorings that had been deployed at the six sites for larval experiments during Cruise No. 2 were recovered. Larval experiment arrays (igloos) were deployed at the same six sites during Leg 1 of Cruise No. 3. Weather delayed recovery of the igloos until Leg 2, at which time five of the six were recovered and redeployed for long-term settling experiments. The sixth igloo could not be recovered due to difficulties associated with the acoustic release; it was recovered during Cruise No. 6.

**Cruise No. 4 (July 7–10, 1992):**

Physical Processes—Two current meter moorings were recovered, serviced, and redeployed. The variable-location mooring was moved to a second location that was nearer to shore than the site occupied during Cruise No. 2.

**Cruise No. 5 (September 24–27, 1992):**

Physical Processes—The current meter mooring from the historical site was recovered, serviced, and redeployed.

Biological Processes—"Cold season" larval experiments were initiated by deploying settling plates for filming at the same six sites described for Cruise No. 2. The plates were collected during Cruise No. 6.

**Cruise No. 6 (October 15–24, 1992):**

Physical Processes—Twelve STs were recovered (three from Leg 1 of Cruise No. 3, three from Cruise No. 3, and the six remaining STs that were not recovered during Cruise No. 3); the STs were redeployed at each of the nine historical stations; the two PMAs were recovered, serviced, and redeployed at the stations described for Cruise No. 3; the second current meter mooring was deployed; and sediment samples were collected with a Van Veen grab sampler near the nine ST stations.

Chemical Processes—Surface sediment and ST samples were collected for trace metal and petroleum hydrocarbon analyses from the twelve ST and nine Van Veen stations described for Physical Processes.

Biological Processes—The larval settling plate moorings deployed at the six sites during Cruise No. 5 were recovered; The six larval experiment igloos at the sites described for Cruise No. 3

were recovered and redeployed; and ROV monitoring studies (70-mm photoquadrats and color video) of the biological communities were conducted at the nine hard-bottom sites surveyed during Cruise No. 1.

**Cruise No. 7 (January 19-21, 1993):**

Physical Processes—CMs were recovered from two stations, one primary mooring near Hidalgo and the second located approximately 1.5 nautical miles inshore and northeast. All data were collected from both CMs, and redeployed.

**Cruise No. 8 (August 2-7, 1993):**

Physical Processes—PMAs and CMs were recovered and redeployed at two stations, with the secondary CM moved to a new location. Nine STs were recovered from their respective stations. All STs were redeployed, with two being relocated from Hidalgo to Hermosa in anticipation of upcoming discharge events.

Chemical Processes—ST samples were collected from nine stations for chemical analyses. "Tuffy Scrubbers", representing settling substrates, were placed for Scripps Institution of Oceanography (SIO) on STs at five of the nine ST locations and the two relocated stations.

Biological Processes—Six larval igloo arrays were recovered, the settling plates were photographed, and the igloos redeployed.

**Cruise No. 9 (September 17-18, 1993):**

Biological Processes—This part of the survey was cancelled prior to deployment of settling plate conditioning moorings due to the rapidly progressing drilling schedule at Hermosa.

**Cruise No. 10 (December 18-21, 1993):**

Physical Processes—Two CMs were recovered and redeployed and all data were collected, except for the General Oceanic (GO) current meter at the bottom of CM No. 1, which was damaged by an unknown cause.

Biological Processes—A total of 12 settling plate conditioning moorings were deployed (as described in Cruise No. 3) to initiate larval experiments for the platform drilling period.

**Cruise No. 11 (January 5-18, 1994):**

Physical Processes—PMA instrumentation was redeployed on "in-line" moorings (i.e., without igloos) due to potential interference of the S4 current meters by the igloo frame. A total of nine STs (eight STs which were recovered plus one reserve) were redeployed at the recovery stations; the ST at PH-I could not be recovered.

Chemical Processes—Sediments from eight STs were collected for chemical analyses. A single VV grab also was taken at the two Hermosa stations.

Biological Processes—All six larval experiment igloos were recovered, settling plates photographed and injected with red abalone larvae, and redeployed for a 3-day settling experiment. The igloos were subsequently recovered and settling plates analyzed. Plankton recorders were deployed at two stations. ROV biological surveys (35-mm photoquadrats and color video) were completed at their nine respective stations.

**Cruise No. 12 (July 20-23, 1994):**

Physical Processes—Two CMs were recovered and all data were retrieved; CM No. 1 was redeployed; CM No. 2 was not redeployed (by plan). PMA No. 2 was recovered at Farfield No. 1 location, while PMA No. 1 could not be recovered, presumably due to failure of the acoustic release.

Biological Processes—Neither of the PR igloos could be recovered from Hidalgo Nearfield or Farfield No. 1 locations due to failure of the acoustic release batteries.

**Cruise No. 13 (January 6-15, 1995):**

Physical Processes—The final PMA was recovered (see Cruise No. 12) at Hidalgo Nearfield and all data were retrieved from the S4 current meter, sediment trap tubes, and optical backscattering sensors. Four passive acoustic reflectors (to mark permanent photoquadrat stations) were deployed at high- and low-relief sites at PH-R and PH-I. All STs were recovered, seven from hard-bottom locations and two from relocated positions at ST-LA3 and ST-LA6.

Chemical Processes—STs were recovered and sampled for PAHs, PHCs, selected biomarkers, Ba, Al, and TOC. Box core samples were taken at 15 stations. All VV surface sediment samples were collected and analyzed for PAHs, selected biomarkers, Ba, and Al.

Biological Processes—Two PR igloos were recovered from Hidalgo Nearfield and Farfield locations. ROV monitoring studies (35-mm photoquadrats and color video) were conducted at their nine respective stations.

## 2.2 PHYSICAL PROCESSES

Physical processes tasks included current measurements (Section 2.2.1), wave/tide/wind measurements (Section 2.2.2), satellite imagery (Section 2.2.3), physical measurements arrays (Section 2.2.4), sediment measurement rods (Section 2.2.5), and particle transport modeling (Section 2.2.6). Parameters such as sediment grain size and mineralogy that are closely integrated

integrated with evaluations of chemistry data from ST, Van Veen grab, and box corer collections are addressed under chemical processes (Section 2.3).

### 2.2.1 Current Measurements

#### 2.2.1.1 Field Survey

Current measurements were made at a primary, fixed-location mooring near Platform Hidalgo and at a secondary mooring that varied in position by a few to several kilometers from the platform (Table 2.2-1 and Figure 2.1-1a). Design of the moorings was similar to Phase II (Steinhauer and Imamura 1990). The primary mooring was placed at the same location as during Phase II and was intended to maintain continuity with these earlier measurements. The purpose of the secondary mooring was to assess the scale over which currents were coherent (similar) compared to the data from the fixed mooring.

Current meters used included Neil Brown Smart Acoustic Current Meters (SACMs) as primary instruments and General Oceanics MkII (GO) current meters as backups. The primary mooring consisted of current/temperature sensors placed at water column depths of 15, 54, and 126-m (Figure 2.2-1). The original design for Phase II utilized telemetry to transmit data to shore from the primary mooring. However, the design was altered for Phase III such that backup current meters were placed at each of the three depth levels and data telemetry was eliminated. The secondary mooring had a similar configuration to the primary mooring except that the current meters generally did not have backup instruments (Figure 2.2-1). Use of backup instruments proved to be a very successful method for maintaining continuous current measurements at the primary mooring site over 2.5 years. Consequently, data return was much greater than during Phase II.

Both mooring designs included a subsurface float (for line tension and vertical stability) that was linked to a surface float. The surface float was the primary means of mooring deployment and recovery. An "anchor last" approach was used during deployment and recovery of the current meters. For this procedure, the survey vessel approached the mooring site by steaming slowly into the current along the target isobath. During deployment, the upper portion of the mooring was placed in the water and allowed to move away from the vessel due to the current and the ship's forward movement. Once at the site, the anchor was lowered to the bottom using an onboard winch and A-frame. When the anchor was on the bottom, an in-line acoustic release was activated and the winch wire was separated from the anchor. A similar procedure was used to deploy the separate (but linked) wave/tide gauge (Section 2.2.2) and the secondary mooring. During recovery, a line in a canister, which was attached above and below the acoustic release, was used to retrieve the anchor. When the release was activated, the main (taut) mooring separated from the anchor and was brought onboard the vessel by sequentially retrieving all

Table 2.2-1. Current Meter Mooring Deployment Information, DOI Phase III.

| Station | Latitude (N) | Longitude (W) | Deployment Period | Bottom Depth (m) |
|---|---|---|---|---|
| P1 | 34°30.1' | 120°43.1' | April 1992 to January 1995 | 133 |
| S1 | 34°32.8' | 120°46.0' | April 1992 to July 1992 | 130 |
| S2 and S3 | 34°31.4' | 120°44.2' | October 1992 to January 1993 | 91 |
| S4 | 34°30.3' | 120°42.2' | January 1993 to August 1993 | 109 |
| S5 | 34°28.3' | 120°40.1' | August 1993 to December 1993 | 130 |
| S6 | 34°29.4' | 120°43.9' | December 1993 to July 1994 | 280 |

P = primary mooring location
S = secondary mooring locations

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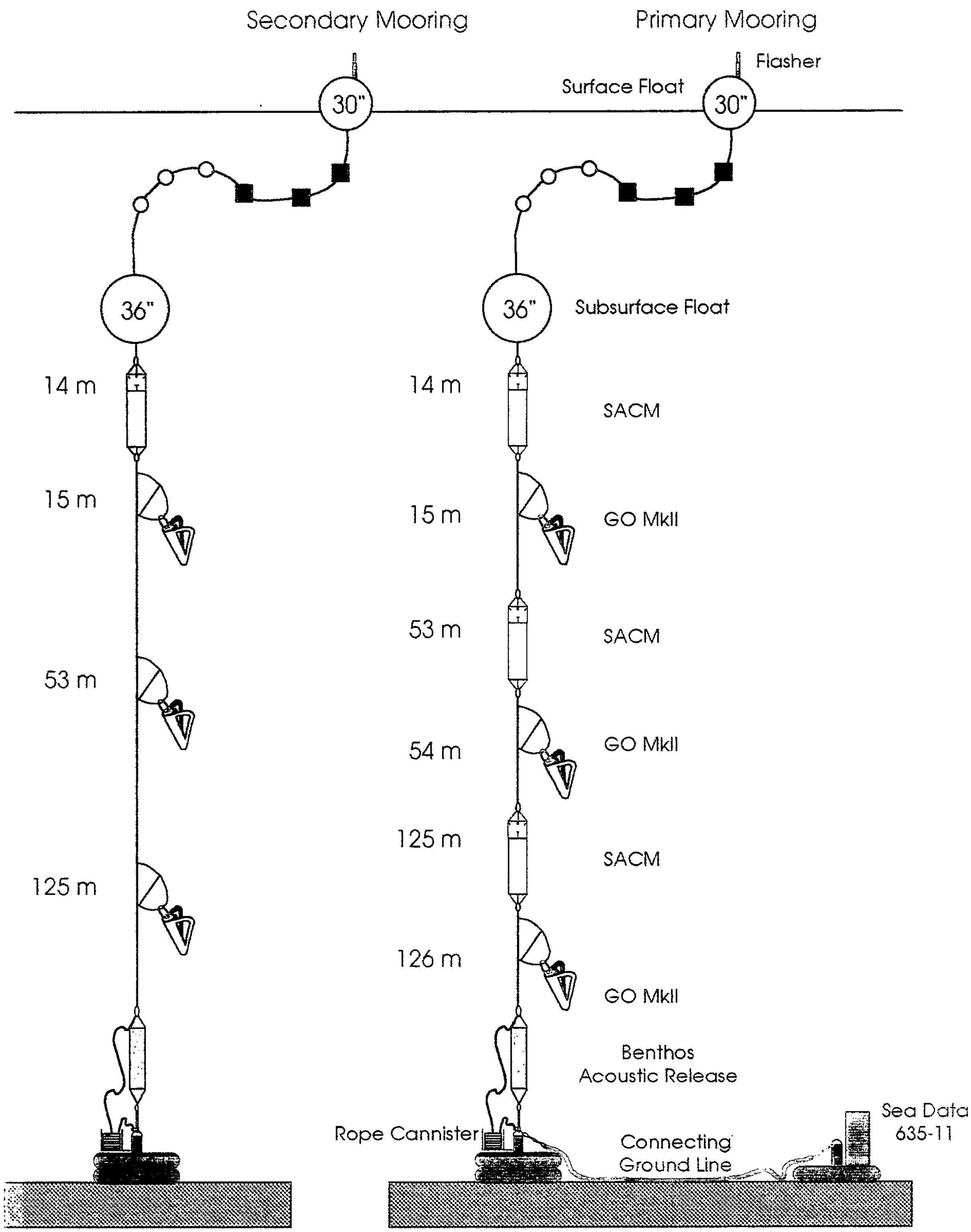


Figure 2.2-1. Schematic of Moorings Deployed as Part of the DOI Phase III Program.

Throughout the field activities, the primary mooring remained in the same location as occupied during Phase II. The secondary mooring was moved every three to six months to provide observations for evaluating coherence scales of horizontal currents.

SACM = Smart Acoustic Current Meter, GO MkII = General Oceanics; Mark II current meter; Sea Data 635-11 is the wave/tide gauge.

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elements from the top down. Once the mooring was recovered, the rope link was used to recover the anchor. The ground line then was used to recover the wave/tide gauge. This approach resulted in all anchors being retrieved.

#### 2.2.1.2 Laboratory/Data Analyses

During mooring rotation cruises (Figure 2.1-1a), current meter instruments were cleaned, data were retrieved, and performance of the instruments was evaluated. Data from the SACMs were stored in digital form in internal memory. These data were downloaded to a computer onboard the survey vessel and scanned to identify any performance problems, usually based on the amount and consistency of tape advance compared to the expected advance.

Each current meter record represents time series of perpendicular (orthogonal) components for current velocity and temperature values at user-specified intervals. During data processing, each velocity component and temperature record was linked temporally.

The following data processing steps were used:

- Translation of current and temperature data from internal instrument formats to calibrated (ASCII formatted) engineering units; and

- Data cleanup, using an interactive computer routine, as appropriate, to remove outlier values and interpolate data gaps to the basic sampling interval.

If the sampling interval was less than or equal to one hour, one- or two-point outliers or data gaps were replaced with interpolated data. For such short records, straightforward linear interpolation of each component was used. For gaps between one and approximately six hours, a bicubic spline under tension was used to provide interpolated values. The frequency and magnitude of the expected current variability was evaluated prior to any interpolation over gaps larger than six hours.

Following translation and cleanup, all time series data were entered into an SAIC Physical Oceanographic Data Management System (DMS) for further processing. The DMS standardizes data formats, allows incorporation of consistent data processing routines, and provides a method of linking any given time series to earlier or later data records. Data recorded as speed and direction then were converted to component vectors for preliminary data analysis.

Preliminary data analysis included the following:

- 3- and 40-Hour Low Pass (HLP) filtering;
- Auto spectra (of velocity components);

- Coherence and phase (of velocity components); and
- Statistical analyses.

For sampling intervals less than 60 minutes, the first step was to apply a 3-HLP filter (with a Lanczos taper) to the data and decimate the filtered data to hourly increments (e.g., $\Delta t = 60$ minutes). The 3-HLP filter suppresses only the very highest frequency variability (e.g., one- to two-hour periods) within the time series. The decimation ensures comparison of current/temperature estimates at comparable time periods. Within a given study period, time series were truncated to a common start time ($t = 0$), typically representing that time when the last instrument began providing useful data. This procedure provided a common period for subsequent detailed analyses (i.e., spectra and statistics).

For time series with initial sampling intervals greater than or equal to 60 minutes, the initial step involved applying a 40-HLP filter (with a Lanczos taper) to the data and decimating the filtered data to six-hour increments. The 40-HLP filter suppresses the amplitude of variability at frequencies greater than or equal to the diurnal frequency.

Auto spectra were used as a method for partitioning the variability of each current component by frequency. This partitioning identified the frequencies at which the more important (larger-amplitude) current fluctuations occur and provided a preliminary step toward resolving and characterizing circulation processes in the study area. This information, when available from different depths and different moorings, provided insight into the regional and depth-dependent structure of these patterns.

Coherence analyses provided an estimate of the correlation between two time series (in this case between the primary and secondary moorings) at each frequency. Similarly, phase data provided an estimate of the relative lag at each frequency between the coherent (correlated) components of the two signals. This analysis helped resolve the following items:

- Relationships between velocity components for a given instrument (u versus v); and

- Horizontal and vertical coherence between comparable velocity components, which helped to define time-averaged spatial scales of the circulation patterns.

Standard statistical analyses of each time series included calculation of the mean, variance, skewness, principal axes, maximum and minimum values, and the ratio of 40-HLP to 3-HLP variance. Additional data products included 3-HLP component and temperature data plots, and vector "stick" plots of 40-HLP data. Velocity variance was directly proportional to kinetic energy at the measurement site. Therefore, this ratio indicated the relative importance of energy at frequencies above and below the diurnal period. A value of 1 means no high-frequency energy and a value of zero means no sub-diurnal current variability. The statistical routine also computed the principal axes of the currents (i.e., relative to true north), thereby minimizing the variance of the cross-axis current component. To help interpret these processes, the principal axes were compared to the general orientation of the isobaths to evaluate the importance of cross-isobath (onshore) flow. Many of these statistical quantities are displayed graphically in the form of 40-HLP variance (or standard deviation) ellipses and mean vectors. A variance ellipse summarizes the standard deviations of the 40-HLP currents in the orthogonal directions of the principal axes (see Appendix A).

To help resolve fluctuations for higher-frequency currents, tidal analysis was applied to the current time series. These results provided an estimate of the amplitude and phase of all primary and interactive tidal constituents. Those constituents that contributed significantly to the observed velocity field then could be presented graphically as tidal hodographs (Appendix A).

### 2.2.2 Wave/Tide/Wind Measurements

#### 2.2.2.1 Field Survey

Wave and tide measurements were made using a bottom-located gauge incorporated as part of the primary current meter mooring (Figure 2.2-1). The deployment period and methods for deployment and recovery were described earlier for the primary mooring (Section 2.2.1). Wind data were obtained from NDBC Buoy Nos. 46023, 46011, and PTGC1.

The Sea Data 635-11 Wave and Tide Gauge used for the study was a self-contained, digitally recording instrument. It included a ParosScientific quartz pressure sensor with a 0–400 psia (pounds per square inch atmospheric) range to measure bottom pressure and a thermistor to measure water temperature. The instrument housing was attached directly to an anchor connected by a ground line to the primary mooring anchor (Figure 2.2-1). This placement helped ensure that measured variations in pressure resulted from changes in the height of the overlying water column rather than changes in the depth of the sensor.

The instrument allowed for separate, user-selected schemes for tide and wave measurements. Wave data collected as a burst of high-frequency pressure measurements were taken one per second for 1,024 seconds (approximately 17 minutes) and recorded once every six hours. Time series data for tidal water level and temperature resulted from pressure and temperature measurements averaged over 3.75 minutes, producing 16 estimates per hour. These data were processed as described below.

### 2.2.2.2 Laboratory/Data Analyses

Processing of wave and tide gauge data was accomplished by first downloading the tape followed by creation of a hexadecimal data file. File creation was performed by Sea Data during the initial stages of Phase III, and then by Woods Hole Instruments, Ltd. (after the owner of Sea Data instruments dropped support for the line).

The resulting data files represented mean pressure and bursts of high-frequency pressure measurements. Mean pressure provided information on tides and other processes producing fluctuations in water level with periods greater than approximately 10 to 12 minutes. The burst duration of approximately 17 minutes also allowed for calculations of statistics for wind-wave frequency fluctuations. Mean tidal pressure was filtered using a 3-HLP filter and then decimated at hourly intervals. During processing, the wave data for each burst were evaluated and a variance of pressure was computed. The variance was used as an indicator of significant wave height for those waves that produced pressure effects (i.e., wave-induced velocities) at the bottom. Significant wave height was defined as the average height of the highest one-third of the waves.

Pressure due to surface (wind-induced) waves was not evaluated. This type of pressure is attenuated with depth as a function of wave length or, equivalently, wave period. This pressure attenuation factor operates as a low-pass filter such that, for a given water depth, the higher-frequency waves are attenuated more severely than low-frequency waves. As a consequence, the high-frequency pressure observations made by the Sea Data gauge do not reflect the complete surface wave field. Rather, they reflect an amplitude attenuated (low-pass filtered) wave field. An example of the pressure attenuation factor for the depth of the Sea Data gauge is shown in Figure 2.2-2. These data indicate that there was a significant reduction in the sensed pressure created by surface waves, even for relatively long-period waves (10 seconds). The pressure attenuation factor is independent of wave height and is only dependent on wave period and water depth. As a consequence, the variance-based estimate of pressure fluctuations was only used as an indicator of events that might produce appreciable wave-induced bottom currents.

Data for wind speed (meters per second) and direction as well as sea-surface temperature (SST) (°C) were measured by NDBC buoys as a time series at one-hour intervals. Initial processing consisted of checking the data for gaps. Relatively short gaps were filled by interpolation, while longer gaps were excluded from the database. The wind data were converted to component forms such as north and east vectors, which were rotated to provide components aligned along and across the local isobaths. The data were processed through a 40-HLP filter to remove noise and decimated to six hour intervals in the same manner as the current meter data.

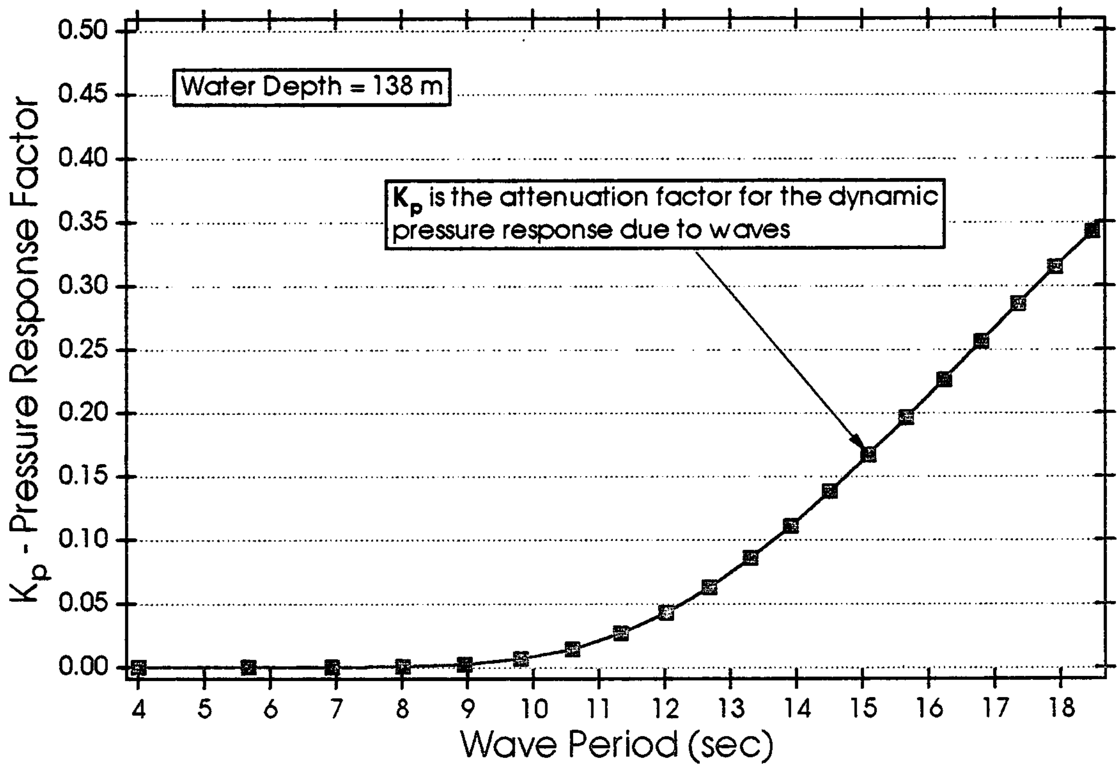


Figure 2.2-2. Example of the Effects of Depth on Wind-Wave Attenuation at the Bottom (138 m).

For even an 18.5-second wave, the effects of depth have reduced the pressure to little more than 30% of that measured near the surface. For approximately 10 second waves, no dynamic pressure was sensed at the bottom; that is, the dynamic pressure was completely attenuated at the bottom (138 m).

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Standard statistical techniques applied to the wind and temperature data included calculation of means and variances of the filtered and decimated wind records and the SST records. Statistics showing frequency of occurrence and duration of different wind speed and direction classes were calculated for monthly intervals and displayed in tabular form and as wind roses. Spectral techniques were used to determine the principal time scales (most energetic frequency bands) in the wind records at each station. Coherence and phase among components at different stations and between stations and the current meter records also were computed.

## 2.2.3 Satellite Imagery

### 2.2.3.1 Field Survey

SST data were collected by the Advanced Very High Resolution Radiometers (AVHRRs) onboard NOAA's polar-orbiting satellites. These sensors measure visible and infrared radiation in four or five separate bandwidths at a spatial resolution of approximately 1.1 km (pixel size). These data were converted from radiance to temperature and corrected for atmospheric effects. Each polar-orbiting satellite passes over a portion of the west coast, including the study area, twice a day. This is generally one daytime and night pass. SST images can be obstructed by cloud cover and fog, which shields the underlying water surface and absorbs sea-surface radiation in the thermal band. Typically, cloud tops appear as consolidated cold/cool areas which are often easily detectable by their shape and location in the images.

### 2.2.3.2 Laboratory/Data Analyses

Raw digital images were received from a subcontractor (Ocean Imaging, Inc.) and then processed by SAIC to create daily or twice daily images of a 512 km x 512 km area centered approximately on Pt. Conception (Figure 2.2-3). For the study, 1,812 images were acquired for the period November 1, 1991 through April 30, 1994. The data processing procedure first involved screening images to reject those with extensive cloud cover. Adjustments were then made to the navigation parameters to place the image precisely over known geographic locations. An overlay was developed that masked the land areas and showed selected bathymetry and other features of interest including the moorings. To minimize the amount of the sea-surface imagery that was cloud-covered, "warmest pixel" compositing was used. This method involved selecting the warmest pixel at each location from among the images. These warmest pixels were then used to create a composite image. The goal was to create one composite per week that showed the study area as essentially cloud free.

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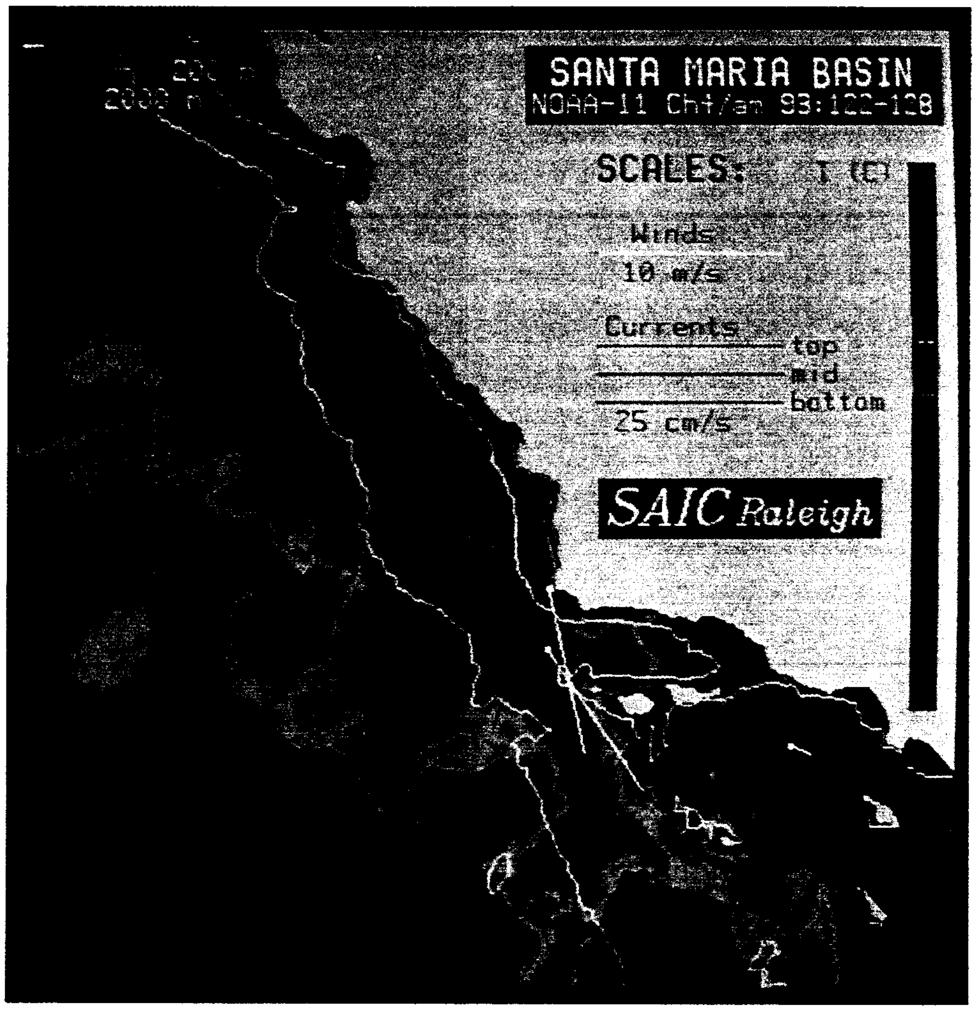


Figure 2.2-3. Representative Composite Satellite Thermal Image of the Phase III Study Area.

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The study region often was characterized by a convergence of cooler water from the north and warmer water from the south, which resulted in comparatively strong horizontal thermal gradients. To distinguish these differences most easily, one-degree Celsius intervals were assigned separate colors. For the images used in this report (e.g., Figure 2.2-3), the warmest to coolest temperatures were presented sequentially as red, orange, yellow, and green to blue. Cold cloud tops were designated as white so they could be easily identified. Specific temperatures are not shown because patterns rather than actual SSTs are used to indicate regional circulation patterns.

For the images presented, scaled vectors that represented current data collected at the upper current meters (approximately 15 m below the surface) at the primary and secondary moorings were overlaid on the SST image. These vectors represent daily-averaged currents that corresponded to the time period of the composite image. This method provided at least two sets of in situ observations that were used with the temperature patterns to aid in describing circulation/current patterns for those dates.

In this report, imagery was used in the analyses primarily in a qualitative manner, for example, to identify circulation patterns typical of eddies (circular, swirling motions) and upwelling (patches of cold water along the coast). Evaluations were made routinely of SSTs measured at the NDBC buoys compared to satellite-determined temperatures. Such checks ensured that features identified in the imagery could be properly related to features observed in the current meter records.

## 2.2.4 Physical Measurements Arrays

### 2.2.4.1 Field Survey

Measurements of near-bottom suspended material and currents in the vicinity of Platform Hidalgo were conducted using two specially designed PMAs, each of different design (Appendix A).

One array was located at a nearfield site approximately 800 m to the southwest of Platform Hidalgo, near Station PH-N, in 195 m of water (Figure 2.1-5). The second array was placed at a farfield site approximately 5 km to the northwest of the platform, near Station PH-W, in 215 m of water (Figure 2.1-5). Both arrays were placed in close proximity to mixed-relief, hard-bottom features as determined from earlier ROV surveys (Section 2.4.1). The farfield array was considered to be beyond the influence of drilling-associated discharges, based on Phase II modeling (Coats 1994), and was intended to represent a control for the nearfield site. The general northwest-southeast trend of the depth contours to the east of Pt. Conception (Figure 2.1-5) is interrupted in the vicinity of the farfield station by a canyon-like formation with a major axis oriented along a northeast-southwest line. This feature, in combination with rocky outcrops in the area, complicates the bathymetry, and presumably the current structure, in the vicinity of the farfield station.

The first PMA design was utilized from April 1992 to August 1993. These PMAs were approximately 2 m high and nearly hemispherical in form, with a network of eight cylindrical legs extending upward from the base to a horizontal platform (Appendix A). This platform provided support for a spherical segment of syntactic foam flotation held in place by an acoustic release (Datasonics ATR-397). A cylindrical line canister containing 300 m of 9.5 mm Kevlar line was positioned below the float and adjacent to the acoustic release. This line, with one end anchored to the upper platform and the other attached to the float, served as the primary recovery line for the array.

Array subsystems as described below were mounted on specially designed, stainless steel (Type 304) frames (Appendix A). The profile, strength, and weight of these frames was intended to minimize the potential for interference with (or disturbance by) bottom fishing activities. The frames were octagonal in form with a maximum width of approximately 4 m. Contoured lead weights were bolted in place around the perimeter of the base, providing a stable, low-profile mass to anchor the array and provide a footing with minimal frontal area and presumed potential for flow disturbance.

However, following analysis of S4 current meter records from Deployments 1 and 2 (Figure 2.1-1a), including comparisons with nearby (primary) mooring data, it was determined that the stainless steel frames were adversely affecting the velocity data by producing a clear bias in both speed and direction. Since the factors responsible for the apparent anomalies could not be simply defined, the decision was made to replace the stainless frames with a taut-wire (in-line) configuration consisting of a floatation array supported by a stainless mounting bracket bolted to and extending upward from the S4 current meter. The lower attachment point on the current meter was shackled to a short length of dacron braided line, which in turn was attached to an acoustic release (Datasonics ATR-397) and a recovery line canister mounted on a lead dead-weight anchor. In this configuration, the optical sensors were positioned approximately 3 m above the sediment-water interface at a single point on the vertical attached to the stainless bracket holding the floatation (Appendix A). Sediment traps were located at two points on the vertical: one set mounted immediately adjacent to the optical sensors (3 m above the bottom (mab)) and a second attached to the recovery line canister on the anchor (<0.5 mab). Data reviews indicated that, although the modified configuration did not provide the physical protection afforded by the original stainless frames, it did serve to eliminate the velocity bias apparent in the data obtained during Deployments 1 and 2. This in-line design was utilized for the Deployment 3 period (January 1994-January 1995; Figure 2.1-1a).

Regardless of the design (hemispherical or in-line), each array contained a single electromagnetic current meter (InterOcean S4) with integral sensors for water temperature, conductivity, and pressure. The current meter and associated sensors were positioned to sample conditions approximately 1 m above the sediment-water interface. This position corresponded to an intermediate substrate relief height relative to the low relief (≤ 0.5 m) and high-relief (~ 1.0 m+)

heights studied for other components of the Phase III program (discussed in this section and Section 2.4.1). The current meter also provided power for and received data output from two optical backscattering probes (Downing & Associates OBS-3) designed to monitor suspended material concentrations. These probes were located approximately 1.0 and 1.5 m above the bottom for the 1992-1993 deployments and 3 m above the bottom for the 1994-1995 studies (see above).

During Deployment 1, each current meter system was programmed to "burst-sample" all sensors four times each hour at a rate of two hertz for a period of approximately sixty seconds. For Deployments 2 and 3, the burst sampling rate was reduced to two times per hour. Following burst-averaging, all data were recorded internally on a solid-state memory system having a one megabyte capacity.

In addition to the electronic systems, each instrument array contained four "mechanical" STs. Two of the traps were positioned immediately adjacent to the sediment-water interface and two were placed at a higher elevation, approximately 1.5 m and 4.5 m above the bottom for the 1992-1993 and 1994-1995 deployments, respectively. All traps were constructed of clear acrylic tubing (6.6 cm internal diameter) with an approximate length of 45 cm. A cluster of 10 mm diameter plastic tubes were used to form a honeycomb (baffle) structure in the upper 10 cm of each trap. Chemical additives to inhibit biological activity in the traps were not used.

Prior to deployment of the PMAs, the electronic subsystems were calibrated in the laboratory to ensure accuracy and proper functioning. The current meter and associated sensors for water temperature, conductivity, and pressure were calibrated by the manufacturer. The optical sensors were laboratory-calibrated at the University of Connecticut using various concentrations of sediments suspended by mechanical agitation in a saltwater bath. Characteristics of the calibrating sediments, with particular emphasis on grain size, were similar to those expected at the study sites. The laboratory data indicated that the response of the sensors was reasonably linear over a concentration range of 0–80 mg/liter (SAIC and MEC 1993). These maxima generally exceeded concentrations observed along exposed continental shelf areas.

The PMAs were deployed by careful lowering while attached to the winch cable on the survey vessel. Following placement of the array on the bottom the cable was released acoustically. Recovery normally was planned using activation of the acoustic release and subsequent surfacing of the float attached to the Kevlar line. However, during some surveys the acoustic release system did not function properly, thus requiring the use of an ROV equipped with a lifting-line attachment.

After recovery of the PMAs, the internally recorded data were downloaded onboard the survey vessel using a portable computer. Calibration data then were applied and each record was initially screened to evaluate sensor performance and any need for sensor replacement. Typical problems included partial malfunction of several of the optical sensors, with some portion of signal degradation associated with biofouling. Additionally, each of the mechanical STs was removed from an array, visually examined (noting stratification, inclination of the sediment-water interface, color, and presence or absence of biota) and then emptied into precleaned glass jars. The jars were refrigerated and returned to the University of Connecticut laboratory for analysis of the dry weight of material and the combustible fraction.

#### 2.2.4.2 Laboratory/Data Analyses

Manufacturer's software (InterOcean, Inc.) was used to convert current speed and direction, pressure, salinity, and temperature data from the S4 current meter systems to engineering units. Data for optical backscattering were output as voltages, which then were converted to units of milligrams/liter using a regression equation derived from calibration data (SAIC and MEC 1993). All data then were plotted and visually inspected for outlier values, which were eliminated from the database. After this first-order quality control procedure, time series data files and plots of instantaneous burst-average values were generated. These instantaneous values were essential for evaluation of local sediment resuspension and/or deposition and, in combination with the low-pass filtered current meter data, complemented efforts to resolve larger-scale routes and fates of sediment transport.

Spectral analysis of selected time series data used a standard Fast-Fourier Transform algorithm (Matlab Mathematical Software). The data were binned and transformed such that each frequency estimate represents an ensemble average having particular degrees of freedom and associated confidence limits. The 95% confidence interval for the spectral estimate also was calculated. The resulting frequency spectrum was plotted with the accompanying 95% confidence intervals.

Sediment flux values ($g/m^2/day$) for the STs were based on dry weight determinations of the material recovered in each trap. The ST samples also were combusted at 550° C for one hour and reweighed to determine organic content (i.e., weight loss on combustion).

### 2.2.5 Sediment Measurement Rods

#### 2.2.5.1 Field Survey

Assessments of changes in bottom sediment levels, potentially associated with sediment transport events, were planned as an incidental activity associated with ROV recoveries of the STs (Section 2.3). For this purpose, SMRs were deployed in October/November 1991 at each of the nine ST sites (Figure 2.1-4). Each SMR consisted of an approximately 0.75 $m^2$ steel base (for stability) with a spring connection to an upright, 1 m tall rod. The spring system was intended to minimize interferences associated with bottom trawling activities. Each rod was coded with separate identifying marks and the length of the rod was marked in centimeters to indicate the height of any sediment accumulation. Location and documentation of changes in sediment levels was to be accomplished using the video system on the ROV. Deployment of each SMR was performed by lowering it to the bottom while attached to the survey vessel's winch cable. Release of the SMR from the cable was accomplished using a pelican-hook system.

Following deployment of the SMRs in October/November 1991, none of the units have been observed again during normal survey operations using the ROV. The reason for the disappearance of the units is unknown but may be related to the low "reflective" profile of the SMRs. Thus, no SMR data are available for this report.

### 2.2.6 Particle Transport Modeling

A simple particle tracking model, detailed in Appendix A, was utilized for the Phase III study. The model is similar to the model of Fry and Butman (1991) which was used to estimate the footprint that would result from the dumping of municipal sludge at the deepwater 106-Mile Site, offshore of New Jersey. The Fry and Butman (1991) model is also the basis of the drilling mud deposition model used in Phase II (Coats 1994), although Coats used only one particle size class instead of the three classes used for Phase III, and Phase III used multiple instead of single current meter mooring data (discussed below).

Tracking a surrogate particle of each size class, in this case coarse sand, coarse silt, and clay-silt, is a good representation of the dispersal of a cloud of material as long as all scales of motion are sampled. This will be the case if sufficient numbers of particles are released over the drilling periods. The number of particles released per hour is proportional to the daily discharge of drilling muds. Thus, the discharge rate of particles is time variable with a daily time step. The basis of the surrogate particle assumption is the theories of Batchelor (1952) and Taylor (1954) on dispersion by random movements. The main result, applicable to particle settling models, is that cloud dispersion from an ensemble mean position is given by single particle statistics (Fischer et al. 1979).

The Phase III model advects particles of the three size classes horizontally according to estimates of local current velocity at each time step. The vertical distance traveled is given by the sinking velocity. The particle's position is computed according to equations presented in Appendix A.

This equation is repeated for all active particles in the water column. To estimate velocity components, (u and v), all available current meter records were used from nearby moorings. For the September 1993 to June 1994 drilling periods, records were used from the Primary (P) (near Hidalgo), S5 (near Hermosa), S6 (offshore from P; Figure 2.1-1a), and the SIO Santa Barbara Channel mooring SMIN. Where records are missing or short, the continuous sections of the 3-HLP records (Appendix A) were merged together using flag values. Thus, each meter position has an associated velocity (u, v) time series covering the year-long deployment period, with flag values denoting data gaps.

At each time step, the valid velocity records at each position for all the moorings are identified. An objective method (Appendix A) is used to find the nearest velocity position to the particle. The procedure weights the nearest mooring more strongly than velocity values at similar depths to z but on moorings further away. In this manner, data gaps on a particular mooring are minimized by employing data at similar depths from other positions.

Linear interpolation between velocity positions on the selected mooring is used to find u and v at depth z, where appropriate. In this manner, the model attempts to account for the vertical and horizontal spatial variability of the current field seen by a particle as it moves away from the disposal site. Some scales of motion, such as tidal variability, will only be partially captured because of the limited vertical and horizontal distribution of the current measurements. Data gaps also cause a deterioration in the quality of the local interpolated velocities. However, over many realizations of particle tracks, the stochastic behavior of dispersing particles should be well captured on average. The larger scale variability of the flow should also be captured, in its essentials, by using an array of moored instruments rather than just a single mooring, as is more usual in particle tracking models.

Because the model estimates the current field at any one time from a limited number of current meters, the accuracy of the estimation deteriorates at distances from the moorings of more than 10–20 km and 5–10 km in the along-isobath and cross-isobath directions, respectively. Thus, the cumulative deposition footprints calculated by the model should be regarded as indicative of the general patterns of deposition that result from platform discharges during Phase III.

The random dispersion velocities are used to account for dispersion caused by small scale turbulence and motions not well resolved by the moored array. The velocity components are randomly selected from the range [-p,p] at each time step (Appendix A). The random velocity fluctuations are related to a horizontal dispersion coefficient (D). For offshore ocean environments, a dispersion coefficient of 1 $m^2/s$ is typical (Ledwell and Watson 1991). The results are not sensitive to values of D less than 10 $m^2/s$.

The time step is chosen from the time for a particle to fall 50 m or the velocity time series interval of 1 hour, whichever is less. Before each execution of the primary model formula, the position of the particle is checked to see if it has intersected the bottom of one of the outer boundaries of the grid. If the particle has intersected the bottom, it is flagged and its position recorded. If it has exited the grid, it is flagged as "lost". At the end of the particle tracking period, the positions on the bottom where the surrogate particles have settled are accumulated onto a regular grid in terms of particles per grid cell.

The model is run for all valid size classes, and the results are reported as concentrations per square meter per kilogram dumped of each size class.

The percent loss is calculated for each size class and then weighted to produce the percent of the total solid material dumped that is not deposited and which escapes through the boundary of the grid. This total percent loss is entirely accounted for by coarse silts and clay-silt (classes 5 and 6).

## 2.3 CHEMICAL PROCESSES

Chemical processes tasks included field surveys (Section 2.3.1) for collections of (1) surface sediment samples using a Van Veen grab, (2) surface and subsurface sediment samples using a box corer, and (3) suspended particle samples using STs. Representative platform discharge samples, including drilling muds, cuttings, and produced waters, as well as formation oils, and a petroleum product (diluent) from the Guadalupe oil fields, also were collected. Laboratory analyses (Section 2.3.2) included analyses of samples for trace metals and hydrocarbon parameters, as well as measurements of sediment grain size (particle size), total organic carbon (TOC) concentrations, and mineralogy. Data analyses (Section 2.3.3) were used to evaluate spatial and temporal trends relative to the platforms and between phases, respectively.

### 2.3.1 Field Surveys

#### 2.3.1.1 Surface Sediments

Surface sediments were collected at nine sites near the hard-bottom study locations associated with Platform Hidalgo (Figures 2.1-1c and 2.1-4). Three separate samples were collected at each station with a 0.1 $m^2$, Kynar-coated Van Veen grab. The 0–2 cm layer of sediments in each sample was removed from the sampler with a Kynar-coated scoop. The three samples were subsequently combined in the analytical laboratory into a single composite for each station. Prior to sampling, the sampler was cleaned by sequential rinses with filtered seawater, hexane, and methanol.

The composite samples of surficial sediments (i.e., from the three grab samples at a given station) were analyzed for trace metals, hydrocarbons, TOC, inorganic carbon, grain size, and mineralogy. Samples for trace metal and hydrocarbon analyses were placed in precleaned glass jars and stored at approximately -20° C until analysis. Samples for analysis of TOC, inorganic carbon, grain size, and mineralogy were placed in Ziploc bags and stored at 4° C. These latter samples were not frozen to avoid chemical and physical changes caused by freezing that could compromise analytical results for these parameters.

### 2.3.1.2 Surface and Subsurface Sediments

A 0.015 $m^2$ box corer was used to collect surface and subsurface sediment samples from the radial array of stations near Platforms Hidalgo, Hermosa, and Harvest (Figures 2.1-1c and 2.1-6). After retrieval of the samples onboard the survey vessel, the box portion of the corer was removed and placed on top of an extrusion stand. The sediment then was pushed through the box portion of the sampler. The surface layer (0–2 cm) was collected with a Kynar-coated scoop and placed in a precleaned glass jar. The subsurface layer (10–12 cm) then was pushed through the box, collected with the scoop, and placed in a glass jar. All samples were stored at approximately 4° C or -20° C until analysis, as appropriate for the different sample types as noted above for surface sediments.

### 2.3.1.3 Suspended Particles

Samples of suspended particles were collected in STs from nine stations associated with Platform Hidalgo (Figure 2.1-4). STs that had been deployed in October 1990 during Phase II first were collected during Phase III in October 1991. The ST arrays for Phase III then were deployed for periods of either six or twelve months (Figure 2.1-1b). The variation in collection schedules for some STs was due to unfavorable weather conditions that forced delays in some recoveries.

Sediment trap arrays consisted of a 1 m diameter cement base with spring supports of stainless steel for four individual traps. Each trap was constructed of butyrate tubing having Hexcel baffles with 1 cm cell spaces in the mouth of the tube to reduce turbulence. The diameter of each trap is 6.6 cm, and the height:diameter ratio of the baffle cells was approximately 7:1. Replicate traps were seven diameters apart and the openings were 1 m above the sea bed. Sodium azide was added to each trap as a preservative.

For retrieval, ST arrays were located using the ship's precision navigation system and the ROV color sonar system. A snap-hook with a line was attached using the manipulator arm on the ROV to a lift ring in the center of the array. The line then was used to hoist the trap array to the survey vessel.

Upon recovery of each array, individual traps were removed and the particles were transferred to prelabeled sample jars. The sampling tubes were thoroughly cleaned with freshwater and the azide preservative was replenished prior to redeployment. Occasionally, the baffles of several ST tubes were completely or partially blocked by attached anemones (*Metridium giganteum*). In these cases, an estimate was made of the percent coverage of the tube by the anemones. Sediments from these tubes were not used for measurements of sample mass.

Samples for measurements of trace metal and hydrocarbons were stored onboard the survey vessel at approximately -20° C. Samples for TOC and particle size measurements were stored at approximately 4° C. Samples were analyzed for total dry weight (for particle flux calculations); trace metal, hydrocarbon, and total organic and inorganic carbon concentrations; and grain size distributions.

#### 2.3.1.4 Platform Samples

Representative samples of platform discharge materials (drilling muds, cuttings, and produced waters) and formation oils from Platforms Hidalgo and Hermosa were collected by the operators and placed in precleaned glass jars provided by SAIC. (No samples were collected from Platform Harvest because no drilling occurred from this platform during Phase III). Samples from multiple wells at each of the two platforms subsequently were composited by well depth into surface, mid-depth, near bottom (muds only), and bottom samples. A sample of the petroleum product from the Guadalupe oil field also was obtained from California Department of Fish and Game.

#### 2.3.1.5 Quality Assurance/Quality Control

Collections of field samples were performed according to Standard Operating Procedures (SOPs) developed for this program. The SOPs included protocols for cleaning sampling equipment prior to deployment, collecting samples using noncontaminating methods, sample labeling, completing chain-of-custody forms for sample shipments, and collecting field blanks and equipment rinse samples to evaluate possible contamination during collection and shipping procedures. QA/QC samples for the field collections consisted of field blanks (i.e., empty sample containers that were taken on a field survey and returned to the analytical laboratory), field equipment rinses (i.e., distilled, deionized water rinses for cleaned sampling equipment in the field), and duplicate field samples. The frequency of collection of each of these three QA/QC sample types was approximately 5% of the total number of field samples.

### 2.3.2 Laboratory Analyses

Analyses for trace metals and hydrocarbons were performed by Texas A&M University/ Geochemistry and Environmental Research Group (TAMU/GERG). Analyses for grain size, TOC, and inorganic carbon were performed by MEC. Mineralogy analyses were performed by the Clay Minerals Analysis Laboratory at San Diego State University (SDSU).

Triplicate samples collected using the Van Veen grabs were composited in the analytical laboratory prior to removal of aliquots for individual chemical analyses. Samples from STs and box cores were aliquoted directly from original containers.

### 2.3.2.1 Hydrocarbons

Sediments and suspended particles, drilling muds and cuttings, formation oils, and the Guadalupe diluent were prepared for hydrocarbon analysis according to TAMU/GERG SOP No. 8902 (Extraction of Sediments for Hydrocarbon Analysis). Briefly, samples were Soxhlet-extracted in methylene chloride (DCM). Extracts were combined and dried by passing through anhydrous sodium sulfate, concentrated, and then solvent-exchanged from DCM into hexane. Final extract volumes were reduced and extracts were subjected to liquid-column chromatography for separation into saturated and aromatic fractions.

Chromatographic separation into saturated and aromatic fractions were performed using silica gel. Saturated hydrocarbons were initially eluted with hexane; aromatic hydrocarbons were subsequently eluted with a mixture of DCM and acetone (1:1, v:v). Final extracts for saturated and aromatic hydrocarbons were concentrated and analyzed by flame ionization detector-gas chromatography (FID-GC) and gas chromatography/mass spectroscopy-selected ion monitoring mode (GC/MS-SIM), respectively. Saturated biomarkers (steranes and terpanes were analyzed in selected suspended and surficial sediment samples, drilling muds and cuttings, and formation oils. Analyses for triterpanes and steranes were performed by GC/MS-SIM (m/z 191 and 217) according to TAMU/GERG SOP No. 9221 (Quantitative Analyses of Steranes and Triterpanes in Sediment Extracts and Oils by GC/MS).

Prior to analyses for saturated or aromatic hydrocarbons, linear calibration curves were developed with standard solutions of appropriate target analytes at five concentration levels. Surrogate spikes were performed in the laboratory for all field samples and quality control samples. Laboratory spikes and analyses, consisting of matrix spikes and matrix spike duplicates, were performed for every 20 samples or with every sample set, whichever was more frequent. Duplicate analyses by FID-GC or GC/MS-SIM were performed with a frequency of one for every 20 samples or sample set, whichever was more frequent.

Analyses of saturated hydrocarbons were performed according to TAMU/GERG SOP No. 8904 [Quantitative Determination of Aliphatic Hydrocarbons and UCM (Unresolved Complex Mixture)]. Samples were analyzed for n-alkanes, pristane, phytane, total resolved hydrocarbons, and UCM. Procedural (method) blanks were analyzed at a frequency of one for every batch of 10 samples. FID-GC analyses for saturated hydrocarbons were performed on a Hewlett Packard 5890 Gas Chromatograph with splitless injection mode and a 30 m long x 0.32 mm I.D. DB-5 fused silica capillary column. Output from the GC was processed using an automated HP-LAS 3357 data acquisition software package.

Analyses for polynuclear aromatic hydrocarbons (PAHs) were performed by GC/MS-SIM according to TAMU/GERG SOP No. STO-3 [Quantitative Determination of Polynuclear Aromatic Hydrocarbons by Gas Chromatography/Mass Spectrometry (GC/MS)-Selected Ion Monitoring (SIM) Mode]. Selected target analytes were identified and quantified using primary quantitation ions and accompanying secondary confirmation ions. Final confirmation of target analytes was based on specific retention-time data for selected compounds.

Detection limits for individual n-alkanes, isoprenoids, and PAHs were estimated to be three times the standard deviation about mean values from replicate analyses of low-level matrix spike samples. One quantitation ion and two confirmation ions per compound were monitored for PAH compounds in specific retention-time windows to establish baselines. Generally, detection limits for saturated and PAH compounds were estimated as 12.5 ng/g dry weight and 5 ng/g dry weight, respectively, for sediment samples.

#### 2.3.2.2 Trace Metals

Samples of sediments, suspended particles, and drilling muds and cuttings were acid digested for subsequent analysis of trace metals (except barium) according to TAMU/GERG SOP No. STO-8 (Digestion of Sediment for Trace Metal Analysis). Samples were initially freeze-dried and digested in concentrated nitric ($HNO_3$) and hydrofluoric (HF) acids at 130° C. Following digestion, the samples were diluted to final volume with boric acid ($H_3BO_3$). Samples for barium (Ba) analyses were dried, placed in heat-sealed polyvials, and then irradiated at a thermal neutron flux of $1 \times 10^{13}$n/cm$^2$/sec with the TAMU Triga Reactor.

Digested samples were analyzed by (1) flame atomic absorption spectrophotometry (FAAS) for aluminum (Al) and chromium (Cr); (2) graphite furnace atomic absorption spectrophotometry (GFAAS) for arsenic (As) silver (Ag), cadmium (Cd), copper (Cu), chromium (Cr), lead (Pb), nickel (Ni), and zinc (Zn); (3) cold vapor atomic absorption spectrophotometry (CVAAS) for mercury (Hg); and (4) instrumental neutron activation analysis (INAA) for Ba. The methods are described in TAMU/GERG SOPs STO-9 (Analyses of Trace Metals by Flame Atomic Absorption), STO-10 (Analysis of Trace Metals by Graphite Furnace Atomic Absorption), STO-11 (Analysis of Mercury by Cold-Vapor Atomic Absorption), and STO-16 [Quantitative Determination of Selected Trace Elements by Instrumental Neutron Activation Analysis (INAA)]. Analyses of procedural blanks, duplicates and matrix spikes, and certified reference materials were performed at the same frequencies as noted for hydrocarbon analyses.

#### 2.3.2.3 Total Organic Carbon

Analyses for TOC were performed on suspended particles and surface sediments, and drilling mud and cuttings samples as described in MEC SOP-III.C.3, Revision No. 1 (Total Organic Carbon Sample Processing). Samples initially were treated with phosphoric acid, distilled water, and potassium persulfate, and then purged with oxygen to remove residual inorganic carbon. Samples then were sealed in individual glass ampules and the organic carbon was converted to carbon dioxide by oxidation at elevated temperature and pressure. The concentration of the resultant carbon dioxide was determined by infrared spectroscopy. QA/QC analyses were performed in conjunction with field samples and consisted of duplicate analyses, surrogate spikes, and external reference standards that were analyzed with every sample set at a frequency of 10%.

#### 2.3.2.4 Inorganic Carbon

Total inorganic carbon in sediment samples was measured in accordance with MEC SOP-III.C.9 (Total Inorganic Carbon Processing Procedures). Inorganic carbon was converted to carbon dioxide by addition of phosphoric acid, followed by sample combustion. The concentration of the resultant carbon dioxide was determined by infrared spectroscopy. QA/QC analyses consisted of a minimum of 10% duplicates. Additional instrument carbon dioxide standards were checked before and after each batch of readings.

#### 2.3.2.5 Grain/Particle Size Distribution

Grain size analyses were performed on all samples collected in STs and Van Veen grabs, as well as drilling muds and cuttings samples. Percentages of gravel, sand, silt, and clay fractions were determined according to MEC SOP-III.C.2, Revision No. 2 (Grain Size). Samples first were treated with a deflocculant to break up aggregated sediment particles. Gravel and sand particles then were separated using decreasing sieve sizes. The separated particles were dried and weighed for percentage determinations. A pipette analysis was performed to determine the silt-clay fraction. Triplicate analyses and analysis of reference standards were performed routinely with each sample batch of one to seven samples.

#### 2.3.2.6 Mineralogy

The < 4-micron size fraction of bottom sediments from Van Veen grab samples was analyzed for mineralogical properties according to procedures in Berry and Nocita (1977). Aliquots of the samples first were dispersed in deionized water. The < 4-micron size particles then were smeared on microscope slides and subjected to air drying, glycolation, and heat treatment. Final X-ray diffraction analysis was performed using a Diano X-ray diffraction (XRD) instrument.

#### 2.3.2.7 Total Dry Weight (Flux)

Measurements for total dry weights were performed on solid materials from each of the STs to determine particle flux. Fluxes were calculated with the following equation:

$$Flux = (g/m^2*day)$$

where:

Flux = grams dry weight per $m^2$ per day,
g = dry weight of particulate matter in a tube,
$m^2$ = surface area of tube (0.0034 $m^2$), and
day = deployment period (ca. 6 and/or 12 months in units of days).

### 2.3.3 Data Analyses

Approaches to analyzing the chemical data emphasized (1) consistency with the Phase II program to permit direct comparison between different phases of the monitoring program, (2) integration with time series data compiled during Phase II, and (3) applications of hydrocarbon composition information to "fingerprint" or identify sources of hydrocarbons in samples. For example, composition information was used for evaluating the relative contributions of petrogenic, pyrogenic, and biogenic hydrocarbons. This procedure facilitated distinctions between oils derived from natural seeps in the study area and other anthropogenic sources.

Statistical analyses, including linear regression, t-tests, and analysis of variance (ANOVA), were used to evaluate spatial and temporal trends and relationships between different physical and chemical variables. Additionally, patterns of excess Ba in sediments near each of the three platforms were evaluated using the procedure developed by Boothe and Presley (1985). Total excess Ba was calculated from measurements in surface and subsurface sediments at the radial array of stations around a platform. Excess Ba was calculated by subtracting the background Ba concentration from the measured concentration. The background concentration was interpolated over the nearfield region of the platform from subsurface sediment concentrations at sites 500 m and 1,000 m from the platform. This approach was used to account for the depth-related gradient in sediment Ba concentrations. The volume of sediment containing "excess Ba" was calculated by multiplying the area described by a linear decrease with depth to a presumed background in Ba concentrations by an unit surface area. The linear decrease with depth represents a reasonable approximation of sediment Ba profiles reported by Crecelius (1990) from the Phase II program. Unit volumes were multiplied by the sediment density (assumed to be 2.6 $g/cm^3$) and the excess Ba concentration. Excess Ba (in kg) was summed for all unit areas within 500 m of Platforms Hidalgo, Hermosa, and Harvest.

Principal component analysis (PCA) was performed using hydrocarbon (PAHs, sterane, and terpane biomarkers) data from selected suspended sediment samples from Stations PH-N, PH-R, and PH-K, formation oil from Platforms Hidalgo and Hermosa, a seep oil collected near Platform Hondo, and petroleum product (diluent) collected at the Guadalupe oil field. The PCA was performed using the program SIRIUS (Pattern Recognition Systems A/A, Bergen, Norway). The data were scaled prior to analysis to avoid biases caused by parameters with large variances.

## 2.4 BIOLOGICAL PROCESSES

Biological processes tasks are described in the following sections for the hard-bottom community assessment (Section 2.4.1); larval experiments, including in situ and laboratory toxicity tests (Section 2.4.2); and reconnaissance of anchor scar/drill cuttings effects (Section 2.4.3).

### 2.4.1 Hard-Bottom Community Assessment

#### 2.4.1.1 Field Survey

The study sites for the hard-bottom community assessment consisted of nine rocky reef areas in the vicinity of Platform Hildago (Figure 2.1-3). These sites were chosen in Phase II to encompass (1) various distances from Platform Hildago (approximately 0.5–6.5 km), (2) a range of water depths (shallow depths of 105–119 m and deep depths of 160–212 m), and (3) different relief heights (low relief of approximately 0–0.5 m and high relief of greater than 1.0 m).

Epifaunal surveys in both phases were limited to low-relief habitats at Stations PH-F, PH-U, and PH-N, while surveys in Phase III noted areas of substantial high relief at Stations PH-I, PH-J, and PH-E that were not found in Phase II. Another difference between Phases II and III was the reported presence of extensive areas of high relief but no low-relief areas at Station PH-K during Phase II, whereas opposite trends were noted in the Phase III surveys.

Phase II sampling was conducted in October 1986, July and November 1987, October 1988, May and October 1989, and October 1990. Phase III sampling occurred in November 1991, October 1992, and January 1994. Surveys at all sites also were conducted in January 1995; however, analysis of these data was beyond the present financial scope and therefore is not addressed in this report.

Survey methods for Phase III generally followed those of Phase II using an ROV equipped with color and black and white video cameras, a 70-mm still camera and strobe, two split-beam lasers for focus, and a Mesotech color side-scan sonar (Hardin 1988; Hardin et al. 1991). One difference was the use of a 35-mm still camera system during the January 1994 and 1995 cruises. This change was made due to the increasing scarcity of 70-mm cameras for lease, considerable time and expense for film processing, and judgment by the project biological observers (who have extensively used both 35-mm and 70-mm systems and data) that there were no important differences in data quality for this study area when 35-mm was used. The ROVs used for the

1991, 1992, 1994 and 1995 surveys were RECON-IV, PHANTOM, and Benthos SEAROVER respectively.

Photoquadrats: A 70-mm or 35-mm Photosea still camera system and Osprey color video camera were used for collecting photoquadrat and broader-view community data, respectively. The still camera had an internal data chamber that was synchronized with the time and station number, allowing for cross-referencing with navigational data (time and navigational position of the ROV) and the video record. Laser images determined the proper distance from the camera to the bottom so that the photographed area represented 1 $m^2$.

The field survey methods used to collect photographic and video data at the nine hard-bottom sites included presurvey, survey, and postsurvey testing and data collection activities. Prior to an ROV launch, the still camera was test fired, the video color image was checked, and the ROV was visually inspected. The ROV was then deployed from the survey vessel and maneuvered to the bottom. Once the ROV was on the bottom, and the navigation and all other systems were verified as functional, the color video and observer commentary were initiated. Biological observers provided video commentary, directed the ROV operation, and controlled the camera operation. The observers recorded photographic information (e.g., time of photographs and relief height) and summarized the species, habitats, and any notable events (e.g., unusual organisms or substrate features) on survey log sheets.

Photographic surveys followed procedures established during Phase II for low- and high-relief stations. The two different relief methods were combined in mixed habitat areas and did not affect data comparability. At low-relief stations, the ROV was directed on a random heading, with the camera directed downward, photographing hard-bottom features approximately once every sixty seconds. When a soft-bottom area was encountered, the ROV was directed along another random heading and the process was repeated. At high-relief stations the procedure was similar, but with the camera directed forward. When a high-relief feature was encountered, the ROV was maneuvered around, up, and down a rock feature, taking non-overlapping photographs. After the feature was photographed, the ROV travelled along another random heading until the next feature was located. In mixed habitat, the relief height determined the photographic method that was used.

Attempts were made to obtain at least 60 photographs (70-mm or 35-mm slides) for each relief category at each site. However, because of some technical difficulties or the lack of appropriate substrate at a few study sites, fewer photographs were obtained in some areas. A total of 476, 815, and 744 photographs were analyzed for 1991, 1992, and 1994 respectively.

### 2.4.1.2 Laboratory Analyses

Still Photographs: Still photographs from the surveys were analyzed using a point-contact method that initially included twelve random grid patterns. Each grid pattern contained fifty randomly placed dots. A different pattern was selected for each slide by random draw from a pool of numbers. Each slide was projected, at life size (1 $m^2$), onto a screen containing one of the random dot patterns. This random grid pattern method was used for the 1991 and 1992 data; however, based on consultation among project scientists, the QRB, and DOI, an evenly spaced, 50-dot grid pattern was used for the 1994 analyses. This change was based on common usage of evenly-spaced grids by several other studies (P. Dayton, pers. comm.) and the greater efficiency achieved during analyses as compared to use of the random grids. Irrespective of the grid pattern, the species or substrate type under each point, as well as the counts of individual or solitary species, were recorded onto computer keypunch sheets. In addition, counts of all taxa that occurred in the slide, regardless of whether they fell under a contact point, also were recorded. A default percent cover of 0.5% was assigned to species counted within each slide but for which percent cover estimates were not appropriate (e.g., for crinoids). This default percent also was used for discrete organisms that were counted but did not fall under a contact point. However, one of the inherent problems in the Phase II databases was that these default percentages were recorded as 1.0%. Because of this, default percentages could not be distinguished from percentages that fell under a contact point and had an actual value of 1.0%. Another difficulty with the Phase II database was that the sum of the percent cover for all organisms in a slide often exceeded 100% by as much as 20–40%. This overestimate also limited comparisons of some Phase II and Phase III data. Similar to methods used in Phase II, the percent cover was adjusted for dots that fell on shadows or soft sediments; counts of individual organisms were normalized to the visible hard substrate in each photograph.

Another difficulty in comparing data between Phases II and III involved taxa that only could be identified by a descriptive name (e.g., yellow encrusting sponge). To maintain taxonomic consistency and comparability of data between phases, a list of all taxa recorded from Phase II was used to establish data sheets for the analysis of Phase III photographs. However, many taxa observed in Phase III were not listed for the Phase II study and, therefore, these new taxa were added to the master list. All taxonomic differences could not be resolved based on available information. However, the results indicated that the data sets were comparable for most of the common taxa. When differences were noted, temporal plots of these taxa combined all species for a particular group at a more general taxonomic level. This allowed greater consistency between Phase II and III comparisons. Some differences also existed in the level to which taxonomists identified various species groups between Phases II and III. For example, ophiuroids and polychaetes were identified to a lower level (e.g., Genus or Species) during Phase III than during Phase II.

Statistical analysis of the community data used multivariate classification analysis of the 50 most dominant taxa for low- and high-relief habitats to delineate the major trends in biological communities, and the 20 most dominant taxa for characterizing the habitats. The analysis utilized the mean percent cover for each taxon averaged for the Phase III surveys. Data were square-root transformed and normalized to the standard deviation before calculation of Bray-Curtis distance (Bray and Curtis 1957). This step was done to keep the most abundant taxa from dominating the analysis. Cluster analysis using the Bray-Curtis dissimilarity coefficient and group-average sorting strategy were used to group the data (Smith 1976). Both normal (stations) and inverse (species) analyses were conducted and plotted as dendrograms. A two-way table of coincidence was produced to aid interpretation of the cluster results and to provide insights on physical features that were associated with community trends. The analyses were run using SAS Version 6 (SAS 1990).

Additionally, to evaluate potential relationships among biological parameters and physical/chemical measurements, correlation coefficients (Pearson product moment) and linear regressions were calculated for dominant taxa and sediment trap physical/chemical data collected near each hard-bottom site (Section 2.3). Analysis of covariance (ANCOVA) also was performed on percent cover of dominant taxa to evaluate differences relative to distance from Platform Hidalgo (Appendix D). Finally, power analyses (Green 1989), based on mean percent cover of dominant taxa, were used to estimate the power to detect decreases in abundance between pre- and post-drilling periods (Appendix D).

Video Transect Data: Video data collected on rock relief were analyzed for all nine stations. Thirty 1-minute segments (band quadrats) of each tape were reviewed for each site. These band quadrats were selected using non-overlapping navigational reference points that traced the location of the ROV coverage. This coverage was located on the video tapes by using the internal time code that was synchronized with navigational records and continuously recorded on tape. In order to obtain reasonably comparable bottom coverage among band quadrats, a standardized time increment of one minute of visually acceptable video was used. Time was counted only when the ROV was in motion and visibility was good. Visibility was considered unacceptable if the ROV was too far off the bottom, or if excessive suspended sediments and/or organisms (e.g., swarms of mysids) prevented identification of benthic taxa and substrate.

Within each band quadrat, all recognizable substrate features and organisms were listed as either present or absent. Substrate type was separated into four general categories: (1) soft-bottom, (2) extremely low-relief (< 0.15 m), (3) low-relief (< 1 m), and (4) high-relief (> 1 m). Other descriptive substrate categories listed as present or absent were shell debris, tar, and oil or gas seeps. Individual organisms are identified to the lowest possible taxon and given either taxonomic or descriptive names that were as consistent as possible with Phase II designations. These data were entered on coded data sheets for direct computer entry.

Statistical analysis of the video data included assessments of communities and species by substrate type and cluster analysis as described for the 70-mm photographic data. Cluster analysis of the fish community utilized all fish data, while macroinvertebrate data were used only when a taxon occurred in more than twenty 1-minute segments for the entire survey.

## 2.4.2 Larval Experiments

Larval experiments consisted of in situ tests of settling and laboratory toxicity tests.

### 2.4.2.1 In Situ Experiments

In situ manipulations of larval settlement were conducted at sites near to and far from drilling platforms. Two types of experiments, one using laboratory-cultured red abalone larvae and one using natural settlement, were performed. The red abalone experiments provided a basis for determining factors which affected the settlement of a controlled population. Because natural settling rates are relatively low (Mullineaux 1988), manipulations were performed in which known numbers of larvae were exposed to a series of treatments in the field to determine how settlement was affected by: (1) waterborne factors (e.g. suspended solids, food, dissolved chemicals); (2) surface films on settlement plates (e.g. bacteria and particulates incorporated into the surface film); and (3) reef height. The specific design of these experiments allowed for the determination of causation related to drilling operations. The natural settlement experiments were conducted over a variety of exposure durations from 3 to 1,000 days to evaluate settlement and recruitment over time, and included both pre- and during/post-drilling periods.

Three nearfield oil platforms and three farfield reference sites were utilized for the study. Nearfield sites were located near hard-bottom reefs adjacent to Platforms Hidalgo, Harvest, and Hermosa (Figure 2.1-5), at approximately 200 m depth. The farfield sites also were near hard-bottom reefs, upcoast (1 site) and downcoast (2 sites) of the platforms along the same depth contour. The farfield sites were selected to be beyond the major influence of Phase III drilling activities based on dispersion and deposition information from previous studies (Phase II, Coats 1994). In addition, experiments were conducted at two heights (0.25 and 0.75 m) above the ocean bottom corresponding to low and high relief reefs in the region (Hardin et. al. 1994).

**Red Abalone Settlement**

Red abalone larvae (*Haliotis rufescens*) were used for this settlement experiment. This species and life history stage has a number of desirable characteristics for use in in situ bioassays (Appendix C; Raimondi and Schmitt 1992), and preliminary studies showed that red abalone larvae could survive and grow for exposures up to 23 days in the field at depths up to 200 m (Raimondi and Barnett, unpublished data). Surviving individuals showed signs of healthy metamorphosis to the juvenile stage, active feeding on bacterial films on the plates, and normal growth. These observations demonstrate that red abalone larvae can settle, survive, and grow under conditions typical of the natural field conditions in the study area.

Manipulated in situ settlement experiments using red abalone larvae were conducted in October 1992 and January 1994 from the survey vessels M/V RAMBO and M/V INDEPENDENCE, respectively. Generally, each experiment consisted of a filming period and subsequent exposure period, as described below.

Settlement plates were placed into canisters and deployed approximately three weeks prior to the start of the scheduled experimental period (Appendix C). The filming canisters were covered with 100 μm Nitex mesh to preclude natural settlement of larvae during the filming process. Filming canisters were placed at each of the six experimental sites at each of two heights, 0.25 and 0.75 m above the bottom.

Following the filming period, the plates were retrieved from the filming canisters and sorted to distribute plates from each filming site to each incubation (exposure) site (a reciprocal transplant design). Plates were secured into individual chambers attached to deployable larval arrays referred to as igloos (Appendix C). Igloos were three-dimensional structures that carried plates on four separate faces to account for potentially confounding effects of currents. Each chamber held one settling plate and was covered with 100 μm Nitex mesh. Plate chambers were "injected" with 500 (± 50) competent red abalone larvae prior to deployment of the igloos for a planned three-day incubation period. Plates remained covered with Nitex mesh for the duration of the incubation to prevent spontaneous natural settlement of other invertebrates, predation, and to contain the red abalone larvae within the chambers. Four replicates were conducted of each combination of filming site, incubation site, and relief height. Plates that were returned to their original filming site were replicated by an additional four plates. In addition to the plates from each filming site, sterile plates (no surface filming) also were transplanted to each site (4 replicates per site).

Completed trays were stored in cool seawater in the dark until just before igloo deployment. When all trays were completed (abalone larvae having been injected into all chambers), covers were placed over the trays to keep them bathed in cool seawater prior to deployment, and covered trays were attached to the igloos. Igloos were then lowered from the ship to a depth of 8–10 m. Divers were deployed to remove tray covers and expose the chambers to in situ conditions.

After the three-day incubation period, the igloos were retrieved and brought onboard the survey vessel. Settled abalone larvae are resistant to desiccation and were attached firmly to plates; therefore, the igloos were brought directly from the bottom to the ship's deck without any attachment of covers on the trays. However, once onboard, covers were immediately placed on each tray and the trays were moved back to the cool seawater baths in a darkened room until the settlers could be counted. The number of settled red abalone larvae were counted microscopically within two hours of igloo retrieval. Experiments carried out in October 1992, and January 1994 yielded one data set each for the "pre-" and "during-drilling" periods.

Data were analyzed using fixed effect analysis of variance procedures (SAS Institute 1988) on $\log_e(x+1)$ transformed data to meet assumptions of homoscedacity. For this design, if drilling had an effect on settlement it would have been evident as an Experiment x Incubation or Experiment x Film Type interaction (after Platform Harvest, where no drilling occurred, is removed from the analysis). Other effects on settlement associated with platform activities, besides drilling, should be evident as either effects of surface films (after the "no film" treatment is removed from the analysis) or of incubation location.

### Natural Settlement Experiments

For the natural settlement experiments, pre-settlement bacterial filming steps (using larval canisters) and deployment and recovery methods (utilizing three-dimensional igloos for attachment of the settling plates), were conducted as described above for the red abalone experiments and as detailed in Appendix C. Natural settlement experiments were conducted from April 1992 through January 1995. Exposure durations varied from short (3–21 days), to medium (180–365 days), to long (460–1,000 days) time intervals. To better separate drilling effects, a series of medium length (300–365 days) experiments were also performed in both the pre-and during/post-drilling periods. Following retrieval of the igloos for each experiment, some settling plates were photographed and redeployed to the bottom and others were returned to the laboratory for analysis.

In April and October 1992, plates removed from the arrays for analysis were preserved in formalin and returned to the laboratory for identification and enumeration of settled larvae. In August 1993 and January 1994, all plates were photographed with 35-mm slide film, long-term plates were returned to the arrays, and a subset of the plates was preserved and returned to the laboratory for analysis. In addition, in January 1994 a new set of filmed plates was deployed at each site to determine effects from the during/post-drilling period. In January 1995 all plates were retrieved, removed, photographed, and preserved in formalin for laboratory analysis.

To address whether settling plate surface conditions (texture) might affect the settlement of larvae, an additional experiment was conducted between August 1993 and January 1994. Three plate surface conditions were tested: (1) smooth plates identical to those used throughout the study; (2) grooved plates; and (3) roughened plates (Appendix C).

In the laboratory, settling plates and slides were examined under a dissecting microscope. The entire surface of the plate was examined and all organisms identified to the lowest possible taxon. Organisms occurring as individuals were counted. Coverage estimates were made for colonial organisms which could not be enumerated. Additionally, photographs collected of the same plates over time were used to estimate the growth and survivorship rates for selected taxa. Fecundity was estimated by observing plates with high (>50%) coverage of hydroids on plates recovered following 365 days exposure during the during/post-drilling period. The proportion of reproductive polyps in each colony was calculated for each plate. To determine if data from photographs of plates were comparable to data collected from direct observation of the plates, an evaluation was made using data collected from a subset of plates that were photographed prior to laboratory analysis.

All data were coded in the NODC taxonomic coding system, double-entry keypunched, and subjected to a minimum 10% QA/QC check on all data fields. Data were stored as SAS databases and all statistical analyses were performed in SAS (SAS Institute 1988). All species occurring were summed for the total number of organisms settled. All organisms except colonial organisms (i.e., hydroids, protozoa, etc.) and eggs were summed for the total number of multicellular organisms settled. ANOVA was performed on data from each set of incubations to examine waterborne and relief height effects. Only taxa that occurred on at least five percent of the plates were analyzed individually.

#### 2.4.2.2 Toxicity Tests

Laboratory toxicity tests were conducted using drilling muds collected from Platform Hidalgo. Drilling muds used in these experiments were water based muds, and samples were collected from active drilling platforms before discharge to the ocean. A sample of drilling mud was collected by platform personnel and shipped in PVC containers on ice to the bioassay laboratory at the University of California, Santa Barbara (UCSB). At the laboratory it was stored in a cold (4° C) room until used in experiments. All experiments were conducted within 14 days of collection of drilling muds.

Concentrations of drilling muds used in experiments were set from 0.002 mg/L to 20,000 mg/L plus controls, except as noted (Appendix C). In the field, concentrations of drilling muds greater than 200 mg/L would be expected only very close to the point of discharge (Coats 1994). Preliminary experiments on fertilization and development indicated no effects for concentrations between 0.002 and 200 mg/L. Therefore, concentrations above 200 mg/L were included to determine if drilling muds had any effect on the targeted performance parameters (i.e. fertilization, development, and survivorship). The period of exposure to drilling muds was generally 52 hours except for assays of fertilization and development, which were shorter because of the shorter duration of these stages.

**Collection and Laboratory Handling of Test Organisms**

Stocks of adult red abalone are maintained in a flow-through seawater system at UCSB. Methods for spawning, fertilization and larval culturing are described in Morse et al. (1977, 1979b, 1980). Stock animals were collected originally from a subtidal reef near Santa Barbara, CA and have been maintained as spawning animals for ongoing studies over several years. In order to mimic conditions that exist at 200 meters, some experiments were conducted, as feasible, at 9° C in the dark. However, because the results of preliminary experiments indicated that development times for cultures were unstable at 9° C, parallel experiments were also performed at 15° C, the typical rearing temperature for red abalone. To help prevent bacterial infection in the laboratory, antibiotics (2 mg/l Rifampicin) were added to laboratory vessels holding larvae; antibiotics do not interfere with normal settlement of red abalone larvae (Morse et al. 1979b). If individuals in any replicate container appeared to be severely affected by bacterial infection that replicate was not used. Typically 2-3 replicates per treatment (concentration) have been used for survivorship and settlement assays with red abalone larvae (Morse et al. 1979a; Raimondi and Schmitt 1992); variability is generally low among replicates. Experiments described in this study used between

3 and 10 replicates per treatment (concentration); the number was in large part dictated by logistical constraints of the experiment. Due to limited holding times for the drilling muds, as noted above, most of the experiments were carried out concurrently.

Individual adult brown cup corals were collected from subtidal rocky reefs near Santa Barbara, CA, at depths between 10 and 20 meters and maintained in the UCSB laboratory. Until use, corals were kept at 9° C in the dark in a flow-through seawater system. The corals were not fed during the experiments.

**Specific Methodology of Experiments: Red Abalone**

*Gametes - (fertilization).*

This experiment tested the relationship between the concentration of drilling muds and the fertilization success of abalone, expressed as a percentage of eggs showing evidence of fertilization. At least 2 male and 2 female adult red abalone were spawned using the method of Morse et al. (1977). Sperm were collected via pipette from spawned abalone. Sperm concentration was determined by first diluting a sample of concentrated sperm 1:10,000 in sterile sea water, then counting 10 $\mu$l samples of the diluted sperm solution on a hemocytometer. Freshly spawned eggs were allowed to settle in 50 mL conical tubes. To determine settled egg density, a 20 $\mu$l sample of settled eggs was mixed in 1 mL of sterile sea water, and 20 $\mu$l samples of the suspended eggs were counted on depression slides.

Concentrations of drilling muds tested were: 200, 20, 2, 0.2, 0.02, and 0.002 mg/L. Clean, sterile sea water was used for control conditions. Subsamples (10 mL) of each drilling fluid dilution were pipetted into individual wells of Falcon six-well tissue culture plates. Ten replicates of each concentration and ten replicates of control conditions were included in this experiment.

Approximately 500 settled eggs were pipetted into each well of the Falcon tissue culture plates, and freshly diluted sperm at a ratio of approximately 800 sperm per egg were added to each well. Fertilization was allowed to proceed at 15° C for 5 hours on a shaker apparatus. At the end of 5 hours, fertilization was stopped by the addition of approximately 1 mL of 10% formalin. Maximum resolution of fertilization success was achieved by sampling 5 hours after gametes had been mixed. Tests for fertilization were only conducted at 15° C because that was the temperature at which the fertilization protocol was established. Due to logistical constraints, it was not feasible to complete the fertilization tests at 9° C. Fertilization success was measured by observing the presence of polar bodies or cell division under a microscope (Hunt and Anderson 1989). At least 100 eggs were counted per well for each replicate.

*Zygotes - (development)*

Experiments on zygotes tested the relationship between drilling mud concentration and early larval development. Freshly spawned red abalone eggs were fertilized at 15° C. Fertilized eggs were examined under the microscope to ensure the presence of between 10 to 50 sperm per egg. Drilling muds were diluted, using sterile sea water, to the following concentrations: 2000, 200, 20, 2, 0.2, 0.02, and 0.002 mg/L (plus control; 0 mg/L). Approximately 500 fertilized eggs were added per well of Falcon six-well culture dishes, into which 10 mL of each drilling mud dilution were pipetted. Ten replicates were done per concentration, and sixteen replicate controls in sterile sea water were performed. Development was allowed to proceed at 15° C on a shaker apparatus for 52 hours.

At the end of 52 hours, approximately 1 mL of 10% formalin was added to each well. At least 100 individuals were scored for normalcy of development. Larvae were defined as "normal", based on characteristic calcified, striated, snail-shaped shells with smooth borders identifed in Hunt and Anderson (1989). "Abnormal" shells showed deviations such as indentations in the shell margins or mis-shapened shells (Hunt and Anderson 1989).

*Larvae - (survivorship, settlement, viability)*
Survivorship was measured as the proportion of organisms alive at the end of the test. Settlement was measured as the proportion of survivors that settled. Viability is the product of the proportion of individuals that survived and the proportion settled. It is an estimate of the proportion of individuals that successfully made the transition from the planktonic to the benthic stage.

Precompetent larvae: This experiment tested the relationship between exposure of precompetent larvae to varying concentrations of drilling muds and subsequent survival to competency, settlement (as competent larvae) or viability. Approximately 500 precompetent abalone larvae were placed in 800 mL of drilling mud solution, and maintained at 9° or 15° C for 52 hours. The precompetent stage was defined as under 7 days post fertilization for individuals reared at 15° C and under 10–12 days for individuals reared at 9° C; the length of the precompetent period is more variable at lower temperatures. Drilling mud was diluted to the following concentrations: 20,000, 2,000, 200, 20, 2, and 0.2 mg/L (plus control; 0 mg/L) for the 9° C experiment , and 200, 20, 2, 0.2, 0.02, and 0.002 mg/L (plus control) for the 15° C experiment. Different concentrations were used for the 9° C experiment for two reasons. First, the results of the 15° C experiment (done first) indicated that the lowest concentrations tested (0.002 and 0.02 mg/L) had no effect on larval performance. Second, because only limited numbers of larvae were available for testing, all treatment conditions could not be made. Consequently, it was decided to forego the lower concentrations and include the two higher (2,000 and 20,000 mg/L) drilling mud treatments to better bracket the expected effects.

After 52 hours of exposure to the various drilling mud dilutions, larvae were transferred to 800 mL fresh, sterile sea water containing 2 mg/L Rifampicin and were maintained at either 9° or 15° C (in closed systems). Upon reaching competency, approximately 75 of the exposed individuals were transferred into 20 mL disposable beakers and challenged with GABA plus 2 mg/L Rifampicin for 24 hours. There were 3 and 9 replicates per concentration for the 9° and 15° C experiments, respectively. Temperatures were maintained as in the precompetent phase. Larvae were scored as settled (attached to the beaker), not settled (lying on their side), or dead (movement could not be detected).

Competent larvae: These experiments tested the relationship between exposure of competent larvae to varying concentrations of drilling muds, and their survival, settlement, or viability. These tests were done to examine the effects of longer term exposure to drilling muds, including the ability to settle and survive during the period of exposure. They were included to evaluate how larvae drifting into, and remaining in, an area of impact might be affected by exposure to drilling muds.

*Settlement ability of abalone larvae exposed to drilling muds at 9° and 15° C during the competent stage: 28h exposure to drilling muds*

Competent abalone larvae, reared at 9° or 15° C were exposed to dilutions of drilling fluids, ranging from 20,000 mg/L down to 0.002 mg/L (plus control), for 28h at 9° or 15° C. Approximately 400 individuals were exposed in 800 mL volumes of the dilutions, replicated two times per dilution for the 9° C experiment and three times per dilution for the 15° C experiment. After 28h, approximately 50 larvae per replicate were transferred to 20 mL disposable beakers containing 10 mL fresh sterile sea water. They were then challenged with 2 mg/L GABA plus 2 mg/L Rifampicin. For the 9° C experiments, three replicates per exposure group were set up for a total of six replicates per dilution. Only one replicate per exposure group (three replicates total) was used for experiments at 15° C. Larvae were scored as settled (attached to the beaker), not settled (lying on their side), or dead (movement could not be detected).

*Settlement ability of abalone larvae exposed to drilling muds at 9° and 15° C during the competent stage: 52h exposure to drilling muds and settlement challenge in the presence of drilling muds*

Competent abalone larvae, reared at 9° or 15° C in a closed system (see above), were exposed to dilutions of drilling fluids, ranging from 20,000 mg/L down to 0.002 mg/L (plus control), for 52h at 9° or 15° C. Approximately 400 individuals were exposed in 800 mL volumes of the dilutions, replicated two times per dilution for the 9° C experiment and three times per dilution for the 15° C experiment. For the 9° C experiment, before the last 24h of exposure, as many larvae as were available per replicate were split among three 20 mL disposable beakers along with 10 mL of the drilling fluid dilution. Larvae were challenged to settle by the addition of 2 mg/L GABA plus 2 mg/L Rifampicin. A total of six GABA challenge replicates per dilution were performed. For the 15° C experiment, before the last 24h of exposure, 50–150 larvae from each replicate were put into 20 mL disposable beakers along with 10 mL of the drilling fluid dilution. Larvae were challenged to settle by the addition of 2 mg/L GABA plus 2 mg/L Rifampicin. A total of three GABA challenge replicates per dilution were run. Larvae were scored as defined for the 28h exposure.

*Interference with settlement inducers*

This experiment was designed to test whether settlement of larval red abalone was affected by alteration of settlement surfaces due to deposition of drilling muds. As such, this experiment differed fundamentally from the other tests using larval red abalone. The other experiments tested whether drilling muds had direct physiological effects that translated into loss of larval performance: fertilization, development, and the ability to settle. In contrast, this experiment tested indirect effects on the performance of individuals (ability to settle) through interference with a necessary step in the settlement process (contact with an inducer). With this treatment the reaction of competent abalone larvae to fouled surfaces was examined. The focus was to determine how larvae might react to potentially inductive surfaces occurring in the zone of impact for drilling muds. This treatment was intended to mimic short-term exposure of these inductive surfaces.

Coralline crusts (known to induce red abalone larvae to settle; Strathman 1987) were placed in solutions of drilling muds for 28 hours at 9° C in the dark at the following concentrations: 20,000, 200, 2, and 0.02 mg/L (plus control: 0 mg/L). After 28 hours, crusts were transferred to small containers (8 crusts per concentration) containing a new solution of drilling muds that was identical in concentration to that used in the initial 28 hr period. New solutions were used to reduce the possibility of contamination when the abalone larvae were added. Approximately 500 competent abalone larvae were added to each container. After 24 hours the crusts were sampled microscopically to determine the density of settlers on coralline crusts as well as the percent of the crust surface that was clear of drilling muds. The latter parameter was sampled to separate interference with settlement due to effects on the inductive quality of the surface (e.g., chemical effects on the inducers) from interference with settlement due to physical covering of the surface with mud.

This experiment alone was not sufficient to distinguish interference with inducers from physiological effects of larvae. To evaluate this distinction, it must be determined that exposure to drilling muds during the competency phase does not affect larval settling ability. This was tested in the previously described experiment on competent larvae using GABA as an inducer. In this experiment, the GABA induced settlement was repeated and, additionally, coralline crusts were used to induce settlement. Coralline crusts and GABA were both used to determine if larvae exposed to natural and artificial inducers responded differently.

For this test, larvae were placed into solutions of the same concentrations as noted above (five replicates each), but without coralline crusts for 28 hours. After 28 hours, larvae were removed from the drilling mud solutions and put into containers of clean seawater. The larvae from each of the replicates were split into two containers: one containing clean coralline crusts, the other containing 2 mg/L GABA solution. Settlement was scored as noted above after 24 hours in these containers.

**Specific Methodology of Experiments: Brown Cup Coral**

This experiment was designed to test whether adult *Paracyathus* are affected by exposure to realistic concentrations of drilling muds. The effect could result from either of two sources: 1) toxicity from a chemical or biological component of the drilling muds, or 2) toxicity from the fine particulate matter in drilling muds that might interfere with physiological processes (e.g. feeding or respiration) of a filter feeder such as *Paracyathus*. Survivorship and tissue loss in adult cup corals were examined as endpoints. For corals such as *Paracyathus,* tissue loss has a direct bearing on reproduction because gonads are located in external tissue in the septa.

Individual *Paracyathus,* 11 per concentration, were randomly selected from a population of adults and placed in solutions of drilling muds with the following concentrations: 20,000, 200, 2, and 0.02 mg/L (plus control; 0 mg/L). Experiments were maintained in a cold room at 9° C. Every two days for 10 days individuals were examined microscopically for survivorship and tissue loss (sub-lethal effects). Individuals were scored as either exhibiting or not exhibiting tissue loss. An additional variable, relative viability, was calculated as the product of survivorship and the proportion of individuals showing tissue loss. Relative viability should be a good predictor of the likelihood of continued survival and reproduction under exposure to drilling muds. New solutions were made of the experimental concentrations of drilling muds every two days (all concentrations were made using drilling muds that were less than 14 days post-collection). Following examination, individuals were replaced into the appropriate fresh experimental concentrations of drilling muds. Since adult *Paracyathus* are sessile, the period that they could be affected by drilling muds is longer than for a larvae. Consequently, this experiment was carried out over a longer period of time. This time frame was within the average period for discharge of drilling muds during drilling activity at the Santa Maria Basin platforms, which usually lasts for several weeks or months (Steinhauer et al. 1992; Raimondi et al. in preparation) for each well drilled.

*Data Analysis*

Results from the experiments are expressed as percent fertilization, survivorship, etc. compared to a control. All values were standardized to the mean for the control set of replicates (the 0 mg/L treatment), including each of the control replicates. This approach allows direct comparisons of results from different experiments with differing units or measured parameters.

Regression analyses were used for all experiments testing for physiological effects of drilling muds on gametes, zygotes, or larval red abalone. All statistical analyses were performed using SAS software (SAS Institute 1988). Separate analyses were done using the concentration and the log of the concentration of drilling muds as the independent variable. This was done because dose response curves have been shown to follow both linear and log-linear trajectories, and there was no objective reason to predict which, if any, was the probable model for biological response to drilling muds.

Experiments testing for interference with inducers of settlement used both multiple and simple regression models. Analysis of covariance models were used to evaluate results from experiments designed to test for the effects of drilling muds on adult brown cup corals. Finally, even though higher exposure concentrations were used, in some experiments, only concentrations ≤ 200 mg/L were included in the statistical analyses. Since concentrations above this level were not representative of conditions in the field. The higher concentrations, however, were included in figures to demonstrate whether very high levels of drilling muds affected the test organisms.

### 2.4.3 Reconnaissance of Anchor Scar/Drill Cuttings Effects

#### 2.4.3.1 Field Survey

The reconnaissance survey using the ROV RECON IV was conducted in the vicinity of Platform Hildago on November 2 and 3, 1991. The survey focused on conditions within approximately 500 m of the platform. The ROV was equipped with a color video camera, 70-mm photographic camera with strobe, and a Mesotech color side-scan sonar for locating bottom features. Weak flashes with the 70-mm strobe and subsequent camera problems prevented use of the photographic data. However, extensive video data was collected during five ROV transects (Transects 1–5) representing almost six hours of bottom time in the vicinity of Platform Hildago.

#### 2.4.3.2 Laboratory/Data Analyses

A qualitative review of the video tapes and navigation postsurvey plots of the ROV transects was used to make a spatial assessment of substrate modification and any evidence of community impacts related to the platform-associated debris field. Additional notes and observations were made on debris and lost equipment (e.g., ladders, tires, and cables), mooring chain, and pipelines.

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# Chapter 3

# INTEGRATION

## 3.1 OVERVIEW

The primary focus of the DOI Phase II and III studies was to conduct long-term monitoring of the effects and related processes of oil and gas platform discharges on deep-water, hard-bottom biological communities. As summarized in Chapter 1, and further detailed in the Appendices, DOI's objectives for the Phase III program included the following:

- Extend Phase I and Phase II studies on the fate and effects of residual platform discharges; and

- Conduct process-oriented studies on potential long-term, chronic impacts from the discharges to hard-bottom communities, as distinguished from natural variability.

Potential or actual impacts to biological communities from chemical contaminants can be considered on relatively small scales corresponding to habitat patches (e.g., tens to hundreds of square meters) or at landscape scales representing the aggregation of multiple patches (e.g., tens to hundreds of square kilometers) (reviewed in Fahrig and Freemark 1995). The appropriate scale of study is best determined by evaluating the type, size, and frequency of disturbance (Lissner et al. 1991); the structure (e.g., patchiness) of the habitat (Fahrig and Freemark 1995); and the demographic and dispersal characteristics of the species/populations (Fahrig and Freemark 1995). These considerations appear to be equally appropriate for evaluations of both terrestrial and aquatic ecosystems.

For the DOI study area, the relatively sparse hard-substrate habitat in the general region of Platforms Hidalgo, Harvest, and Hermosa is comprised of discontinuous patches of exposed rock on scales of centimeters to kilometers, separated by a relatively homogenous soft bottom of muds and fine sands (BBA/ROS 1986; Steinhauer and Imamura 1990; SAIC and MEC 1993). These conditions produce a corresponding patchiness in the distribution of sessile and attached marine organisms and, presumably, their abundances as well, as influenced by the size and location of a habitat patch relative to other patches (Lissner et al. 1991; Freemark 1995).

Potential effects to hard-substrate communities from drilling mud discharges should be evaluated in terms of localized and regional (i.e., landscape scale) influences. The severity of any impacts will be greatest when the effects propagate from local patches to landscape scales. The probability that "toxic events" will propagate in such a manner was ranked, from lowest to highest, by Fahrig and Freemark (1995) based on the type of event and populations, including:

(1) Single, local event in a continuous population;

(2) Single, local event in a patchy population;

(3) Multiple, local events in a continuous population;

(4) Single, large-scale event in a continuous population;

(5) Multiple, local events in a patchy population; and

(6) Single, large-scale event in a patchy population.

To this list might be added the following:

(7) Multiple, large-scale events in a patchy population (the significance of which would depend, among others, on the frequency of the events).

Using this theoretical background, the likelihood of impacts to deepwater hard-substrate communities from discharges of drilling muds can be placed into a comparative ecological framework. For example, discharges in the Phase III study area appear to correspond most closely to item (7) above, representing multiple, point source events of which the majority of the material is deposited over many tens of square kilometers (see Appendix A) onto patchy hard substrate habitat. The critical focus for this study then relates to the assessment of changes in the biological communities or test organisms, represented in the study design as discharge-period changes to populations of multiple species, and documentation of the occurrence of toxic levels of any components from the discharges.

A generalized ecosystem model of the DOI study region, including physical, chemical, and biological subsystems, is described in Chapter 1 (Figure 1.3-1). This model provided a conceptual framework upon which the Phase III study design, summarized in Chapter 2 and Appendices A through D, was structured. This design represented a field and laboratory analysis program with collections and measurements that primarily were conducted synoptically (Figure 2.1-1) within a discrete study region (Figures 2.1-3 through 2.1-6). This temporal and spatial focus allowed direct comparisons and integration among many task elements comprising the model subsystems. For example, data were collected from both low- and high-relief heights, at nearfield and farfield locations relative to Platform Hidalgo, for particle flux measurements (Appendices A and B), biological community analyses (Appendix D), and larval filming and settlement experiments (Appendix C). Further, data for community analyses and for chemical dose/particle flux evaluations were collected near the same nine hard-bottom sites (Appendix B). In situ and laboratory toxicity tests addressed potential acute and chronic effects from platform discharges to larval and adult invertebrates (Appendix C). Measurements of water column and bottom boundary layer currents, as well as concentrations of suspended particulate matter in near-bottom waters, provided information for evaluating transport and dispersion of platform discharges (Appendix A). Finally, modeling of drilling mud discharges was performed to extend the spatial scales for predicting depositional fluxes and exposure dose (Appendix A). This study design allowed the specific objectives of the Phase III program to be addressed and provided continuity with the long-term monitoring objectives represented by Phase I and Phase II programs.

## 3.2 CONCLUSIONS AND INTEGRATION

Key questions that were addressed by the Phase III program include the following:

- Is there a difference in the physical oceanographic conditions between phases and between locations during the same phase?
- Is there a difference in the concentrations of barium (Ba) and other chemical contaminants from drilling activities between phases and drilling periods?
- Is there a difference in particle fluxes at platform nearfield compared to farfield sites, at high- (> 1.0 m) versus low-relief (0–1.0 m) heights, or at shallow versus deep bottom depths, during drilling versus non-drilling periods?
- Is there a difference in biological communities between phases and drilling periods, at high- versus low-relief heights, or at shallow versus deep bottom depths?
- Is there a difference in larval settlement and recruitment at platform nearfield compared to farfield sites, or at high- versus low-relief heights, during drilling versus non-drilling periods?
- Is there a toxicity response by larval and adult invertebrates from laboratory exposures to drilling muds?

### 3.2.1 Phase II Overview

This section contains a synopsis of the Phase II results and conclusions as a framework for integration with the Phase III results. Questions regarding differences between phases include specific changes in predrilling, drilling, and postdrilling conditions.

The Phase II studies were conducted from October 1986 through October 1990. The focus of these studies was to assess potential long-term changes in physical, chemical, and biological characteristics in the vicinity of oil and gas platforms and to determine whether observed changes were caused by drilling-related activities or by natural processes (Steinhauer and Imamura 1990; Brewer et al. 1991; Coats 1994; Hardin et al. 1994; Steinhauer et al. 1994). Phase II studies focused on hard-bottom communities in the vicinity of Platform Hidalgo. Initial studies of soft-bottom communities were discontinued because of delays in drilling at a proposed site (Platform Julius). However, these background surveys provided useful information on physical, chemical, and biological processes within the general vicinity of the site (Steinhauer and Imamura 1990).

Production drilling at Platforms Hidalgo, Hermosa, and Harvest occurred during January 1987 to January 1989. Drilling operations resulted in total discharges of 11,225,500 kg of drilling muds and 5,400 kg of cuttings (Steinhauer and Imamura 1990; Table 1.1-1). Muds and cuttings samples collected from the platforms contained elevated concentrations of several inorganic and organic constituents. Specifically, average concentrations of Ba, zinc, lead, and polycyclic aromatic hydrocarbons (PAHs) were up to 150, 18, 130, and 350 times higher, respectively, than corresponding concentrations in bottom sediments (Steinhauer et al. 1994).

During periods of active drilling, collections and analyses of bottom sediments and suspended particles indicated increases in Ba concentrations up to 40% and 300% above background, respectively (Steinhauer et al. 1994). These increases were attributed to episodic discharges of drilling muds and cuttings from the platforms through subsurface shunts with subsequent settling to the bottom. Based on estimates of the amounts of excess Ba (i.e., relative to background concentrations) in suspended particles, the contributions of particulate wastes to the total particle fluxes in the vicinity of the platforms were calculated as approximately 2% (Hyland et al. 1994; Coats 1994). Computer simulations of these discharges were performed to estimate depositional fluxes of waste particulates at distances of 1–10 km from Platform Hidalgo (Coats 1994). Results from these simulations were in reasonable agreement with flux measurements from sediment traps, and suggested that much of the initial deposition of drilling muds was not derived from Platform Hidalgo. Instead, relatively greater contributions to the particulate fluxes were from Platforms Harvest and Hermosa discharges, which were dispersed and eventually overlapped with depositional patterns from Platform Hidalgo discharges (Coats 1994).

With the exception of Ba, no significant changes in concentrations of other chemical constituents, or in grain size or mineralogical properties of the bottom sediments or suspended particles were associated with the platform discharges (Steinhauer and Imamura 1990). Barium was the most sensitive indicator of drilling mud and cuttings discharges because it is highly enriched (relative to background concentrations) in the source material, it is essentially insoluble in seawater, and it is not expected to be altered by natural, chemical, or biological processes (Steinhauer et al. 1994). Despite the fact that concentrations of some classes of hydrocarbons (e.g., lower molecular weight PAHs) were elevated in muds and cuttings, concentrations and component ratios of these hydrocarbons in bottom sediments and suspended particles did not indicate significant contributions from particulate wastes. Although increases in total petroleum hydrocarbons occurred during the drilling period, the general absence of lower molecular weight PAHs suggested that these increases could be attributed to natural, petrogenic sources (Steinhauer et al. 1994). Any contributions from platform discharges to concentrations of petroleum hydrocarbons either were masked by the dominant background signal of hydrocarbons from natural sources (e.g., local oil seeps) or reduced due to selective solubilization and/or microbial degradation of these less refractory compounds.

Overall, increased Ba concentrations were the only chemical or physical characteristics of bottom sediments and suspended particles that were affected significantly by platform discharges (Steinhauer et al. 1994). Barium, in the chemical form associated with drilling muds (barite), is considered to be essentially nontoxic to marine organisms, including embryos and larvae (NRC 1983). Nevertheless, excess Ba concentrations (i.e., levels above background) in suspended particles were used during the Phase II studies as a surrogate measure of the relative exposure or dose to hard-bottom organisms of the particulate fractions from platform discharges. Estimated dose levels subsequently were used as a factor for analysis of variance in the hard-bottom community data (Steinhauer and Imamura 1990).

Comparisons between predischarge and postdischarge surveys in the abundances of 22 taxa associated with high- and low-relief hard-bottom sites indicated significant differences ($p < 0.05$) for four taxa: sabellid polychaetes, the tunicate *Halocynthia hilgendorfi*, the cup coral *Caryophyllia* spp., and galatheid crabs. These differences were restricted to deeper reefs (160–212 m) near Platform Hidalgo, whereas no significant differences were apparent at shallower reefs (105–119 m) (Hyland et al. 1994). The Phase II study concluded that these differences likely were not related to a toxic response, because the only constituent that appeared to be elevated compared to background concentrations was Ba. Instead, it concluded that these differences probably were a response to increased particle fluxes represented by settling particulate wastes. The effect was presumed to be related to disruption of feeding, respiration, and/or postlarval survivorship due to burial (Hyland et al. 1994). However, the possibility that differences were due to an acute response to toxic, but transient, petroleum constituents of the drilling muds (e.g., naphthalenes and phenanthrenes) could not be evaluated from these data (Steinhauer and Imamura 1990).

Independent of the source of impact, any effects appeared to be localized near the platform and, based on combined Phase II and Phase III data, were not expected to extend in a significant manner from these "patches" to a larger landscape scale (e.g., Freemark 1995). Source populations outside of an effect zone would be expected to contribute to recolonization in the absence of additional disturbance (Lissner et al. 1991).

Subsequent to the end of the drilling period, concentrations of Ba in suspended particles decreased over time. By the end of the Phase II study, concentrations of Ba in suspended particles, as collected from sediment traps, had reached background concentrations. In contrast, Ba concentrations in bottom sediments still were considered slightly elevated due the presence of residual barite particles (Steinhauer and Imamura 1990; Hyland et al. 1994).

## 3.2.2 Phase III Results and Integration

The Phase III field studies, conducted from October 1991 to January 1995, corresponded to two main drilling-related periods: (1) post-Phase II drilling/pre-Phase III drilling (generally October 1991 through August 1993) and (2) Phase III drilling and post drilling (September 1993 through January 1995). A summary of impacts by study element for the two periods is presented in Table 3.2-1. The first period represented approximately a four and one-half year interval since the last Phase II discharges in January 1989 (Table 1.1-1), and was anticipated to be characterized by progressive decreases in any discharge-related changes noted from the Phase II studies. This hypothesis was based on expected dispersion and mixing of sediment contaminants by local transport processes, as well as natural colonization and recovery by biological organisms, in the absence of new discharges (e.g., Lissner et al. 1991). Further, severe or large-scale impacts to the biological communities would not be predicted during the second (drilling) period since the discharges were only 10% of those during Phase II.

**Physical Oceanography/Sediment Transport**

The physical oceanographic conditions of the study area are subject to strong waves and currents associated with confluence regions of the California Current System, as well as exposure to numerous Pacific storm systems that impinge on this relatively open area of the coast. These conditions produce strong mixing of the upper water column and, potentially, resuspension of sediments in relatively shallow shelf regions, extending from shore to approximately 100-m bottom depths (SAIC and MEC 1993; Appendix A). Results from the Phase III studies emphasized the dynamic nature of these currents and transport mechanisms, also as noted during Phase II (Steinhauer and Imamura 1990; Appendix A). These conditions likely serve as an effective dispersal mechanism for the eggs and larvae of invertebrates and fish, thereby resulting in large (landscape) areas over which potential colonizers may be distributed. Further, the study area is in a region of active upwelling (Dugdale and Wilkerson 1989) as well as near a transition zone of two biogeographic provinces (Newman 1979), all of which should serve to enhance the diversity and abundance of source populations for colonization/recolonization.

Detailed current measurements indicated that flows were generally upcoast during summer/winter and downcoast in spring, although the duration and characteristics of these seasonal patterns varied among the phases and study years. Features such as eddies and meanders also produce much local variability. This was reflected in the relatively small scale of coherence between currents measured at a long-term mooring near Platform Hidalgo compared to a variable-location mooring that was positioned from a few to several kilometers away (Appendix A).

The near-bottom sediment transport regime also exhibited large spatial and temporal variability. Substantial differences between the phases in rainfall and associated runoff from land (Figure 1.4-1) may have resulted in much greater sedimentation and transport during Phase III. Increased sedimentation including, in extreme cases, burial of hard substrate and biota or reduced feeding efficiency (by clogging) of filter feeding organisms, has been theorized to potentially reduce the

Table 3.2-1. Comparison of Predrilling and During-Drilling Period Impacts Among Study Sites, DOI Phase III.

| | Predrilling (Residual Phase II) Study Site[1] | | | | During-Drilling Study Site[1] | | | |
|---|---|---|---|---|---|---|---|---|
| | High-Relief | Low-Relief | Shallow | Deep | High-Relief | Low-Relief | Shallow | Deep |
| **Sediment Chemistry** | | | | | | | | |
| Barium | NM | NM | Yes | Yes | NM | NM | Yes | Yes |
| Other Metals | NM | NM | No | No | NM | NM | No | No |
| Hydrocarbons | NM | NM | No | No | NM | NM | No | No |
| **Suspended Particle (Sediment Trap) Chemistry** | | | | | | | | |
| Barium | NM | NM | No | No | NM | NM | Yes[2] | No |
| Other Metals | NM | NM | No | No | NM | NM | No | No |
| Hydrocarbons | NM | NM | No | No | NM | NM | No | No |
| **Particle Flux (Physical Measurements Array)** | No | No | NM | No | No | No | NM | No |
| **Particle Tracking Model** | NM | NM | NM | NM | NM | NM | Yes[2] | No |
| **Hard-Bottom Community** | No | No | No | No | Yes[3] | Yes[3] | Yes[3] | Yes[3] |
| **In Situ Larval Experiments** | No | No | NM | No | Yes[4] | Yes[4] | NM | Yes[4] |

NM = Not measured as part of study.

(1) Represents both nearfield and farfield stations for each site category, except as noted under (2) and (3) below. High-Relief = > 1 m height above bottom; Low-Relief = 0 to 1 m above bottom; Shallow = 105 to 119 m; Deep = 160 to 212 m.

(2) Nearfield only.

(3) Nearfield only based on ANCOVA of Phase II and Phase III data combined.

(4) Manipulated red abalone only; no effects for natural settlement experiments.

abundance of many species (Lissner et al. 1991). This may be particularly evident in low-relief habitats that are more susceptible to burial by sediment encroachment.

Results from wave and tide gauge measurements during Phases II and III indicated that surface-generated waves usually did not cause resuspension at deeper bottom depths (e.g., >138 m, representing the primary mooring depth). This conclusion was substantiated further during Phase III by current and sediment resuspension data from near-bottom (200 m depth) physical measurements arrays. These results indicated very limited resuspension of bottom materials associated with meterological events and surface waves (Appendix A). Near-bottom concentrations of suspended particles typically were low, averaging 1-5 mg/l, and correlations between suspended particle concentrations and current speeds were poor. However, aperiodic increases in near-bottom particle concentrations were up to several orders of magnitude above background conditions. Several suspended sediment movement events were noted at both nearfield and farfield sites relative to the platform, although it appears most likely that these events were caused by resuspension in shallower, inshore areas, and runoff from storm events, followed by movement offshore through the study region. Large-scale events such as increased storm activity and rainfall runoff during Phase III, compared to drought conditions that prevailed during Phase II, would be expected to have a significant effect on coastal and shelf transport processes (Section 1.4). There was no evidence of drilling-period related increases in suspended sediments; however, this conclusion undoubtedly is influenced by the somewhat limited discharge volumes during Phase III.

The potential for greater transport and resuspension at shallower depths is consistent with particle flux data from sediment traps located at both shallow (105–119 m) and deep (160–212 m) bottom depths (Appendix B). These traps represent particle collections from approximately 1 m off the bottom, corresponding to a distance that is intermediate between the low- and high-relief heights associated characteristically with natural differences in biological communities. Particle fluxes during both phases were higher at shallow compared to deep stations. For example, a significant negative correlation between depth and particle fluxes was observed during Phase II (Steinhauer and Imamura 1990). The physical measurements arrays, which were located at a single depth (approximately 200 m), supported individual traps positioned at both low- and high-relief heights, consistent with the distinctions for the biological communities. Fluxes were approximately 25 to 65% higher at low- compared to high-relief levels, reflecting the greater amounts of resuspended sediments in water layers closer to the bottom (Appendix B). These results likely indicate a higher potential for biological impacts in low-relief areas due to sediment cover and burial, although common species (e.g., several cup coral species and seastars) in these habitats should be adapted to relatively high particle/sediment fluxes (Lissner et al. 1991).

### Chemical Contaminants

Pre-Phase III drilling (period one) results indicated that concentrations of chemical contaminants, other than slightly elevated Ba in bottom sediments from residual (Phase II) platform discharges, remained at or near background levels in surficial and suspended particle (i.e., sediment trap) samples (Appendix B). Changes in concentrations of other drilling-related contaminants, including petroleum hydrocarbons and other metals, were not evident.

The only other contaminant-related trend in the period one data was unusual increases in low molecular weight PAHs in surficial and suspended sediments that occurred sporadically at selected stations during October 1991 (Appendix B). These increases possibly were caused, in part, by discharges of a non-drilling related petroleum product ("diluent") from a land-based spill source during 1990 and 1991. Chemical "fingerprinting" analyses and the correspondence of spill timing with contaminant results suggest, based on weight-of-evidence, that the diluent was present in these samples. Other petroleum hydrocarbons also were present that appeared to be related to natural seeps and anthropogenic combustion products (Appendix B).

During the drilling period (period two) for Phase III, slight increases in Ba were evident, but only for suspended particles (from sediment traps) at three stations near Platform Hidalgo. Residual excess Ba, primarily from Phase II discharges, was present in sediments within 500 m of the three platforms at concentrations up to an order of magnitude higher than background. These elevated levels likely are associated with drill cuttings deposited near the platforms (see Phase III modeling results in Appendix A; Coats 1994). No significant increases in other metals or hydrocarbons were observed during Phase III. This likely is due to the minimal enrichment of most metals in the discharges, solubility of lower molecular weight PAHs in drilling muds, large natural variability in background hydrocarbon concentrations, relatively low discharge volumes (only 10% compared to Phase II), and high dispersion related to dynamic local and regional currents and relatively deep water depths. These latter assumptions of high dispersion of the discharged material are confirmed by results from the particle tracking model performed for Phase III (Appendix A). Sediment deposition depths and bottom footprint size are influenced by differences in discharge volumes and current velocity and direction. However, only very thin layers (average bottom accumulation of 1.5–7.5 microns) of deposited material are likely, corresponding to a very large footprint for fine-grained particles (approximately 100–550 square kilometers, depending on the particle size), and substantial fine material (40–80%) that is dispersed beyond the study region. Based on the chemistry and particle tracking model results alone, deposition of particulate contaminants from platform discharges would not be expected to cause significant impacts to hard-bottom communities in the study region.

This type of depositional pattern and the irregular frequency of platform discharge events is consistent with an impact model of multiple, large-scale events in a patchy population (Section 3.1). Substantially greater discharge volumes occurring at more frequent intervals should produce correspondingly greater effects, although the highest Phase II discharges only represented 2% of the total particle fluxes in the vicinity of the platforms (Coats 1994).

**Biological Community**

The hard-substrate epifauna of the Santa Maria Basin are diverse (286 taxa from Phases II and III combined) and abundant (Appendix D). Dominant phyla are cnidarians, echinoderms, and sponges. Primary and secondary differences in the biological communities are associated with differences between shallow and deep hard-bottom sites and high- versus low-relief features, respectively (Appendix D). Combined Phase II and Phase III results indicated that deeper sites (160–212 m) have more taxa (mean = 20.7) and higher percent cover (mean = ~ 40%) than shallow sites (105–119 m; mean taxa = 15.6; mean % cover = ~ 29%), and more taxa favored high relief (mean = 22) than low relief (mean = ~ 17) (Appendix D). Taxa characteristic of shallow sites include several cup corals (*Balanophyllia, Caryophyllia*, and *Paracyathus*) and seastars (*Mediaster, Stylasterias*, and *Rathbunaster*), while deep sites are typified by other cup corals (*Desmophyllum*), colonial corals (*Lophelia*), and seastars (*Hippasteria* and *Poraniopsis*), in addition to various anemones, sponges, and basketstars (*Gorgonocephalus*). In contrast, numerous taxa such as ophiuroids, large anemones (*Metridium*), crinoids (*Florometra*), and tunicates (*Halocynthia* and *Pyura*) are ubiquitous, generally occurring over the range of study depths. Most of the shallow water taxa preferred low-relief, although this may be influenced by the scarcity of shallow high-relief study sites (Appendix D).

Some of the community patterns may be associated with differences in particle fluxes and sediment movement between depths and relief heights, although direct evidence for this relationship is not available. Nonetheless, review of the ecology and natural history of key taxa associated with these communities indicates that many of the high-relief species, such as anthozoans and sponges, are filter or particle feeders that are likely to be sensitive to high concentrations of suspended particles (Lissner et al. 1991). Observations from submersibles and remotely operated vehicles (ROVs) have documented numerous examples of hard-bottom organisms, such as cup corals, that were partially to fully buried by sediments, or examples of attached filter feeders, including sponges, that appeared to be heavily fouled by sediment particles (BBA/ROS 1986; SAIC 1986; SAIC and MEC 1989; Lissner et al., personal observations during Phase III surveys). Natural sediment and particle transport, as well as discharges of drilling muds, can contribute to the fluxes to which these organisms are exposed. Impacts potentially can result from physical effects such as burial or clogging of filter-feeding structures, or from toxic effects (see larval and toxicity experiments below). Taxa, including ubiquitous species, that are common in shallow and/or low-relief habitats are assumed to be reasonably adapted to high particle fluxes and sediment resuspension. Fluxes in these habitats can be twice as high as in deep and/or high-relief habitats (Appendix B). Ubiquitous taxa are mainly represented by comparatively large, mobile forms that would be expected to have broad habitat tolerances, particularly as related to an ability to relocate to more favorable areas or to potentially extend above turbid, near-bottom waters (Lissner et al. 1991). However, it is notable that several small (e.g., 1 cm tall), sessile cup coral taxa also prefer shallow, low-relief habitats. The success of these cup corals may be related to greater reproductive output and/or growth rates compared to the larger taxa, although definitive studies are presently lacking. Other relatively motile species, such as sea stars, brittle stars, feather stars, and crustaceans, or "tall" (e.g., 1 m high) species, such as the anemone *Metridium,* should be able to emigrate from or avoid areas of high particle fluxes, thereby minimizing exposure and potential impacts (Lissner et al. 1991).

Based on combined Phase II and Phase III data, the rank order of dominance of most hard-bottom taxa was relatively stable over time as related to drilling discharge periods and distance from Platform Hidalgo (Appendix D). Linear regression analyses of changes in abundance (percent cover) for 24 dominant taxa indicated significant negative trends for 35% of the 72 possible combinations of taxa and depth/relief height, although there was no consistent, platform-related pattern for any one taxon. ANCOVA tests of abundance changes for 20 taxa with distance from the platform identified 18 positive and 17 negative effects. However, Chi-square contingency analysis of the significance of the multiple positive, negative, and inconclusive results from ANCOVA analyses indicated that the results may be expected based on chance alone (Appendix D, Table 9). The negative effects were observed for a wide variety of taxa, most of which are filter or suspension feeders. Only two of these taxa (*Caryophyllia* and *Halocynthia*) were also associated with the same potential drilling-related effects during Phase II (Hyland et al. 1994; Appendix D). Overall conclusions were that the combined trends for the various taxa were not statistically significant.

Photographic characterizations of the hard-bottom community provide little evidence of significant, broad-scale effects from drilling discharges (Appendix D). This is consistent with limited particle discharges and physical/chemical effects. However, some of the difficulties in distinguishing platform effects are related to the apparently high variability and patchiness of the hard-bottom habitat and associated communities, as well as the relatively low statistical power to detect change based on the random photoquadrat study design (Appendix D).

A key residual question from the biological community results is whether the negative trends (based on ANCOVA) for some taxa have long-term ecological significance. As discussed in the section on chemical contaminants, there were no persistent toxic components from the particulate fractions of the platform discharges that would be expected to cause these negative effects. Further, the small amount of additional particulates from the discharges, particularly as compared to Phase II, should be inconsequential relative to the overall particle and sediment transport budget of the study region (Appendix B). A natural variable that may influence these results is the substantially greater sediment loading to the shelf ecosystem that likely occurred from storm runoff during Phase III as compared to Phase II (Chapter 1). The occurrence of negative effects at shallow low-relief sites, and to a variety of taxa and feeding types, may be indicative (in part) of broad-scale, natural sediment transport events. Such effects might be expected based on (1) greater sediment fluxes in these habitats (compared to deep, high-relief), and (2) natural differences between the nearfield sites (PH-E, -I, and -J) and the farfield (reference) site, PH-U. PH-U is located in relatively close proximity to a canyon system (Figure 2.1-3) and could be associated with different oceanographic and sediment flux regimes (as noted in Appendix A for deep nearfield and farfield sites studied with the physical measurements arrays). Differences in these regimes could result in some of the apparent statistical differences in species trends observed from this study.

Alternately, assuming (as noted above) that effects associated with the particulate fractions of platform discharges are inconsequential, the only other potential platform-related source of contaminants is dissolved chemical components such as those present in produced water (see larval and toxicity experiments discussion below). Dissolved petroleum hydrocarbons have been shown to be a toxic agent in oil-field produced waters (Cherr et al. 1993; Higashi and Crosby 1993).

## Larval Experiments and Toxicity Tests

The in situ larval settling experiments provided a focused study design for evaluating drilling discharge-related effects to (1) red abalone as an indicator species during manipulated studies, and (2) natural (unmanipulated) colonizers. The larval settlement experiments tested location (platform versus reference), waterborne (particulate and dissolved fractions combined), and substrate relief height (high versus low) differences, and were the first studies to integrate potential impacts to the larval community into the Santa Maria Basin monitoring program. This was of particular importance since factors that affect larval recruitment can have longer-term effects at the population and community level (Mullineaux 1988; Raimondi 1990). Results from both experiments indicated that natural filming of settling plates by bacteria was necessary to optimize settlement by the larvae (Appendices C-1 and C-2). However, relief height was not a significant factor, independent of the general filming site location. Results from the red abalone experiments concluded that settlement at near-platform and reference sites was lower during drilling than predrilling periods. Settlement was significantly lower near the platforms than at the reference site, thereby suggesting drilling-related impacts (Appendix C-1).

In contrast, natural settlement experiments that tested growth, survivorship, and fecundity did not imply significant drilling-related effects (Appendix C-2). This was the case for both newly settled organisms and those that were established (previously settled) on the plates as part of longer-term (e.g., 300 days or more) studies. Approximately 50 different taxa were identified from the natural settlement experiments, although only nine, including one bivalve (*Delectopectin sp.*), two bryozoans, two hydroids (e.g., *Triticella sp.*), Komokoiacea, total organisms, total multicellular organisms, and serpulid worms, occurred on even 5% of all plates (Appendix C-2). Overall results indicated very high spatial and temporal variability in settlement. The patchy distribution may reflect low larval abundance and/or food availability, as also influenced by physical oceanographic factors. This limited settlement restricted the ability of natural settlement experiments to detect drilling-related effects and supports the use of manipulated in situ experiments to assess larval impacts, as performed using the red abalone larvae (Appendix C-1). Nevertheless, some significant differences between natural settlement at high- versus low-relief heights was observed for four taxa, but height preference also varied by taxon (i.e., some preferred low- and some high-relief). The reasons for these differences cannot be determined based on the present data; however, the results provide a distinct example of early settlement patterns that potentially could produce later community differences. Qualitative observations of the larval experimental structures (igloos) in the field indicated that the lower-relief heights often were characterized by higher amounts of sediments in the experimental trays holding the settling plates. Assuming that this represented actual differences in suspended material loads, consistent with the results from the physical measurements arrays (Appendix A), these differences could represent larval selection for substrates having less sediment cover.

Laboratory toxicity tests indicated that the fertilization mechanism and early developmental stages of red abalone larvae were unaffected by exposure to drilling muds (Appendix C-3). In fact, some experiments suggested that survivorship may be enhanced at higher concentrations. In contrast, significant negative effects were found for the ability of the larvae to respond to a natural settlement inducer. This is consistent with the general finding of drilling-period impacts to in situ manipulated red abalone larvae. Negative effects also were evident for adult brown cup corals, which had significantly increased mortality due to progressive tissue loss following exposure to drilling muds (Appendix C-3). These effects were observed even under the lowest concentrations tested (0.02 mg/L), and may provide evidence of a mechanism for direct impacts to at least this member of the hard-bottom community.

Marine larvae can be highly selective in their search for a suitable settlement site (Keough and Downes 1982; Rodriguez et al. 1993). This process often involves complex biochemical mechanisms (Morse 1990) that can be disrupted by waterborne contaminants and suspended particulates which interfere with physiological receptors of the larvae. Post-settlement processes including metamorphosis from larval to juvenile forms also may be affected. Even slight effects to larval settlement can result in reductions in recruitment, thereby leading to broader, population- or community-level changes (Keough and Black 1995; Nisbet et al. 1995). Such effects may partly explain Phase II results which indicated significant decreases in the mean abundance of four taxa following a drilling period. However, the time lag between any significant reductions in recruitment and corresponding decreases in adult populations would vary substantially among taxa (e.g., long-lived, slow-growing sponges compared to many mat-forming species such as hydroids) and be very difficult to predict due to limited life history information on most of the species. At present the processes linking larval and adult benthic dynamics are poorly understood, representing an active area of ongoing research (Raimondi and Schmitt 1992), and the specific mechanism, presumably chemical, in the Santa Maria Basin study region is presently unknown.

The timing of abundance decreases for some hard-bottom epifauna and the reduced settlement noted from the in situ red abalone experiments appears to coincide with periods of active drilling and platform discharges. However, analyses of bottom sediments and suspended particles did not indicate significantly elevated concentrations of metal or hydrocarbon contaminants, other than Ba. This suggests that any alterations in biological communities were attributable to conditions or exposures to sources other than particle-sorbed contaminants. Other possible explanations include: (1) exposures of epifaunal organisms to dissolved lower molecular weight hydrocarbons that partitioned from settling/deposited muds and cuttings to bottom waters; or (2) exposures of organisms to dissolved components of the produced water plume.

Recent studies (e.g., Krause 1995) have demonstrated toxic effects to invertebrate gametes at high dilutions (low concentrations; 10–0.0001%) of produced waters. The toxic component(s) responsible for these effects have not been identified. However, produced waters, including those analyzed for the present study, are known to contain elevated concentrations of the more toxic lower molecular weight PAHs (e.g., naphthalenes), as well as dissolved Ba. Low concentrations of dissolved Ba (e.g., 100 μg/L) have recently been shown to inhibit developmental stages of some invertebrate species (Cherr, pers. comm., 1995). Since 1992–1993, several million liters per day of produced waters have been discharged from Platforms Harvest, Hermosa, and Hidalgo. Theoretically, the higher the density of the produced waters compared to ambient seawater, the greater the likelihood that the plume would sink and expose benthic communities to potentially toxic concentrations of soluble contaminants. However, the density of the produced water discharged from Platform Hermosa is less than one (Chevron 1994); consequently, the plume initially would be buoyant. Further, initial dilutions of the produced water plume of 970:1 are expected to occur within approximately 30 m of the platform (Chevron 1994). This dilution rate alone would reduce the concentrations of PAHs and Ba in the receiving waters by approximately three orders of magnitude. Therefore, it is apparent that the produced water plume would be highly diluted, and concentrations of dissolved components would be greatly reduced, prior to potential exposures to epifaunal communities. Some pelagic larvae likely would be subjected to less diluted components, particularly near the discharge; however, the percentage exposed out of the total available larvae in the region should be very low. Nonetheless, it appears unlikely based on considerations of plume density and initial dilution that dissolved components of produced water discharges represent a significant impact source to the hard-bottom communities of the Santa Maria Basin.

**Synopsis**

Decreasing trends in abundance (percent cover) were observed for many common taxa from Phase II to Phase III, but there were no consistent, platform-related patterns for any one taxon. ANCOVA tests of changes in abundance relative to distance from Platform Hidalgo, based on combined Phase II and Phase III data for 20 taxa, indicated a nearly even number of positive and negative effects (Appendix D, Table 8). Chi-square contingency analyses of the combined negative, positive, and inconsistent results for the various taxa suggest that these differences may be attributable to random chance alone (Appendix D, Table 9). A conclusion of no significant drilling-related impacts would be consistent with results from the physical/chemical studies, which indicated no changes in particle-associated contaminants or sediment fluxes due to platform discharges (Appendices A and B). Further, it is unlikely based on general characteristics of the produced water discharges (buoyant relative to seawater and highly diluted) that dissolved components would cause these types of community effects, although dissolved fractions have not been studied directly by the Phase I–Phase III studies. Additionally, since the produced water discharges were not initiated until 1992, only the Phase III changes could be relatable to these exposures. Nonetheless, potential effects that may be represented by the ANCOVA results seem to be relatively subtle and do not suggest severe, broad-scale impacts. Natural factors that may influence the community results could include large-scale events such as El Niño, and a return to normal rainfall patterns (after extended drought conditions during Phase II) that may be associated with increased particulate loads from runoff, as well as resuspension and transport of nearshore sediments from storms. However, no direct studies have been conducted on the potential effects of these types of particulate loads on hard-bottom epifauna of the study region.

The chemistry and community studies are somewhat in contrast to results from the in situ larval settling experiments and laboratory toxicity tests (Appendix C) which suggested some effects from drilling discharges. The in situ larval experiments provided a more sensitive measure of impacts from drilling activities than was possible using community data alone (Appendices C and D). Differential settlement of larvae or greater sensitivity to low concentrations of waterborne contaminants could result in chronic, long-term impacts to some species, with corresponding community effects. However, species-specific variability and incomplete knowledge on life history and growth rates for most taxa limit predictions of time lags between impacts to larvae and subsequent changes in adult populations. Nonetheless, independent of the chemical or physiological mechanisms, long-term, large-scale (i.e., landscape) impacts to hard-bottom epifaunal communities from the combined Phase II and Phase III drilling discharges were not evident based on the present data.

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# Chapter 4

# RECOMMENDATIONS

Recommendations for modifications and additions to the physical, chemical, and biological study tasks are presented in Sections 4.1 through 4.3, respectively.

## 4.1 PHYSICAL PROCESSES

The primary objective of the physical oceanographic component of the Phase III program has been to provide a description of the current regime to which biological, chemical, and sediment monitoring could be related, and to provide data on current fields for input into a numerical particle tracking model that aids in predicting drilling mud transport and deposition. The present study has been successful in providing continuous times series of current velocity and temperature data at three depths for over two and one-half years. This is in addition to the several years of similar data collected at the same (primary) mooring location during Phase II. Such long-term, continuous records are relatively rare in oceanography and can be important in resolving trends and interannual variability. This is particularly relevant in the complex transition zone that is representative of the study area. Consequently, it would be very beneficial if at least the primary mooring was redeployed to maintain and continue these data records. Any other recommendations on deployment of additional moorings should be coordinated with measurements available to DOI from other major studies, such as the SIO/MMS Santa Barbara Channel and Santa Maria Basin field experiments. Because of the locally short, cross-isobath coherence scale of currents in the vicinity of Pt. Arguello (Appendix A), it would be important to conduct additional studies of this variability, particularly offshore of the primary mooring. In a regional context, an improved understanding of this often abrupt transition between current patterns may have application to other regions in the Southern California Bight (e.g., Santa Monica Bay). The design of further current monitoring studies should consider more modern instrumentation (such as bottom-mounted ADCPs) that could provide better resolution of the current field. Regular drifter deployments from the platforms could also be useful for resolving Lagrangian scales of the dispersion of drilling muds.

The oceanographic regimes that influence seasonal and other low frequency currents in the vicinity of Pt. Arguello and Pt. Conception often have an expression in the sea surface temperature field. As shown during the present project, satellite thermal images are one of the few data sources that provide a synoptic, regional view of this key oceanographic variable. Consequently, SST imagery in conjunction with subsurface observations of currents and temperature would help provide regional-scale, three-dimensional descriptions of the oceanographic regimes that govern local transport patterns.

Near-bottom clouds of suspended material measured during this study do not appear to be caused by conditions that are local to these measurements. Consequently, to understand the potential for biological impacts from suspended material, including ambient material, it is important to conduct studies, such as through the use of PMAs, of remote resuspension events and subsequent offshore transport of the material towards the hard-bottom study sites. Based on the recurring long period and potentially high local wave field, wave-induced resuspension in shallower water and advection to these deeper sites is a likely candidate for this process.

Thus, specific recommendations are:

(1) Continue and extend monitoring of the physical oceanographic regime, including sediment and bottom boundary layer processes.

(2) Maintain and continue the primary mooring in its present location. Different configurations may provide greater vertical resolution of currents using similar effort. However, the three depths (approximately 14, 53, and 125 m) monitored during Phases II and III should be maintained at a minimum.

(3) Deploy a small scale array of current meter moorings to investigate cross-isobath scales of variability. A possible design would be two secondary moorings, one at the site of S4 and another on the 500-m isobath seaward of S4. This could be linked to the coastal currents by a mooring on approximately the 50 m isobath, just seaward of the three-mile limit.

(4) Regular deployments (e.g., 1 or 2 per week) from a platform of satellite-tracked drifters should be evaluated as a method for estimating dispersion and providing a Lagrangian perspective of variability of the current field.

(5) Design and deploy near-bottom instrument arrays, such as PMAs, containing instruments to measure local instantaneous velocities, temperature, and suspended particle loads. The PMAs should be placed at several (2-3) inshore locations in 25-50 m water depths. At least one of these could be placed on a shoreward extension of the small mooring array described in (3) above. In this context, the wave-tide gauge used at the primary mooring would provide more useful wave data if deployed in shallower water.

(6) Continue satellite imagery collection for use in conjunction with moored and bottom-mounted instrumentation.

Collection of optical data from PMAs that are of sufficiently high accuracy to permit calculation of concentrations of near-bottom suspended materials would require maintenance of sensor units on approximately three-month servicing cycles. Despite the use of aggressive antifoulants, data quality degrades rapidly beyond this period due to intensive biological growth on the sensor windows. Therefore, ship scheduling and array recovery procedures should be modified to permit maintenance on a quarterly schedule. This may require some redesign of array recovery systems to provide a reliable backup and to facilitate recovery in the absence of support by an ROV. Alternatively, if longer-term deployments must be maintained, alternative sensing techniques including acoustics and/or revised optical systems should be evaluated.

## 4.2 CHEMICAL PROCESSES

Continued analyses of surface sediments and suspended particles, as well as platform discharges, formation oils, and seep oils, for hydrocarbons and selected metals are recommended to evaluate potential effects of future drilling activities. The present list of hydrocarbon analytes is very useful for distinguishing and quantifying contributions from petrogenic, pyrogenic, and biogenic sources. Additionally, it is recommended that measurements for stable petroleum biomarkers (e.g., triterpanes and steranes) be incorporated into the measurement program on a routine basis. Measurements for these compounds will enhance the ability to detect signals from petrogenic sources, even when more traditional chemical indicators for oil [e.g., n-alkanes and polycyclic aromatic hydrocarbons (PAHs)] have been reduced to nondetectable levels.

Limited useful information is gained from laboratory analyses for mineralogy, carbonate, or metals other than barium and aluminum. Other metals are not particularly enriched in drilling muds or cuttings, and are at or near background concentrations in sediments and suspended particles. Therefore, present operational discharges from platforms do not appear to affect these analytes, and the ability to detect potential changes related to drilling operations is low. Therefore, some reduction in the list of analytes is possible, although this may be less important than maintaining the consistency of the long-term monitoring record.

Because results of the in situ larval settling experiments suggest that proximity to platforms during periods of active discharge may be associated with some adverse effects (Appendix C), additional measurements of the dissolved and particulate fractions of produced water plumes could be informative. In particular, analyses of lower molecular weight PAHs (e.g., naphthalenes and phenanthrenes) in receiving waters near the base of platforms could be used to evaluate exposures and potential toxicity of organisms to hydrocarbons which are present in the dissolved phase of produced waters (Cherr et al. 1993; Higashi and Crosby 1993). The presence of elevated concentrations of these relatively toxic compounds could provide better correlations with observed effects to larval organisms than measurements of suspended or surficial sediments.

## 4.3 BIOLOGICAL PROCESSES

### 4.3.1 Biological Community Study

Substantial high-relief habitat was identified and surveyed at Stations PH-I, PH-J, and PH-E that was not reported from Phase II. This high-relief habitat occurs at shallow-depth stations and provides an important basis for comparison of high-relief habitat between shallow and deep stations. Cluster analysis of dominant taxa from the Phase II and Phase III data indicated that high-relief habitats were distinct for the shallow and deep depths and from associated low-relief habitats. This additional information provides for a more balanced study design as well as additional insights on epifaunal community structure and organization. Therefore, it is recommended that these additional high-relief habitats continue to be monitored in all future surveys.

Some of the key limitations in distinguishing effects to epifaunal communities from drilling discharges as compared to natural changes is the apparently high spatial variability of the hard-bottom communities. Therefore, an important element of future studies should be to perform additional monitoring at permanent stations representing low- and high-relief reefs, located at shallow and deep depths and at nearfield, midfield, and farfield distances from a platform(s). Close-up photography including measurement scales in the photographs could be used to augment studies at permanent stations, particularly as related to temporal trends in the size structure of populations (e.g., cup corals). These studies would be in addition to randomly-collected photoquadrat and color video data as performed during Phases II and III, and should be initiated during a non-drilling period to allow sufficient time to document natural temporal and spatial variability.

Finally, from a methodological standpoint, either 35-mm or 70-mm photographic techniques appear to be appropriate for documenting the types of communities in the study region. However, based on the greater ease and cost effectiveness provided by 35-mm photography, this is recommended as a better long-term approach (Section 2.4).

### 4.3.2 In Situ Larval Experiments

The following recommendations are based on the natural and manipulated (red abalone) settlement experiments.

- The present in situ experiments demonstrated conclusively that biogenic surface films have a statistically significant effect (increases) on settlement. Therefore, it is important to ensure adequate filming by retaining transplantation of settlement plates in the experimental design. Additionally, this procedure will help determine how perturbations such as drilling discharges may affect film development, how settlement is affected by films from disturbed areas, and aid in the design of further laboratory experiments.

- Given that natural settlement rates are very low and probably variable (this may be typical for deep-sea environments), it is important to retain manipulated settlement experiments to address questions about impacts to settlement. Such experiments have at least three benefits, as noted below:

  (1) Encounter rate is standardized between locations, thereby removing a potentially confounding source of variation.

  (2) Settlement numbers can be relatively high over short periods (e.g., 3 days). This allows settlement questions to be addressed that are not complicated by post-settlement mortality.

  (3) Short-term settlement experiments allow empirical questions to be addressed concerning particular mechanisms of toxicity, for example, waterborne effects versus surface film effects.

- Natural larval experiments should be maintained in situ for at least 180 days to enable sufficient settlement to develop for meaningful statistical analysis.

- Experiments still need to be conducted with plankton recorders to estimate the supply of meroplankton. This would allow better estimates of larval encounter rates and improve understanding of settlement mechanisms from the natural experiments. These data also would aid in verifying recommendations for 180-day minimum exposure times.

- The existence of location-related (nearfield and farfield) effects to larvae should be verified further by continued experiments using selected taxa for which waterborne effects were demonstrated.

- In situ experiments have many advantages over laboratory studies because the latter usually cannot simulate the appropriate range of naturally fluctuating variables, thereby introducing laboratory-related bias.

- Based on the lack of evidence of significant chemical contamination from field measurements of sediments and particle flux, future in situ larval experiments should be coordinated with studies of dissolved- as well as particulate-phase chemical contaminants. This recommendation is consistent with studies on toxicity from dissolved petroleum fractions, particularly in produced waters (Cherr et al. 1993; Higashi and Crosby 1993).

- The filming and larval array (igloo) study methods and equipment represented an excellent approach for performing deep-water in situ experiments. However, the design of smaller-scale equipment may be desirable due to requirements for a large survey vessel (e.g., 180-200 ft) to deploy and recover the igloos.

### 4.3.3 Toxicity Tests

The larval red abalone and adult brown cup coral laboratory experiments demonstrated some toxic responses from exposure to drilling muds, although the mechanisms are presently unknown. Therefore, future studies of this nature should focus on identifying the chemicals (or physical mechanisms) involved in these responses. In particular, since field measurements focusing on particulates have not indicated any significant chemical contamination, studies of dissolved-phase contaminants may be important (Section 4.3.2).

### 4.3.4 ROV Reconnaissance

ROV reconnaissance efforts to evaluate near-platform community impacts from drill cuttings and anchor scars were limited by the extensive occurrence of shell debris (from the platform) which obscured most features. Therefore, it is recommended that future surveys of this type be eliminated, or significantly limited, for platforms that have been in place for a period of years and which likely are associated with significant shell-debris mounds.

## References

## REFERENCES


Batchelor, G.K. 1952. Diffusion in a field of homogeneous turbulence. II. The relative motion of particles. Proceedings of the Cambridge Philosophical Society 48:345-362.

BBA/ROS. 1986. Biological Survey of "Proteus" Lease OCS P-0512 Offshore Point Conception, California. Report to Texaco USA.

Berry, R.W. and B. Nocita. 1977. Clay mineralogy of recent marine sediments found on the Southern California Outer Continental Shelf. Short Contributions to California Geology, California Division of Mines and Geology, Special Report 129:101-106.

Blumberg, A.F., L.H. Kantha, H.J. Herring, and G.L. Melbor. 1984. California Shelf Physical Oceanographic Circulation Model. Final Report (Volumes 1 and 2) to the U.S. Department of the Interior, Minerals Management Service. Dynalysis of Princeton, Princeton, New Jersey.

Boesch, D.F. and N.N. Rabalais. 1987. The Long-Term Effects of Offshore Oil and Gas Development: An Assessment and a Research Strategy. Report to the Interagency Committee on Ocean Pollution, Research, Development and Monitoring. Elsevier Applied Sciences Publishing, London, England.

Boesch, D.F. and G.A. Robilliard. 1987. Physical alteration of marine and coastal habitats resulting from offshore oil and gas development activities. Pages 1-53, In: D.F. Boesch and N.N. Rabalais, editors. Long-Term Environmental Effects of Offshore Oil and Gas Development. Elsevier Applied Sciences Publishing, London, England.

Boothe, P.N. and B.J. Presley. 1985. Distribution and Behavior of Drilling Fluids and Cuttings Around Gulf of Mexico Drilling Sites. Final Report to the American Petroleum Institute, Washington, D.C.

Bray, J.R. and J.T. Curtis. 1957. An ordination of the upland forest communities of southern Wisconsin. Ecological Monographs 27:325-349.

Brewer, G.D., J.L. Hyland, and D.D.Hardin. 1991. Effects of oil drilling on deepwater reefs offshore California. American Fisheries Society Symposium 11:26-38.

Chelton, D.B., P.A. Bernal, and J.A. McGowan. 1982. Large-scale interannual physical and biological interactions in the California Current. Journal of Marine Research 40:1095-1125.

Cherr, G., R. Higashi, J. Shenker, and T. Fan. 1993. Assessment of chronic toxicity of petroleum and produced water components to marine organisms. Final Report for the

Southern California Education Initiative. University of California, Davis and Minerals Management Service. Contract No. 30761.

Chevron. 1994. Discharge Monitoring Report - Platform Hermosa. Unpublished report submitted to EPA, Region IX for NPDES Permit No. CA0110516.

Coats, D.A. 1994. Deposition of drilling particulates offshore Point Conception, California. Marine Environmental Research 37:95-127.

Cornelius, N.I., N.I. Kline, and S.H. Cornelius, Jr. 1985. Manual of Mineralogy, 20th Edition. John Wiley and Sons, New York, New York.

Crecelius, E. 1990. Chemical analysis of trace metals in sediments, pore waters, and animal tissues. In: M. Steinhauer and E. Imamura, editors. California OCS Phase II Monitoring Program, Year Three Annual Report. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, under Contract No. 14-12-0001-30262.

Denny, M.W. 1988. Biology and Mechanics of the Wave-Swept Environment. Princeton University Press, Princeton, New Jersey.

Drake, D.E., P. Fleischer, and R.L. Kolpack. 1971. Transport and deposition of flood sediment, Santa Barbara Channel, California. Volume 2, In: R.L. Kolpack, editor. Biological and Oceanographic Survey of the Santa Barbara Channel Oil Spill 1969-1970: Physical, Chemical, and Geological Studies. Allan Hancock Foundation, Los Angeles, California.

Dugdale, R.C. and F.P. Wilkerson. 1989. New production in the upwelling center at Point Conception, California: Temporal and spatial patterns. Deep-Sea Research 36(7):985-1007.

EHA (Espy, Houston and Associates, Inc.). 1990. A Review of Drilling Mud Research. Prepared for Mobil Oil Exploration and Producing Southeast, Inc. New Orleans, Louisiana. Document No. 890601.

Fahrig, L. and K. Freemark. 1995. Landscape-scale effects of toxic events for ecological risk assessment. Chapter 11, In: J. Cairns and B. Niederlehner, editors. Ecological Toxicity Testing. Lewis Publishers, Boca Raton, Florida.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. 1979. Mixing In Inland and Coastal Waters. Academic Press, New York, New York. 483 pp.

Freemark, K. 1995. Assessing effects of agriculture on terrestrial wildlife: Developing a hierarchical approach for the U.S. EPA. Landscape and Urban Planning 31:99-115.

Fry, V.A. and B. Butman. 1991. Estimates of seafloor area impacted by sewage sludge dumped at the 106-Mile Site in the Mid-Atlantic Bight. Marine Environmental Research 31:141-160.

Hardin, D.D., J. Toal, T. Parr, P. Wilde, and K. Dorsey. 1991. Spatial variation in hard-bottom epifauna in the Santa Maria Basin, California: The importance of physical factors. Chapter 7, In: California OCS Phase II Monitoring Program Final Report. Report MMS 91-0083 to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, California.

Hardin, D.D., J. Toal, T. Parr, P. Wilde, and K. Dorsey. 1994. Spatial variation in bottom epifauna in the Santa Maria Basin, California: The importance of physical factors. Marine Environmental Research 37:165-193.

Hardin, D.D. 1988. Hard-bottom epifaunal assemblages. Chapter 2.11, In: Summary Report on the Second Annual Progress Meeting for the MMS California OCS Phase II Monitoring Program. Battelle Ocean Sciences, Ventura, California.

Higashi, R. and D. Crosby. 1993. Environmental degradation and identification of toxic compounds of petroleum and associated materials. Final report for the Southern California Education Initiative. University of California, Davis and Minerals Management Service. Contract No. 30761.

Hunt, J.W. and B.S. Anderson. 1989. Sublethal effects of zinc and municipal effluents on larvae of the red abalone *Haliotis rufescens*. Marine Biology 101:545-552.

Hyland, J., D. Hardin, D. Coats, R. Green, M. Steinhauer, and J. Neff. 1994. Environmental impacts of offshore oil development on the outer continental shelf and slope off Point Arguello, California. Marine Environmental Research 37:195-229.

Keough, M.J. and K.P. Black. 1995. Predicting the scale of marine impacts: Understanding planktonic links between populations. In: Schmitt, R.J. and C.W. Osenberg, editors. The design of ecological impact assessment studies: Conceptual issues and application. *In press.*

Keough, M.J. and B.J. Downes. 1982. Recruitment of marine invertebrates: The role of active larval choice and early mortality. Oecologia 54:348-352.

Ledwell, J.R. and A.J. Watson. 1991. The Santa Monica Basin tracer experiment: A study of diapycnal and isopycnal mixing. Journal of Geophysical Research 96:8695-8718.

Lissner, A.L., G.L. Taghon, D.R. Diener, S.C. Schroeter, and J.D. Dixon. 1991. Recolonization of deep-water hard-substrate communities: Potential impacts from oil and gas development. Ecological Applications 1(3):258-267.

Mooers, C.N.K. and A.R. Robinson. 1984. Turbulent jets and eddies in the California Current and inferred cross-shore transports. Science 223:51-53.

Morse, D.E. 1990. Recent progress in larval settlement and metamorphosis: Closing the gap between molecular biology and ecology. Bulletin of Marine Science 46:465-483.

Morse, D.E., H. Duncan, N. Hooker, A. Baloun, and G. Young. 1980. GABA induces behavioral and developmental metamorphosis in planktonic molluscan larvae. Federal Proceedings 39:3237-3241.

Morse, D.E., H. Duncan, N. Hooker, and A. Morse. 1977. Hydrogen peroxide induces spawning in molluscs, with activation of prostoglandin endoperoxide synthetase. Science 196:298-300.

Morse, D.E., N. Hooker, H. Duncan, and L. Jensen. 1979a. γ-aminobutyric acid, a neurotransmitter, induces planktonic abalone to settle and begin metamorphosis. Science 204:407-410.

Morse, D.E., N. Hooker, L. Jensen, and H. Duncan. 1979b. Induction of larval abalone settling and metamorphosis by γ-aminobutyric acid and its congeners from crustose red algae: II. Applications to cultivation, seed production and bioassays: Principal causes of mortality and interference. Proceedings of World Mariculture Society 10:91-91.

Mullineaux, L.S. 1988. The role of settlement in structuring a hard-substratum community in the deep sea. Journal of Experimental Marine Biology and Ecology 120:247-261.

Newman, W.A. 1979. California transition zone: Significance of short-range endemics. Pages 399-416, In: J. Gray and A. Boucot, editors. Historical Biogeography, Plate Tectonics, and the Changing Environment. Oregon State University Press, Corvallis, Oregon.

Nisbet, R.M., W.W. Murdoch, and A. Stewart-Oaten. 1995. Consequences for adult fish stocks of human induced mortality on immatures. In Press, In: R.J. Schmitt and C.W. Osenberg, editors. The Design of Ecological Impact Assessment Studies: Conceptual Issues and Applications.

NRC (National Research Council). 1983. Drilling Discharges in the Marine Environment. National Academy Press, Washington, D.C.

O'Neill, R.V., D.L. DeAngelis, J.B. Waide, and T.F.H. Allen. 1986. A Hierarchical Concept of Ecosystems. Monographs in Population Biology 23. Princeton University Press, Princeton, New Jersey.

Raimondi, P.T. 1990. Patterns, mechanisms and consequences of variability in settlement and recruitment of an intertidal barnacle. *Ecol. Monogr.* 60:283-309.

Raimondi, P.T. and R.J. Schmitt. 1992. Effects of produced water on settlement of larvae: Field tests using red abalone. Pages 415-430, In: J.P. Ray and F.R. Englehardt, editors. Produced water: Technological/Environmental issues. Plenum, New York, New York.

Reed, W.E. and I.R. Kaplan. 1977. The chemistry of marine petroleum seeps. Journal Geochemical Exploration 7:255-293.

Rodriquez, S.R., F.P. Ojeda, and N.C. Inestrosa. 1993. Settlement of benthic marine invertebrates. Marine Ecology Progress Series 97:193-207.

SAIC (Science Applications International Corporation). 1986. Assessment of long-term changes in biological communities in the Santa Maria Basin and western Santa Barbara Channel. Final Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, California, under Contract No. 14-12-0001-30032.

SAIC and MEC (MEC Analytical Systems, Inc.). 1989. Benthic Reconnaissance of Central and Northern California OCS Areas. Final Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, California, under Contract No. 14-12-0001-30388.

SAIC and MEC. 1993. Monitoring and Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III, Year One Report, Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, California, under Contract No. 14-35-0001-30584.

SAS Institute. 1988. SAS/STAT User's Guide, Release 6.03 Edition. SAS Institute, Inc., Cary, North Carolina.

SAS Institute. 1990. SAS Reference Manuals, Version 6, First Edition. SAS Institute, Inc., Cary, North Carolina.

Simoneit, B.R.T. and I.R. Kaplan. 1980. Triterpenoids as molecular indicators of paleoseepage in recent sediments of the Southern California Bight. Marine Environmental Research 3:113-128.

Smith, R.W. 1976. Numerical Analysis of Ecological Survey Data. Ph.D. Dissertation. University of Southern California, Los Angeles, California.

Steinhauer, M., E. Crecelius, and W. Steinhauer. 1994. Temporal and spatial changes in the concentrations of hydrocarbons and trace metals in the vicinity of an offshore oil-production platform. Marine Environmental Research 37:129-163.

Steinhauer, M. and E. Imamura (Editors). 1990. Chemical analysis of hydrocarbons in sediments, pore water, and animal tissues. Chapter 5, In: California OCS Phase II

Monitoring Program. Year Three Annual Report. Volume I. Report No. MMS 90-0055 prepared for the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, California.

Steinhauer, W.G., E. Imamura, J.R. Barminski, and J.M. Neff. 1992. California study compares natural/drilling discharge contaminants offshore. Oil and Gas Journal 4:74-93.

Strathman, M.F. 1987. Reproduction and development of marine invertebrates of the northern Pacific coast: Data and methods for the study of eggs, embryos, and larvae. University of Washington Press, Seattle, Washington. pp 220-267.

Taylor, B.D. 1978. Progress Report No. 4 on Sediment Management for Southern California Mountains, Coastal Plains and Shoreline. Environmental Quality Laboratory Open File Report No. 78-1. California Institute of Technology, Pasadena, California.

Taylor, G.I. 1954. The dispersion of matter in turbulent flow through a pipe. Proceedings of the Royal Society of London, Series A 223:446-468.

USGS (United States Geological Survey). 1988-1993, 1994, and In Press. Water Resources Data Guide, California Water Years 1987-1994.

# Appendix A

# APPENDIX A

## PHYSICAL OCEANOGRAPHY
(Currents, Waves, Tides, Winds, Satellite Imagery, Physical Measurements Arrays, and Particle Transport Modeling)

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# 1.0 INTRODUCTION

## 1.1 OVERVIEW

This appendix presents the objectives, results, conclusions, and recommendations for the DOI Phase III physical oceanographic tasks, including currents, waves, tides, wind, satellite imagery, physical measurements arrays, and particle transport modeling.

As summarized in Chapter 1, the physical oceanographic measurements and studies have been used to provide:

- Improved understanding of circulation patterns affecting the transport of material discharged from oil and gas platforms during drilling, and

- An observational data base for use by a particle transport model that estimates the diffusion and deposition of material released from platforms in the Phase III study region.

The plan to measure currents at three levels on a single taut-wire mooring, as originally proposed, was adjusted, in response to a recommendation by the Quality Review Board, to incorporate a second instrumented mooring. This second mooring was deployed and relocated approximately every three months to a different along shore or cross-shelf location. A comparison of data from these moorings (primary and secondary) provided a quantitative estimate (the spatial coherence scale) of how far from the primary mooring it could be assumed that currents remained similar to, and hence represented by, those measured at the primary mooring. The result from this comparison determined whether velocity data from the primary mooring alone could be used for all sediment transport modeling.

Data on water column currents were supplemented by near bottom current measurements, optical backscattering sensors (OBS), and sediment traps. The objective of this program element was to document the potential for local resuspension of muds and cuttings as well as the total sediment depositional load.

To support the overall task objectives, field observations were supplemented by satellite thermal imagery, coastal/buoy winds and air and water temperatures, and coastal water levels. All of these latter data were obtained directly from NOAA, either through the National Weather Service (NWS) or the National Data Buoy Center (NDBC).

As a supplement to the present study, current measurements made by Scripps Institution of Oceanography (SIO), under separate contract with the Minerals Management Service, were used to provide a broader, more regional basis for understanding circulation patterns at the primary mooring site. Dr. C. Winant is thanked for making data available from two SIO moorings at the western end of the Santa Barbara Channel.

A numerical model was used to quantify deposition of drilling muds and cuttings discharged from local platforms. With the model, using concurrent histories of discharge from the rig and the measured current profiles, muds and cuttings were dispersed and eventually either deposited on the local bottom or transported out of the study area. The model allows for any combination of size classes (settling velocities), uses actual bathymetry on a closely spaced grid, and time dependent current profiles. Model results include the pattern and amount of deposition by size class and accumulated depth. This information is available for individual or composite size classes.

## 1.2 REPORT ORGANIZATION

The physical oceanographic report is organized into five chapters:

- **Chapter 1: Introduction** provides a brief overview of objectives, methods, and activities associated with circulation patterns in the water column and near the bottom.

- **Chapter 2: Data Acquisition and Processing** describes the methodology used in these activities, including instrumentation, field procedures, data processing, and modeling.

- **Chapter 3: Results** presents information developed in support of the overall task objectives as presented in the Introduction. This involves a discussion of the general circulation patterns, near-bottom currents and material transport, and modeling results.

- **Chapter 4: Summary and Recommendations** provides a summary presentation of conclusions and recommendations as related to the project objectives.

- **Chapter 5: References**

# 2.0 DATA ACQUISITION AND PROCESSING

## 2.1 DATA ACQUISITION

### 2.1.1 Introduction

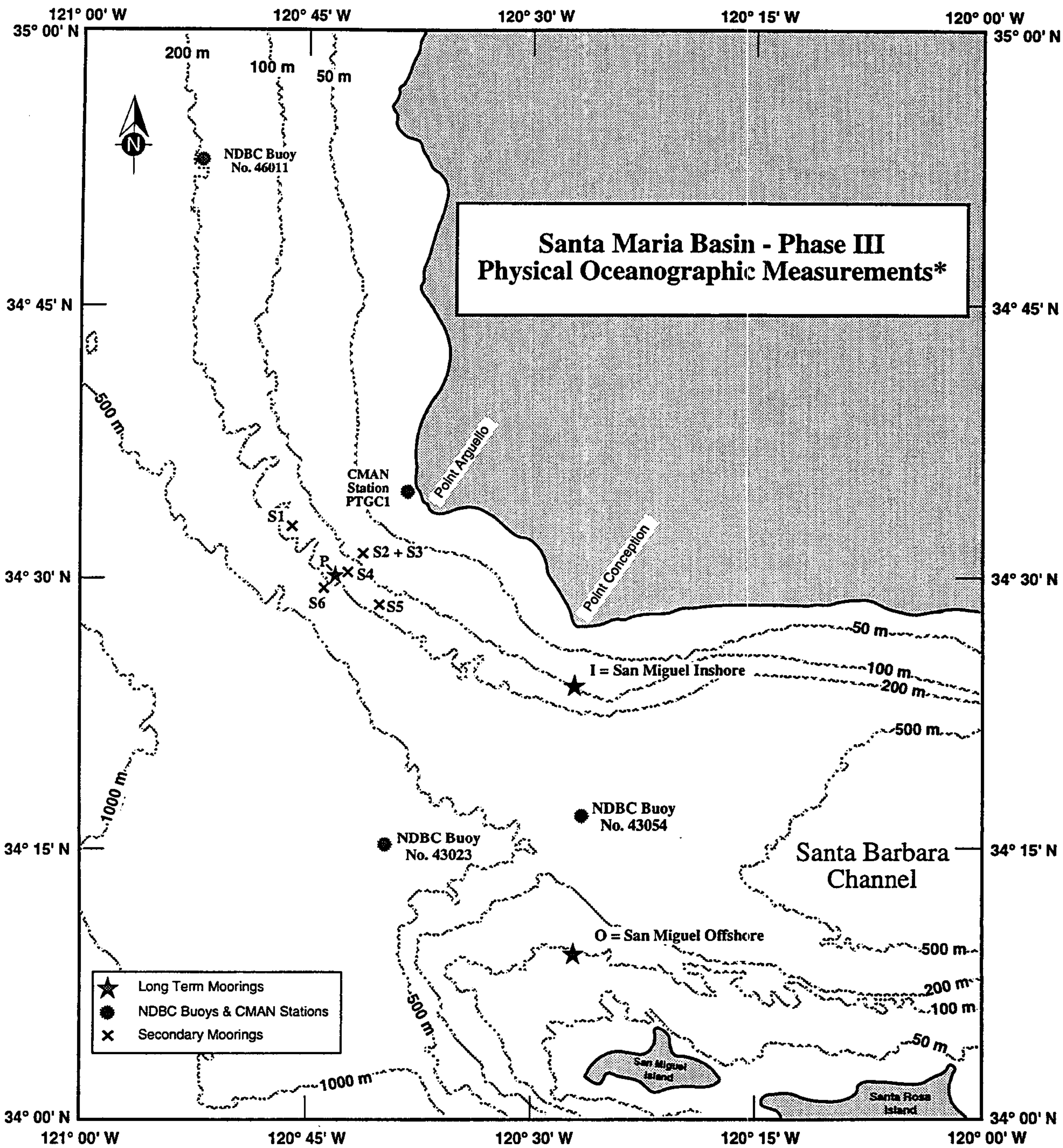
Two taut-wire moorings were deployed in the study area and rotated at three- to seven-month intervals (Table 2.1-1).

Table 2.1-1. Current meter mooring cruises and dates.

| Vessel | Dates |
|---|---|
| M/V GLORITA | 04/02/92 - 04/04/92 |
| M/V GLORITA | 07/07/92 - 07/10/92 |
| M/V CAVALIER | 09/24/92 - 09/27/92 |
| M/V CAVALIER | 01/19/93 - 01/22/93 |
| M/V INDEPENDENCE | 08/02/93 - 08/06/93 |
| M/V WM. A. MCGAW | 12/18/93 - 12/21/93 |
| M/V WM. A. MCGAW | 07/20/94 - 07/22/94 |

The primary mooring was maintained at the same location in approximately 130 m water depth for a 28-month interval beginning in April 1992 and ending in July 1994. The secondary mooring was maintained over this same interval but was moved to along shore or shallower/deeper sites with each rotation. Figure 2.1-1 shows the mooring locations. Tables 2.1-2 and 2.1-3 provide specific deployment information including the deployment intervals, locations, water depths, and instrument depths.

Physical Measurements Arrays (PMAs) were deployed at two locations (Nearfield and Farfield sites) for three deployments over the course of the field program (Table 2.1.4).




* Moorings I and O were maintained by Scripps Institute of Oceanography with funding from the MMS. SIO made these data available to the Phase III Program.

Figure 2.1-1. Map of study area showing the location of moorings, buoys and CMAN stations from which data were used. Moorings I and O are part of an MMS-funded program being conducted by Scripps Institution of Oceanography.

Table 2.1-2.Deployment information for the Primary mooring (P).

| Dates | Location | Water Depth (m) | Instrument Depths (m) |
|---|---|---|---|
| 04/04/92 - 07/08/92 | 34° 30.145'N 120° 43.077'W | 130 | 14*, 53*, 125*, 130 |
| 07/10/92 - 09/26/92 | 34° 30.441'N 120° 43.357'W | 132 | 14*, 54, 126, 130 |
| 09/27/92 - 01/20/93 | 34° 30.180'N 120° 43.630'W | 129 | 14*, 53*, 125*, 130 |
| 01/22/93 - 08/03/93 | 34° 30.120'N 120° 43.070'W | 130 | 14*, 53*, 125*, 130 |
| 08/05/93 - 12/19/93 | 34° 30.120'N 120° 43.070'W | 130 | 14*, 53*, 125*, 130 |
| 12/21/93 - 07/21/94 | 34° 30.441'N 120° 43.409'W | 130 | 14*, 53, 125*, 130 |
| 07/22/94 - 01/14/95** | 34° 30.150'N 120° 43.080'W | 130 | 14*, 54, 125*, 130 |

* Also backup instrument one meter deeper.
** Recovered by Scripps Institution of Oceanography; data not discussed in this report.

Table 2.1-3.Deployment information for the Secondary mooring (S).

| Dates | Location | Water Depth (m) | Instrument Depths (m) |
|---|---|---|---|
| 04/04/92 - 07/08/92 | 34° 32.873'N 120° 46.032'W | 130 | 15, 54, 126 |
| 07/10/92 - 08/14/92* | 34° 31.324'N 120° 41.264'W | 91 | 14, 87 |
| 10/16/92 - 01/20/93 | 34° 31.371'N 120° 41.336'W | 91 | 14, 54 |
| 01/21/93 - 08/04/93 | 34° 30.300'N 120° 42.170'W | 112 | 15, 54 |
| 08/06/93 - 12/20/93 | 34° 28.560'N 120° 40.162'W | 130 | 15, 54 |
| 12/21/93 - 07/21/94 | 34° 29.390'N 120° 43.880'W | 256 | 28, 128 |

* Recovered early by fishing vessel.

Table 2.1-4. Deployment sites and water depths for the Physical Measurements Arrays (PMAs).

| Station | Latitude | Longitude | Water Depth |
|---|---|---|---|
| Nearfield | 34°29.231'N | 120°42.364'W | 195m |
| Farfield | 34°31.448'N | 120°45.496'W | 215m |

## 2.1.2 Taut-Wire Mooring Arrays and Instrumentation

The primary mooring, when fully instrumented, included three Smart Acoustic Current Meters (SACMs), three Mk2 Niskin winged current meters (as backups to the SACMs) and one wave/tide recorder (Figure 2.1-2). As shown, the wave/tide recorder was attached to a secondary anchor and set off from the primary mooring at the end of 160 m of 1/2 inch Yalex rope. The secondary mooring was initially outfitted with one SACM and three Mk2 current meters. This was subsequently adjusted to just two Mk2 current meters to move one SACM to the primary mooring as a replacement. The number of Mk2s was reduced as an accommodation to the three month changes in the water depth at which this mooring was deployed. Both moorings were equipped with an acoustic release and appropriate flotation to implement mooring recovery. They were also equipped with rope canisters to implement anchor recovery during each rotation.

Mooring hardware elements included 5/16" Nilspin wire, 3/8" chain, a 37" diameter subsurface float, some vinyl floats (to support the chain), and a 30" diameter surface float with a flasher.

### 2.1.2.1 Benthos 865-A Acoustic Release

The 865-A release was used on both the primary and secondary moorings. It has a load capacity of 10,000 lbs and a depth rating of 12,000m. Release is implemented by acoustically activating a motor driven actuator which, in turn, retracts a locking pin holding the release hook closed. This uncouples the release from the anchor and the mooring rises to the surface with its flotation elements.

The instrument is powered by a battery pack composed of 12 alkaline D-size batteries (to provide two strings at a nominal nine volts and 16 amp-hour (AH) capacity). The projected operating life is 12 months and 250,000 transponds. However, batteries were generally replaced at four- to seven-month intervals due to the close proximity of an operational drilling rig and the instrument's inability to "sleep" (not respond to environmental noise).

**Schematic Drawings of Primary and Secondary Moorings**
(Not to Scale)

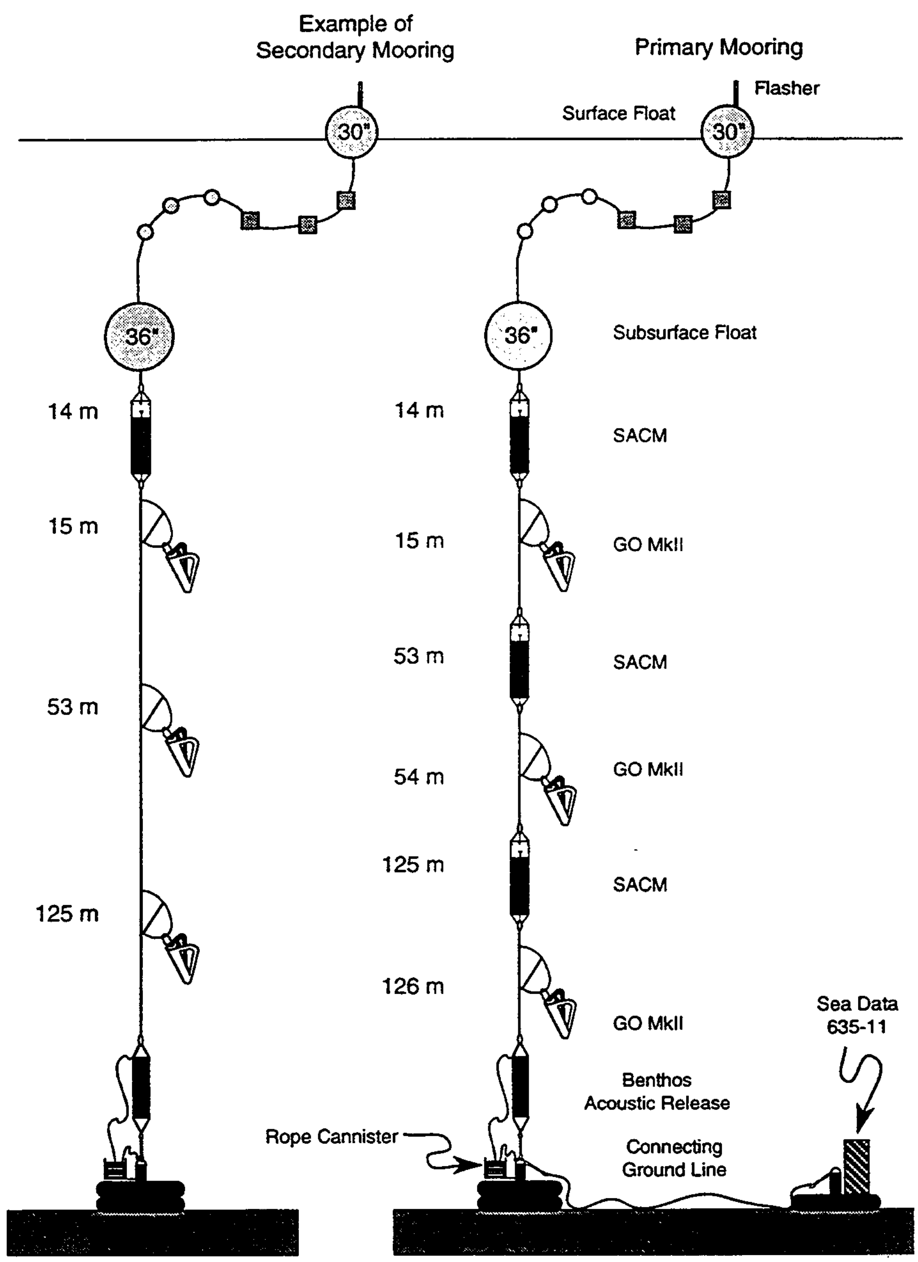



Figure 2.1-2. Schematic drawing of the Primary and Secondary moorings as originally planned. As S was moved to different locations and two instruments were lost, the secondary mooring was changed to include only a near surface and near bottom current meter.

### 2.1.2.2 E G & G Smart Acoustic Current Meter (SACM)

This instrument measures currents by monitoring the phase shift of an acoustic signal. The measurement range is 0 to 360 cm/s with a stated accuracy of $\pm$ 1.0 cm $s^{-1}$ or $\pm$ 3%, whichever is greater. Directional accuracy is stated as $\pm$ 2.0°. The temperature range is -2 to 35° C with a stated accuracy of $\pm$ 0.05° C.

SACMs were deployed at up to three levels on the primary mooring. The instruments were set to collect data every thirty minutes with either an "on" time of 5 minutes and an "off" time of 25 minutes, or an "on" time of 11 minutes and an "off" time of 19 minutes. This latter setting was not planned but was a default setup that could not be overridden on one of the instruments. Each instrument was configured with 64 Kbytes of memory and was powered by a lithium battery pack. The battery packs were generally replaced at 9- to 12-month intervals.

### 2.1.2.3 General Oceanics Mk2 Niskin Winged Current Meter

This instrument measures currents by determining the tilt of a winged cylinder attached by a swivel assembly to a wire mounting support called a standoff (see Figure 2.1-2). Three different wing sizes are available: low speed (0 to 70 cm $s^{-1}$), standard (0 to 225 cm $s^{-1}$), and high speed (0 to 300 cm $s^{-1}$). Only the low speed and standard wings were used during this program. Speed accuracy is stated as $\pm$ 1 cm $s^{-1}$ and directional accuracy as $\pm$ 2°. The temperature range is -5 to 45° C with a stated accuracy of $\pm$ 0.25° C.

Mk2 current meters were deployed at up to three levels on the primary and secondary moorings. The instruments were set to collect vector averaged data at 30-minute intervals using a two-second burst interval and 32 samples per burst, for a total averaging time of 64 seconds. Data were recorded on Phillips-style data cassettes with a capacity of 20,000 samples. Each unit was powered by a 7.8 volt (14 AH) lithium battery pack composed of two D-size lithium batteries. The battery packs were replaced at 9- to 12-month intervals.

### 2.1.2.4 Sea Data 635-11 Wave and Tide Recorder

This instrument is equipped with a 400 psia (272m) Paroscientific DIGIQUARTZ pressure sensor with a stated accuracy of $\pm$ 2.72 cm ($\pm$ 0.01% of full scale). The temperature range is -4.5 to 34.5° C with a stated accuracy of $\pm$ 0.07° C.

The 635-11 wave and tide recorder was deployed on the bottom (in approximately 130m water depth) adjacent to the primary mooring. The instrument was equipped to record 30,800 data records on a 300 foot cassette tape. It was programmed to measure tides at 3.75 or 7.5 minute intervals (384 or 192 tide samples/day) and waves at six hour intervals (four wave bursts/day) with 512 or 1024 wave samples/burst. Wave sample bursts were programmed at one scan every two seconds or one scan each second, respectively. The recorder was powered by a 20 AH SDB-4 alkaline battery pack, good for six months or two full cassettes. This power pack was replaced during each servicing.

### 2.1.3 Physical Measurements Arrays (PMAs) and Instrumentation

During Deployments 1 and 2, each of the bottom arrays contained a single electromagnetic current meter (InterOcean S4) with integral water temperature, conductivity, and pressure sensors (Table 2.1-5) supported within a stainless steel frame (Figure 2.1-3). All instruments were positioned to sample conditions approximately one meter above the sediment-water interface. The current meter provided power for and received the data output from two optical backscattering probes (Downing & Associates OBS-3 - Table 2.1-6). The OBS are designed to monitor suspended material concentrations and for this study were located 1 m and 1.5 m above the bottom. During Deployment 1 each meter was programmed to burst-sample all sensors four times each hour at a rate of two hertz for a period of sixty seconds. Following burst-averaging, all data are internally recorded on solid-state memory having a capacity of one megabyte. During Deployments 2 and 3, programming was modified to provide two burst samples per hour. All other sampling characteristics remained unchanged.

During Deployments 1 and 2, the array subsystems were mounted on a stainless steel (Type 304) frame. For Deployment 2, the floatation subsystem on the array was modified slightly due to the loss of the integral hemispherical floats. This was caused by corrosion of the attachment brackets during Deployment 1 (Figures 2.1-3 and 2.1-4). The main body of the frame remained identical to that used in Deployment 1.

The profile, strength, and weight of these frames were intended to minimize the potential for disturbance by bottom fishing activities. In plan view, the frames were octagonal in form with a maximum width of approximately four meters (Figure 2.1-5). Contoured lead weights were bolted in place around the perimeter of the base providing a stable, low-profile mass to anchor the array and to provide a footing having minimal frontal area and potential for flow disturbance. In elevation, the array was approximately 2 m in height and nearly hemispherical in form with a network of eight cylindrical legs extending upward from the base to a horizontal platform. As originally deployed, this platform provided support for a spherical segment of syntactic foam flotation held in place by a transponding acoustic release (Datasonics ATR-397; Table 2.1-7). Following loss of the foam, floatation was provided by two glass spheres, 40 cm in diameter, housed in molded plastic retainers ("hard-hats") and held in place by the acoustic release. In both configurations, a cylindrical line canister containing 300 m of 9.5 mm Kevlar line was mounted on the frame, below and adjacent to the acoustic release. This line, with one end attached to the upper platform and the other to the float, served as the primary recovery line for the array.

Table 2.1-5. Specifications for the InterOcean S4 current meter.

| | |
|---|---|
| **SPEED SENSOR** | |
| **Type:** | 2-axis electromagnetic |
| **Range:** | 0-350 cm/sec |
| **Resolution:** | 0.2 cm/sec |
| **Accuracy:** | 2% reading, ± 1 cm/sec |
| **COMPASS** | |
| **Type:** | Flux-gate magnetometer |
| **Tilt:** | ± 25 degrees |
| **Resolution:** | 0.5 degrees |
| **Accuracy:** | 2 degrees |
| **PRESSURE** | |
| **Type:** | Semiconductor strain guage |
| **Range:** | 0-1000 dBars |
| **Resolution:** | 14 bit |
| **TEMPERATURE** | |
| **Type:** | Thermistor |
| **Range:** | -2.5 to 36° C |
| **Resolution:** | 0.05° C |
| **Response Time:** | 63% (1 minute) |
| **CONDUCTIVITY** | |
| **Type:** | Conductive |
| **Range:** | 5-65 mSiemens |
| **Resolution:** | 0.1 mSiemens |
| **Accuracy:** | ± 0.2 mSiemens |
| **CONTROL** | |
| **Type:** | EPROM microprocessor |
| **Memory:** | 1024 Kbytes (optionally expandable) |
| **Format:** | Vector average, burst adaptive combination; externally programmable or default settings |
| **CLOCK** | |
| **Type:** | Quartz oscillator |
| **Power:** | Non-restricted lithium battery |
| **Accuracy:** | 12 min /year |
| **POWER SUPPLY** | |
| **Type:** | 6 internal Lithium cells or 6 alkaline "D" cells |
| **MECHANICAL/ENVIRONMENTAL** | |
| **Size:** | 10 inch diameter sphere |
| **Weight:** | 24 lbs in air; 4 lbs in water |
| **Mooring:** | In-line |
| **Through Load:** | 10,000 lbs working |
| **Drag:** | 18 lbs @ 250 cm/sec |
| **Depth:** | 1000 meters |
| **Temperature:** | -40° to 70° C (storage); -2.5° to 36° C (operating) |
| **Material:** | Glass-filled cycloaliaphalic expoxy sphere; Titanium 6 AL-4V mooring rod |

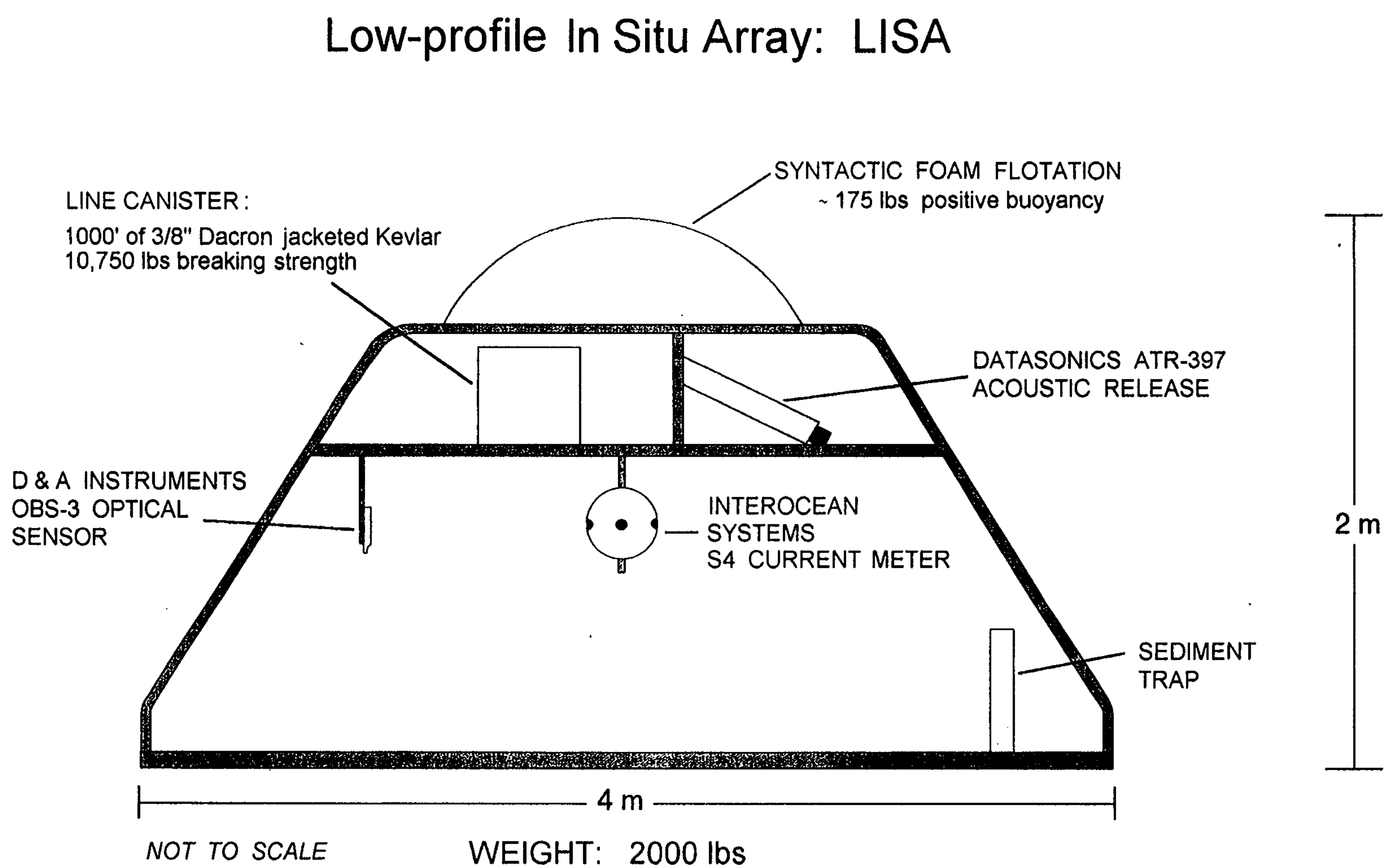



Figure 2.1-3. Schematic drawing of the PMA as originally proposed and fabricated.

Table 2.1-6. Specifications for the Optical Backscatter Sensor (OBS).

| | |
|---|---|
| DYNAMIC RANGE | |
| Turbidity | 0.02 - 2000 FTU |
| Mud (maximum)[1] | 0.1 - 5000 mg/l |
| Sand (maximum)[2] | 2 - 100,000 mg/l |
| FREQUENCY RESPONSE | 10Hz |
| AMBIENT LIGHT REJECTION | Optical filtering and synchronous detection |
| TEMPERATURE COMPENSATION | Solid state temperature transducer |
| NONLINEARITY[3] | |
| Turbidity (formazin, 0-2000 FTU) | 2.0% |
| Mud (0-4000 mg/l) | 2.0% |
| Sand (0-60,000 mg/l) | 3.5% |
| DRIFT | |
| Time[4] | -3.5% per decade |
| Temperature | 0.05% /°C |
| SUPPLY VOLYAGE COMPLIANCE | 250 $uV/V$ |
| SETTLING TIMES | |
| Power-up | < 1s |
| 25°C Step Change in Water Temperature | 15s |
| OUTPUT SPAN[5] (maximum) | 0 - 5V f.s. |
| OUTPUT IMPEDANCE | <300 Ohms |
| RMS NOISE AT 0 FTU | <50 $uV$ |
| POWER REQUIREMENTS[6] | +6 - 15V/12mA |
| OUTPUT FILTER | 20 Hz(-3dB) |
| PHYSICAL DIMENSIONS (Inches/pounds) | |
| Sensor | 2 x 0.7 |
| Housing Length | 4.5 |
| Housing Diameter | 1.2 |
| Weight(air) | 0.4 |
| Weight(submerged) | 0.16 |
| WORKING DEPTH | 2000 meters |

[1] Amazon River Mud, $D_{50}$ = 10$um$.
[2] Beach Sand, $D_{50}$ = 200$um$.
[3] Maximum deviation of response from a least-squares straight line, expressed as a percentage of the calibration range.
[4] The output will not drift more than -3.5%, continuous operation, or more than -3.5% x (duty cycle), burst operation, in the first 2000 hours.
[5] Output span depends on adjustable gain settings.
[6] 9-12V/32mA for units with 4-20mA current loop.

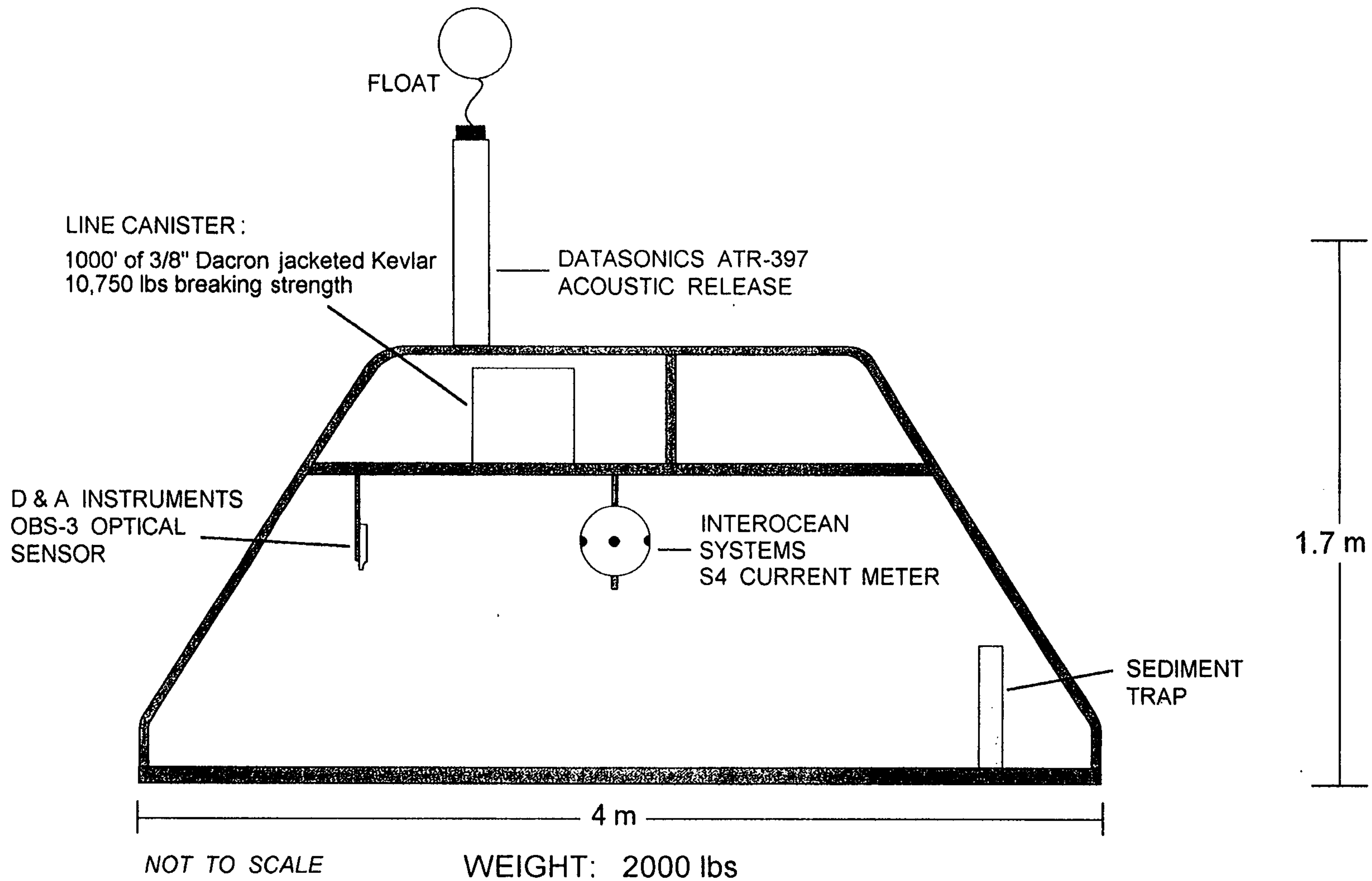



Figure 2.1-4. Schematic drawing of the PMA after the foam float at the top of the array was removed following Deployment 1.

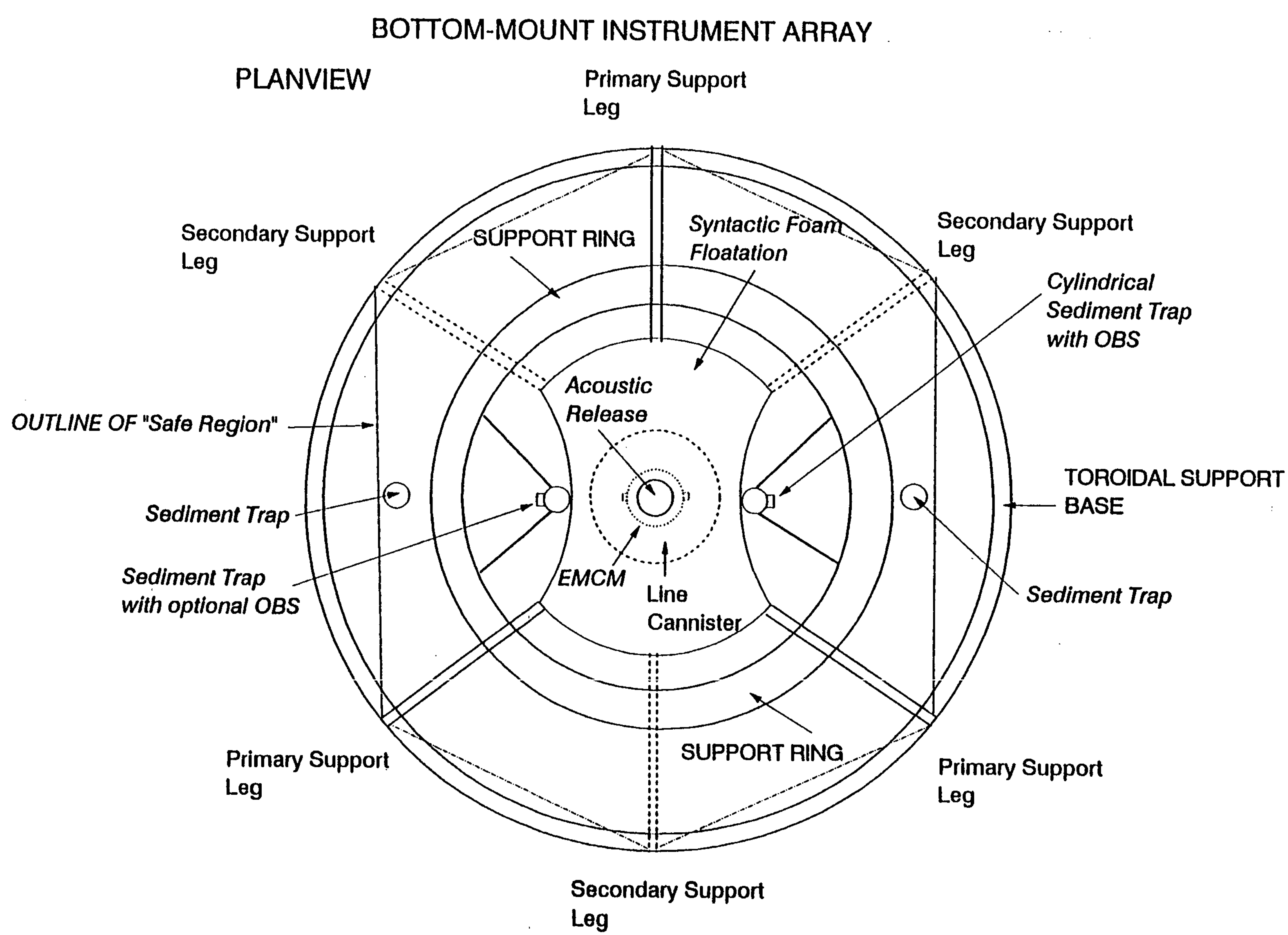



Figure 2.1-5. Schematic of the PMA in plan view.

Table 2.1-7. Specifications for the Datasonics Model ATR-397 Acoustic Release.

<u>MODEL ATR-397</u> <u>RELEASABLE ACOUSTIC TRANSPONDER</u>

GENERAL SPECIFICATIONS

| | |
|---|---|
| Interrogate Frequency: | 26KHz for the Model 397/30 |
| Reply Frequency: | <u>Model 397/30 kHz</u><br>28KHz<br>29KHz<br>30KHz<br>31KHz<br>32KHz<br>(user-selectable) |
| Command Frequency: | <u>Model 397/30 kHz</u><br>24KHz "A"<br>25KHZ "B"<br>27KHz "C"<br>(user-selectable) |
| Release Command: | Pulse-time coded FSK (27 codes - user-selectable) |
| Pulse Width: | <u>Model 397/30</u><br>7 milliseconds |
| Turn-around Time: | 20 milliseconds (stability 0.1 milliseconds) |
| Transmit-inhibit (LOCKOUT): | <u>Model 397/30</u><br>1 second |
| Source Level: | 188 Db ref 1 upa @ 1 meter |
| Beam Pattern: | Horizontal - omnidirectional/Vertical - cardioid |
| Operating Life: | @ 188 Db -- 1 yr / 100,000 replies |
| Battery Packs: | Transceiver/Receiver B397-3589<br>Release Battery A397-3955<br>AA Alkaline Solid Pack Receiver 6v blue,<br>Transmitter 12v red<br>Ground green |
| Operating Depth: | 0 - 1000 meters |
| Maximum Release Load: | 1500 pounds |

Following analysis of S4 current meter records from Deployments 1 and 2, including comparisons with nearby (primary) mooring data, it was determined that the stainless steel frames were adversely affecting the velocity data by producing a clear bias in both speed and direction. Since the factors responsible for the apparent anomalies could not be simply defined, the decision was made to replace the stainless frames with a taut-wire configuration consisting of a floatation array supported by a stainless mounting bracket bolted to and extending upward from the S4 current meter. The lower attachment point on the current meter was shackled to a short length of dacron braided line, which in turn was attached to an acoustic release (Datasonics ATR-397) and a recovery line cannister mounted on a lead dead-weight anchor. In this configuration, the optical sensors were positioned approximately 3 m above the sediment-water interface at a single point on the vertical attached to the stainless bracket holding the floatation (Figure 2.1-6). Sediment traps were located at two points on the vertical: one set mounted immediately adjacent to the optical sensors (3 m above the bottom (mab)) and a second attached to the recovery line cannister on the anchor (<0.5 mab). Data reviews indicated that, although the modified configuration did not provide the physical protection afforded by the original stainless frames, it did serve to eliminate the velocity bias apparent in the data obtained during Deployments 1 and 2.

Prior to Deployments 1 and 3, all of the electronic subsystems were calibrated to insure accuracy and proper functioning. The electromagnetic current meter and associated water temperature, conductivity, and pressure sensors were calibrated by the manufacturer just prior to delivery and returned for recalibration prior to Deployment 3. The optical sensors were laboratory calibrated at the University of Connecticut using various concentrations of sediments suspended by mechanical agitation in a salt water bath. The sediments used in these calibrations were laboratory archival samples selected to provide grain size characteristics similar to those expected at the study sites. The laboratory data indicate that the response of the sensors is reasonably linear over a concentration range of 0-80 mg/l (Figures 2.1-7 and 2.1-8). This maximum generally exceeds that observed on exposed continental shelves.

In addition to the electronic systems, each instrument array contained four mechanical sediment traps. Two of the traps were positioned immediately adjacent to the sediment-water interface, and two were placed at a higher elevation. During Deployments 1 and 2, the upper traps were located approximately 1.5 m above the bottom. During Deployment 3, the modified mooring configuration resulted in the placement of the upper traps at a point approximately 4.5 m above the bottom. All traps were constructed of clear acrylic tubing 6.6 cm i.d. and approximately 45 cm in length. An assemblage of 10 mm diameter plastic tubing was used to form a honeycomb structure in the upper 10 cm of each trap. Chemical additives to inhibit biological activity were not used in the PMA sediment traps. Despite the extended duration of several of the deployments, there was little indication of bio-fouling sufficient to affect trap efficiency.

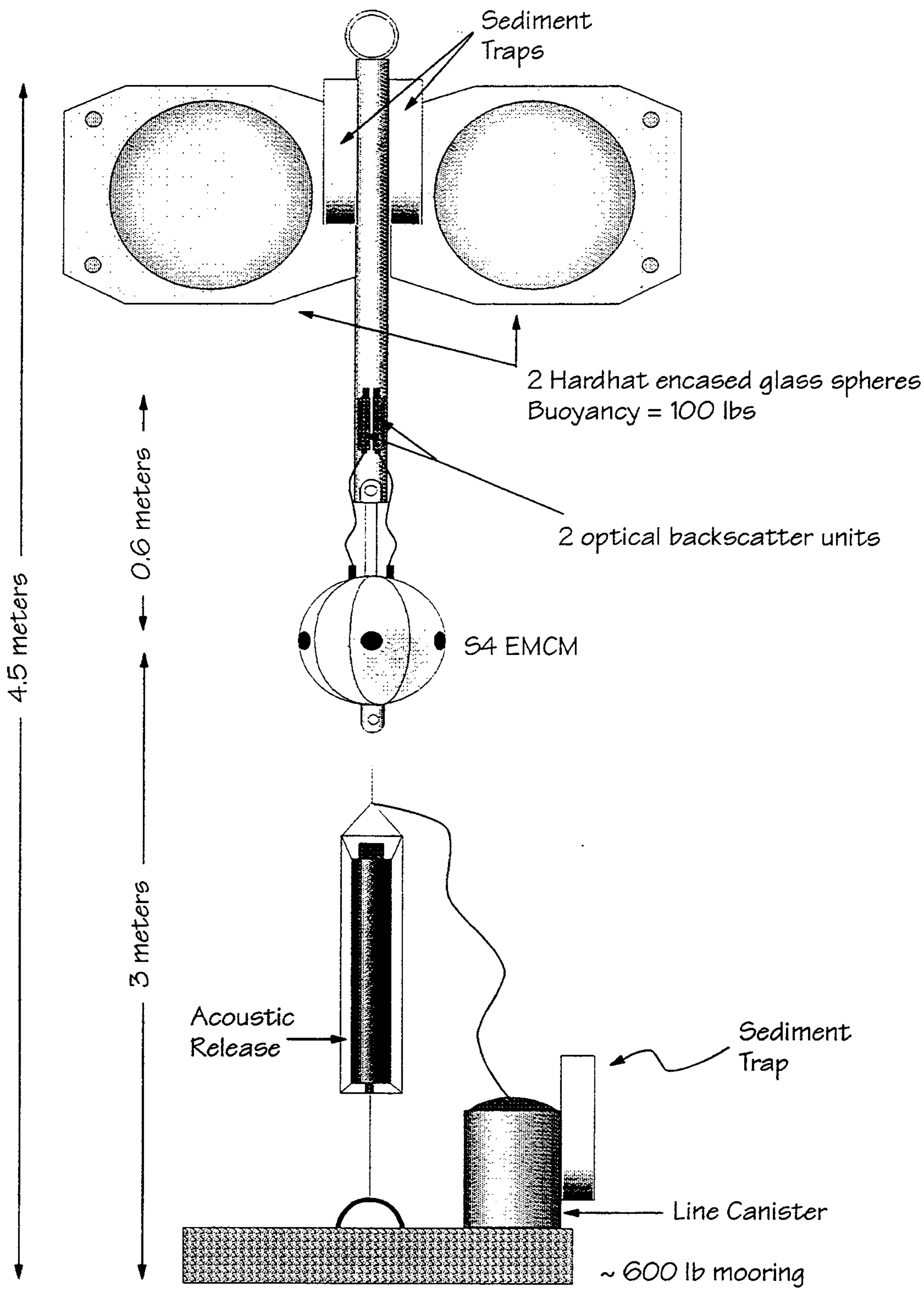



Figure 2.1-6. Schematic of the mooring used in place of the PMA during Deployment 3.

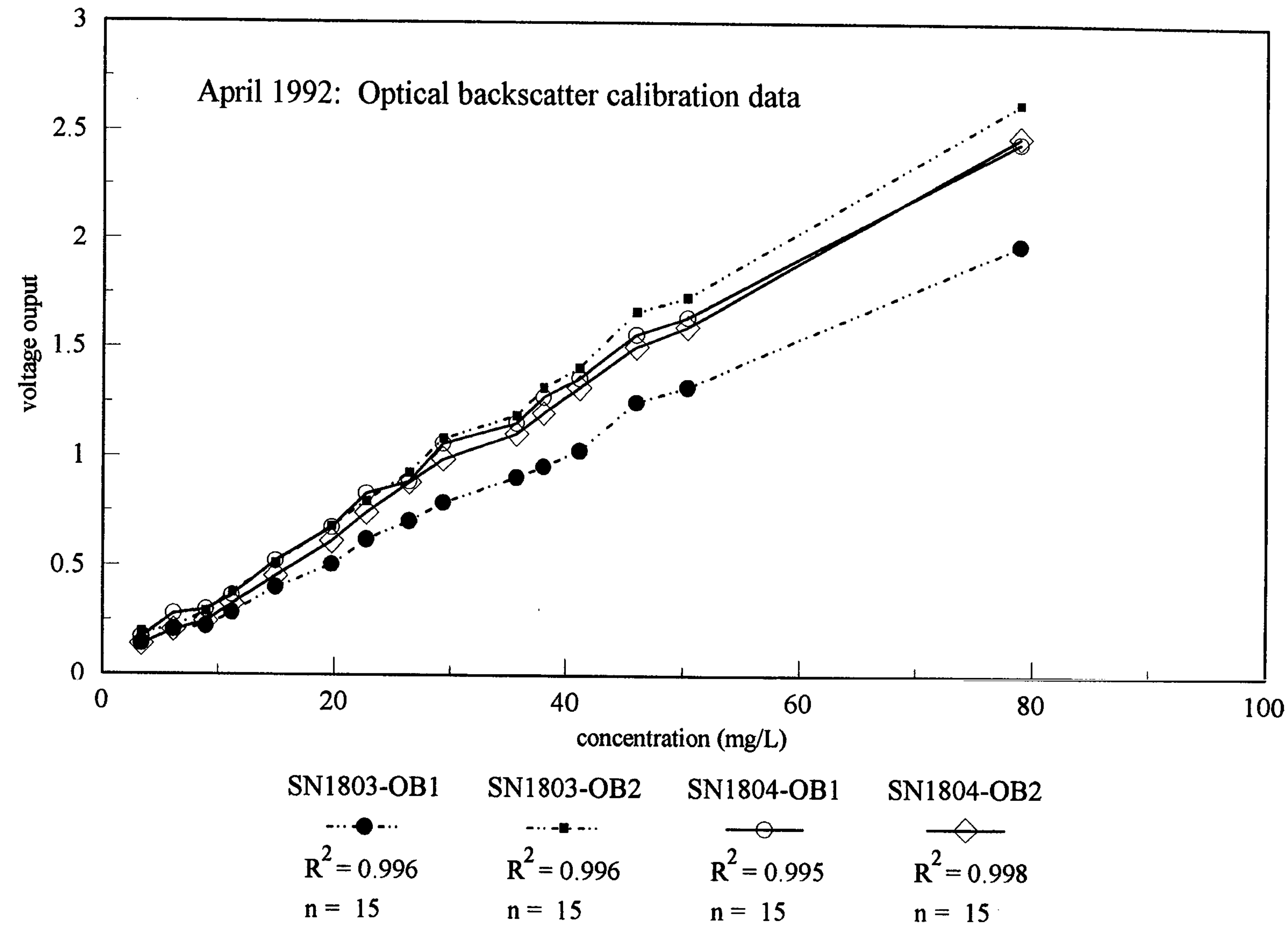



Figure 2.1-7. December 1993 calibration data for four optical backscattering units which relates measured and recorded voltages to suspended load (mass per volume).

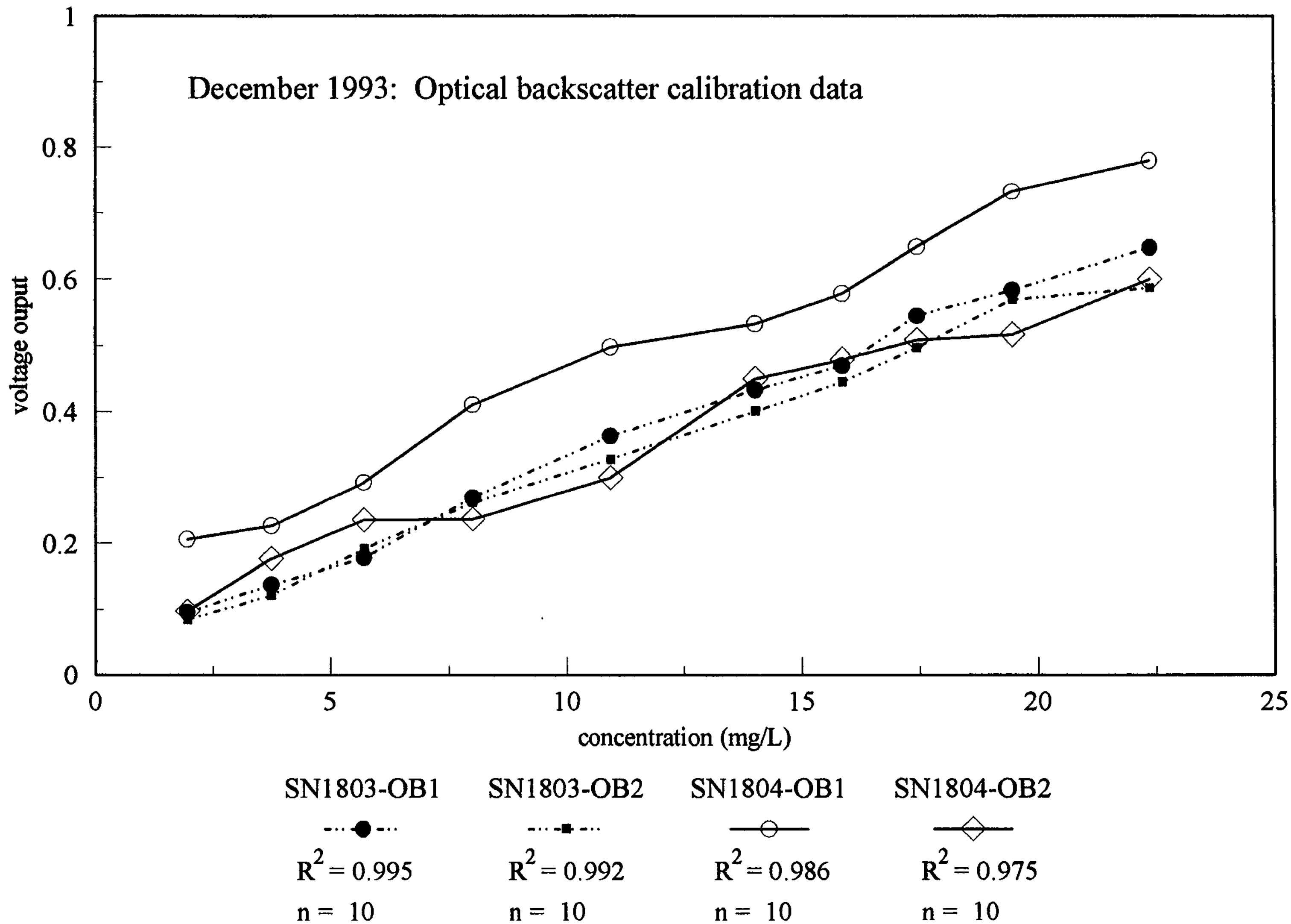



Figure 2.1-8. April 1992 calibration data for four optical backscattering units which relates measured and recorded voltages to suspended load (mass per volume).

## 2.1.4 Instrument Calibrations

All of the instruments used on the primary and secondary moorings were provided by the MMS from an existing instrument pool. Five SACMs and two wave/tide recorders were provided directly from the Phase II contractor's storage facility and eight Mk2 current meters were provided directly from MMS storage in Herndon, Virginia. One each of the SACMs and wave/tide recorders was inoperable and unrepairable and was subsequently used for parts to maintain the remaining instruments.

All eight of the Mk2s had been recalibrated by the manufacturer in February or March 1990 at which time the clock batteries had also been replaced. Each of the four operational SACMs was tested under zero current conditions and in a towed configuration in a test tank to evaluate general operation. The wave/tide recorder was also tank tested for general operation and reasonableness of data.

A number of direct comparisons between the SACM and Mk2 current meters were possible due to the close proximity of the instruments (one meter apart) on the primary mooring. These comparisons indicated good correlation of both temperature and current velocity. An example is provided in Figure 2.1-9.

## 2.1.5 Field Procedures

### 2.1.5.1 Introduction

Prior to deployment, each instrument underwent an operational check and physical inspection. Repairs and anode replacements were made and the instruments were cleaned and refurbished with new batteries and cassette tapes, as applicable. Anti-fouling paint was applied to the Mk2 current meters prior to the initial deployment.

### 2.1.5.2 Taut-Wire Moorings

Both of the taut-wire moorings were deployed and recovered in the same manner. Deployment was initiated by trailing the surface buoy behind the vessel while steaming slowly towards the deployment site. All subsequent in-line elements were trailed behind the vessel leaving on board only the main anchor and a coiled length of 1/2 inch Yalex rope (in a barrel) attached to a smaller secondary anchor, all of which were positioned on the stern. A length of 3/8 inch line was then tied to the secondary anchor and secured to the vessel. When the station was reached, the main anchor was deployed while the vessel continued to steam slowly past the site. The

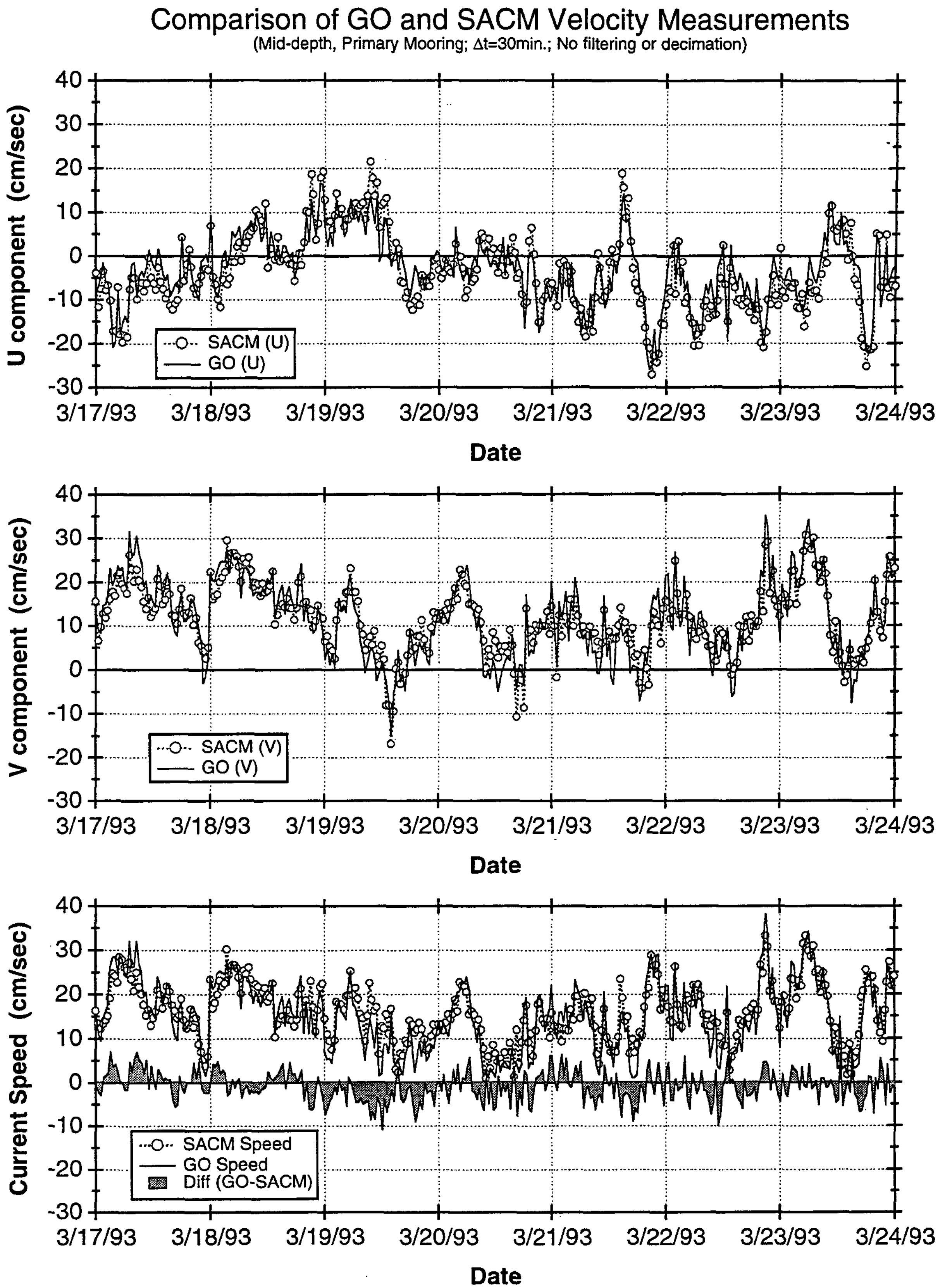



Figure 2.1-9. Comparison of concurrent and adjacent current measurements made with the GO and SACM current meters. The only changes to these original data were elimination of a few obvious outliers, i.e., single point spikes.

Yalex rapidly uncoiled and put tension on the secondary anchor. This tension was allowed to build briefly before the 3/8 inch line was cut and the secondary anchor was pulled overboard and deployed.

Mooring recoveries were implemented by activating the acoustic release or by grapnelling during infrequent events of release failure. On several occasions, during the longer deployments, grapnelling was required as the release batteries had died due to the noisy environment (an active drilling rig) and the instrument's inability to ignore and not respond to such noise.

Following release activation, during normal recovery, the mooring elements were brought on-board, beginning with the surface buoy. Once the release was on-board, a length of 1/2 inch Yalex (from the rope canister), extending up from the main anchor, was recovered along with the main anchor, and then more 1/2 inch Yalex and the secondary anchor. If grapnelling was required, the length of line between the two anchors was the target for the effort and the mooring was recovered bottom first including both anchors.

## 2.1.6 Time Lines and Data Return

### 2.1.6.1 Moorings

The data return from the taut-wire mooring instrumentation was quite good (96.2% for all measurement levels) as most of the data losses were attributable to the backup current meters installed on the primary mooring. Here, two Mk2 current meters were lost during grapnel recoveries of the mooring, a third unit experienced a clock battery failure, and a fourth unit had a tape advance problem. One SACM collected only a short record (for unknown reasons) during its initial deployment and the wave/tide recorder had a defective battery connector which caused it to collect no data during its second deployment. Some additional SACM data were lost during the sixth deployment due to instrument memory limitations. The data return is summarized by instrument type and mooring in Table 2.1-8, and time lines of available data for each instrument level are presented in Figure 2.1-10.

### 2.1.6.2 Physical Measurements Arrays

Field observations of the near-bottom suspended material field associated with the PMAs in the vicinity of Platform Hidalgo began on April 18, 1992 with the deployment of two instrument arrays, designated "Nearfield" and "Farfield," respectively (Figure 2.1-11). Each array was

Table 2.1-8. Data return summary for each instrument type deployed on the Primary (P) and Secondary (S) Santa Maria program mooring arrays (April 1992 - July 1994).

<table>
<tr><th rowspan="2">Instrument Type (No. of Instrument Deployments)</th><th rowspan="2">Mooring (No. of Levels)</th><th colspan="3">Percent Data Return</th><th rowspan="2">Comments</th></tr>
<tr><th colspan="2">Instruments</th><th>Measurement Levels</th></tr>
<tr><td>EG&G SACM (16)</td><td>P(3)</td><td colspan="2">91.4%</td><td rowspan="2">96.4%*</td><td>Instrument failure during first deployment and memory limitations during sixth deployment.</td></tr>
<tr><td>General Oceanics MK2 (17)</td><td>P(3) [Backup]</td><td>73.6%</td><td rowspan="2">85.0%</td><td>One clock battery failure, one tape advance failure, and two instrument losses during grapnel efforts.</td></tr>
<tr><td>General Oceanics MK2 (13)</td><td>S1(3)<br>S2(2)<br>S3(2)<br>S4(2)<br>S5(2)<br>S6(2)</td><td>100.0%**</td><td>100.0%**</td><td>No data between August 14, 1992 and October 16, 1992 as instruments not in water.</td></tr>
<tr><td>Sea Data 635-11 (6)</td><td>P(1)</td><td colspan="2">84.4%</td><td>84.4%</td><td>Bad battery connector during second deployment.</td></tr>
<tr><td>TOTAL: (52)</td><td>All</td><td colspan="2">86.9%</td><td>96.2%</td><td>Entire Program.</td></tr>
</table>

* Obtained by combining SACM and MK2 data records to fill data gaps as instruments were deployed at same depth (one meter apart).

** During the second deployment period, the mooring was recovered early by a fishing vessel.

bottom mounted, self-contained, and free-standing. Both arrays were placed in close proximity to mixed relief hard-bottom features. Farfield was considered to be beyond the influence of drilling associated discharges and was intended to represent a control for the measurements obtained at Nearfield. The in-water intervals for Deployments 1, 2, and 3 are shown in Figure 2.1-12.

On July 8, 1992 the M/V GLORITA attempted to recover the PMAs by acoustic command. The attempt was unsuccessful due to the lack of response by the acoustic releases and, as discovered on the recovery, the loss of the spherical floatation elements. On October 17, 1992 the PMAs deployed in April were recovered using an ROV to place a lifting line. Following recovery, instruments were serviced, data downloaded, the floatation and release configuration were

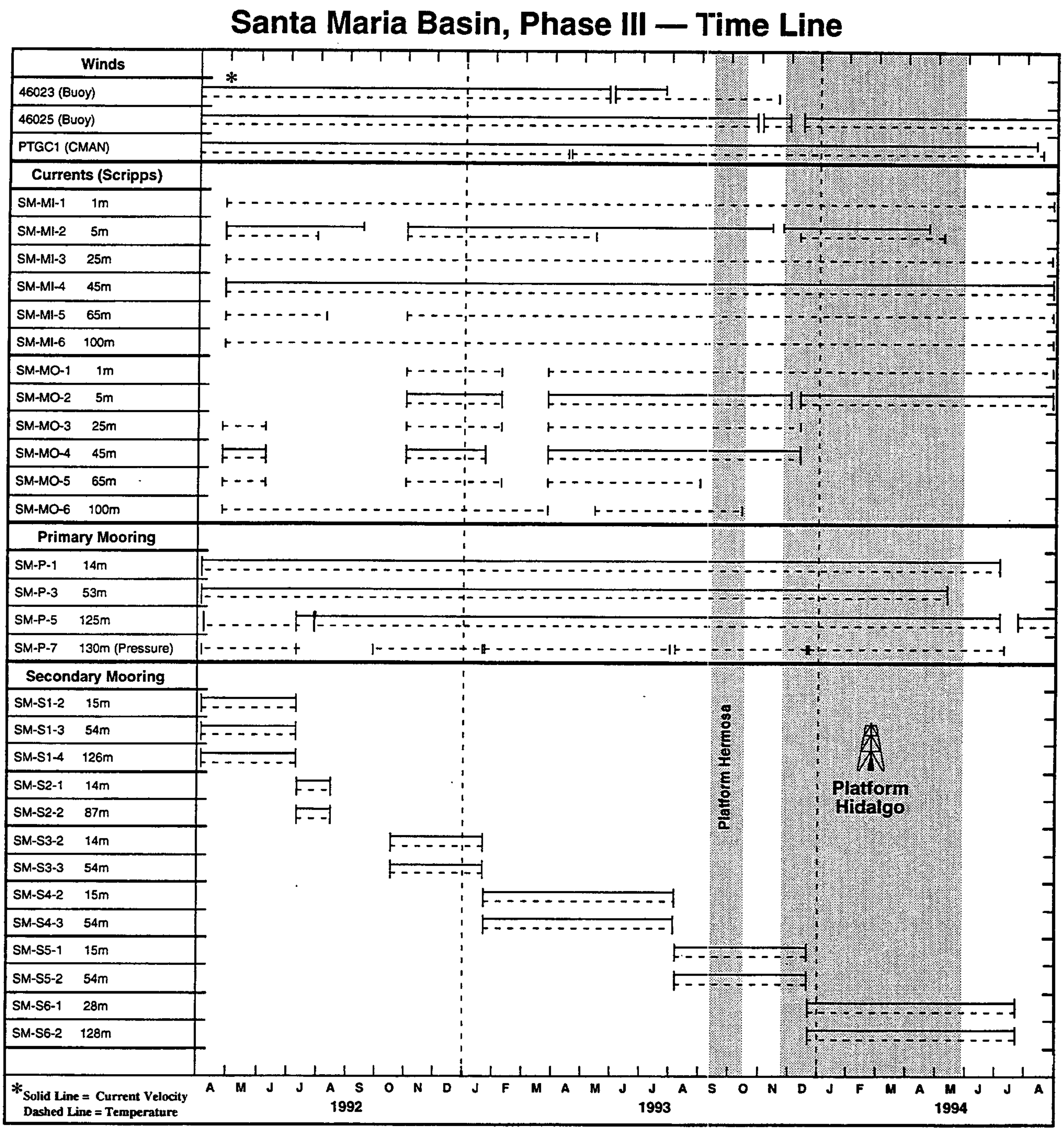



Figure 2.1-10. Time line of observations used to determine the circulation patterns and for particle transport estimates during the modeling phase. Gray patterns indicate platform discharge periods.

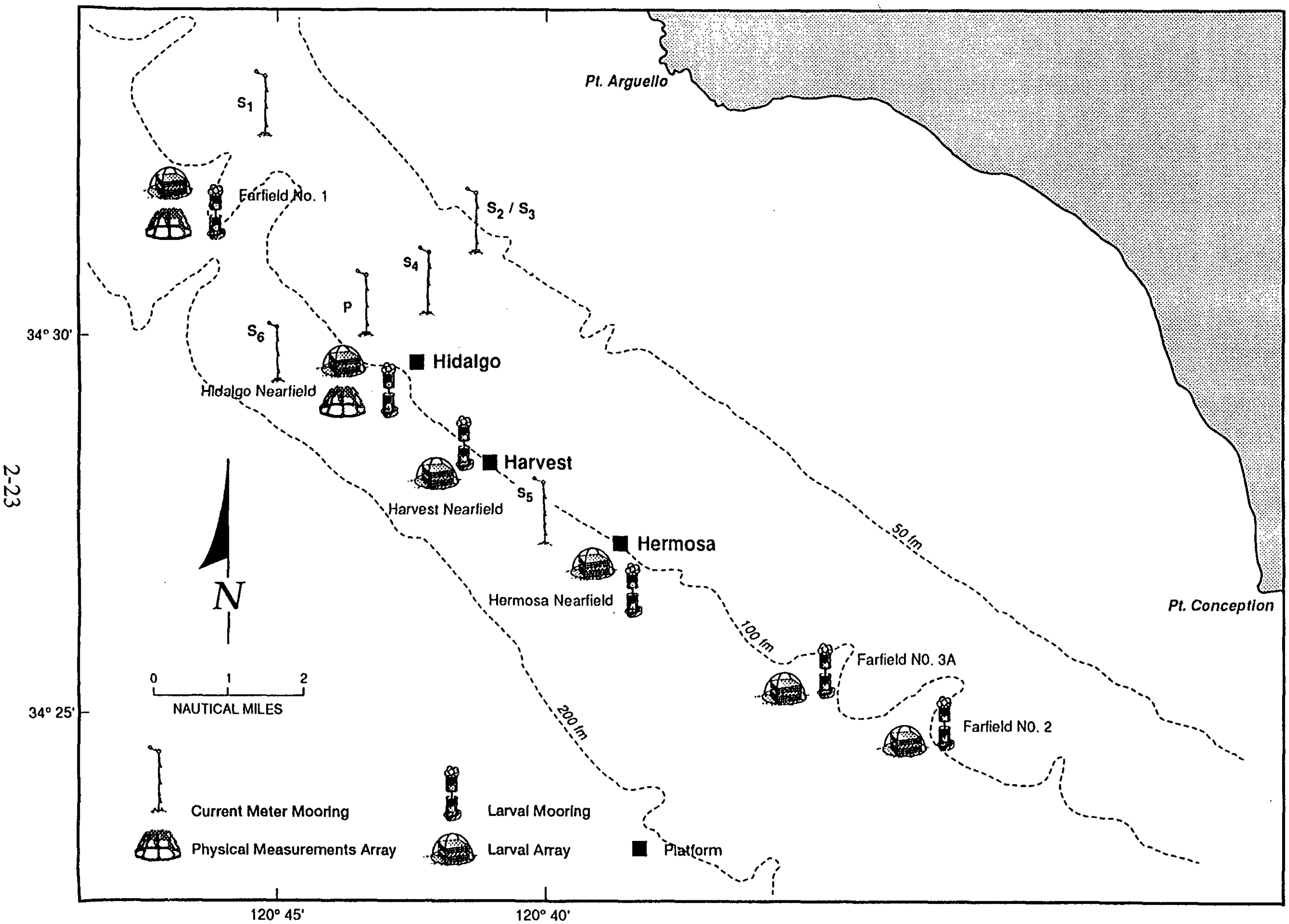



Figure 2.1-11. Map showing bathymetry and the location of the PMAs at the Nearfield (adjacent to Platform Hidalgo) and Farfield (several miles northwest of Platform Hidalgo) sites.

## Platform Hidalgo Deployment History

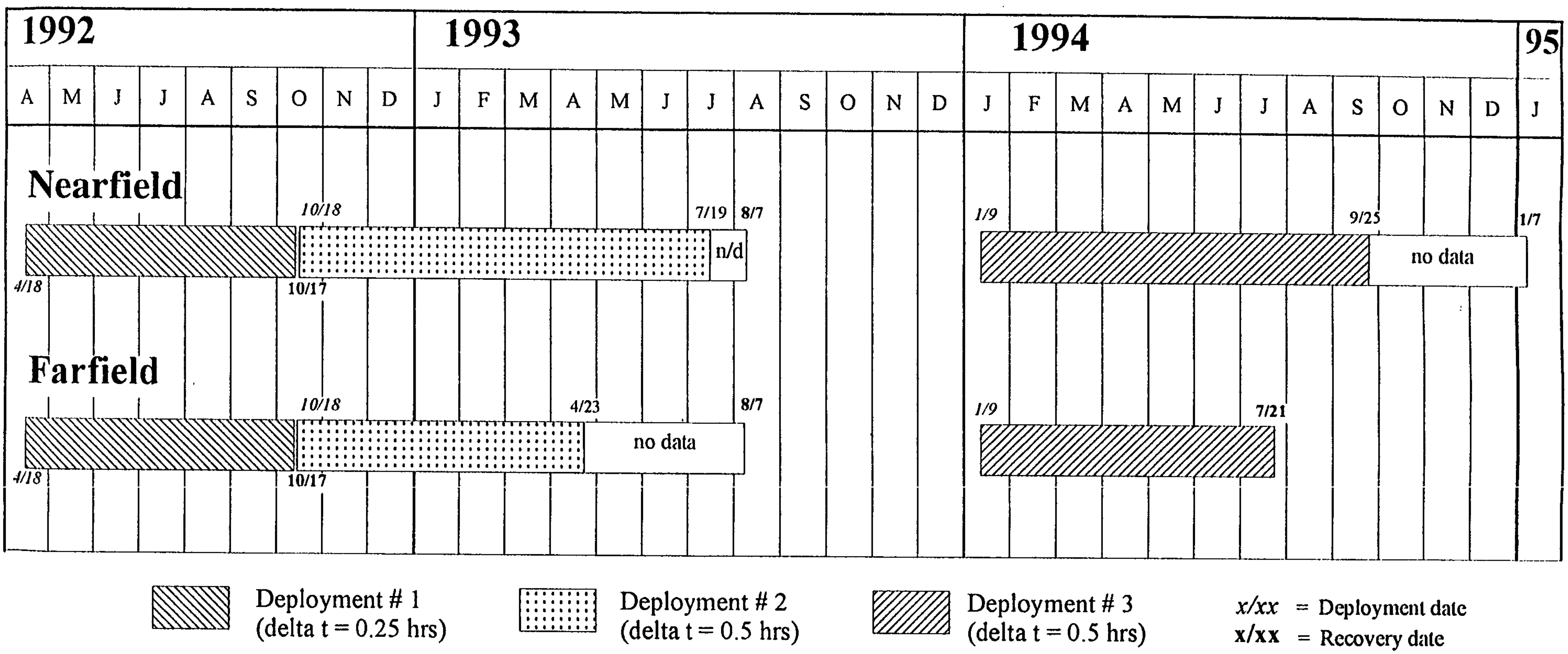



Figure 2.1-12. Time line showing the duration of the three deployments of the PMAs at the Nearfield and Farfield sites.

modified, and the arrays prepared for redeployment. Deployment 2 began on October 18, 1992 with the bottom mounted arrays placed at the same locations used during Deployment 1 (Table 2.1-4).

Deployment 2 ended on August 7, 1993. Following recovery and data downloading, the instruments were returned to the laboratory for servicing and recalibration. The current meters were recalibrated by the manufacturer. The optical sensors were calibrated at the University of Connecticut laboratory using procedures identical to those used prior to Deployment 1.

Deployment 3 began on January 9, 1994. Prior to array placement, a short field test was conducted to examine the possibility that anomalies observed in the near-bottom velocity data obtained during Deployments 1 and 2 were caused by the stainless mounting frame. A single S4 meter was taut-wire moored in close proximity to the Nearfield array for a period of approximately twenty-four hours. Subsequent analysis of these data (Figure 2.1-13) indicated a bias in the velocity record from the array mounted instrument. As a result, the stainless steel arrays used in Deployments 1 and 2 were replaced by simple in-line taut-wire moorings. These moorings were placed by the M/V RAMBO at the same locations occupied during Deployments 1 and 2.

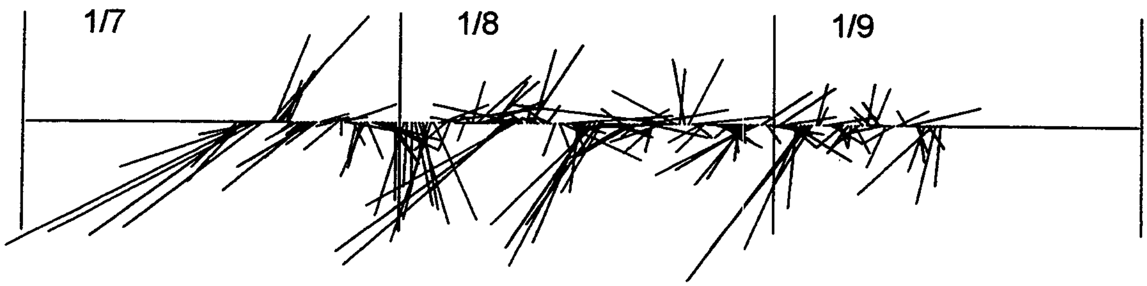
On July 21, 1994 recovery of the taut-wire bottom arrays were attempted using acoustic command. The Farfield array was successfully recovered, but the acoustic release on the Nearfield array failed to respond. As a result, the Nearfield mooring remained on station until January 7, 1995 when it was recovered using an ROV to place a recovery line. Data from the Nearfield array actually ended in September 1994 due to battery/data storage limitations.

### 2.1.7 Satellite Imagery

Infrared imagery of the earth's surface is available from the NOAA Polar Orbiting satellites' advanced very high resolution radiometer (AVHRR), which measures visible and infrared radiation in four or five bandwidths. Each satellite has a slightly different suite of instruments; however, the even numbered satellites (NOAA-6, -8, and -10) generally measure radiation in four bandwidths (channels) while the odd numbered satellites (NOAA-7, -9, and -11) and NOAA-12 measure in five bandwidths. Data transmission is always five channels. The fifth data transmission channel repeats the fourth bandwidth of radiometer data from a four channel radiometer. Technical details and data formats are given in the NOAA Polar Orbiter Data Users Guide (Kidwell 1991). A review of the uses of satellite data, including a discussion of errors, can be found in Abbott and Chelton (1991).

Spatial resolution of the AVHRR is nominally 1.1 km at nadir and temperature resolution is about 0.10K in the study region. High resolution data are broadcast continuously in the High Resolution Picture Transmission (HRPT) mode or limited time periods are stored for later transmission to NASA ground stations as Local Area Coverage (LAC) data. Data are also

Hidalgo Deployment Jan 94 : Single In-line Mooring




Hidalgo Deployment Jan 94 : Frame

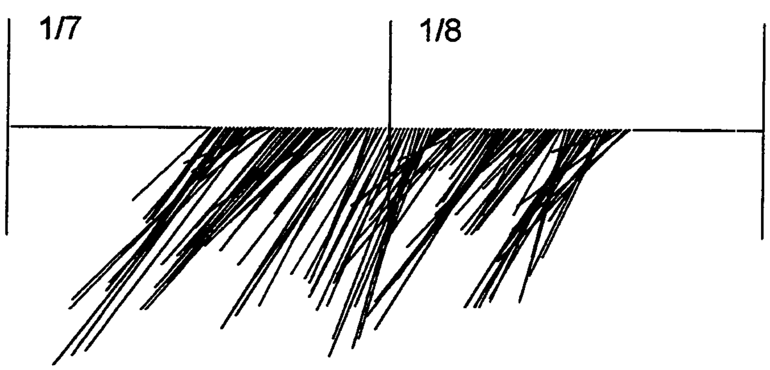



Figure 2.1-13. Stick plots of currents measured by S4 current meters; one was in the PMA frame and the other was on a short, tautline mooring. Although only about 100 m apart, there was an evident difference in the measured currents. This provided strong evidence of current velocity data bias resulting from some aspect of the PMA frame prior to Deployment 3. With these data it became apparent that the tautline mooring would have to be used if usable data were to be obtained.

averaged and stored in the satellite in a lower resolution Global Area Coverage (GAC) mode. The GAC data provide global coverage at a maximum resolution of four kilometers.

One thousand eight hundred twelve images, consisting of separate channel 4 (10.3–11.3 μm) and 5 (11.5–12.5 μm) data from the NOAA-11 satellite, were acquired during the period November 1, 1991 through April 30, 1994. These data were screened to reject scenes with a significant amount of cloud cover. During the first four months (120 days) of 1994, for example, there were about twenty relatively cloud free views of the central California coast. Eighty-five morning pass and 101 afternoon pass weekly composites, each prepared from two or three images, provided a relatively cloud free view of the study area beginning April 1, 1992 when current meter data were available from most of the moorings. There were five weeks (four in 1993 and one in 1994) when no usable composites could be prepared. During six weeks in 1992 and 10 weeks in 1993 no morning pass composites were possible while two additional weeks in 1992 permitted no afternoon pass composites.

## 2.2 DATA PROCESSING

### 2.2.1 Introduction

Primary data types included time series of environmental variables and sea surface temperature images obtained from satellite borne sensors. A brief discussion of processing steps is given below.

Time series observations include current and wind velocity, bottom pressure, temperature, and optical backscattering. For each of these data types, a sequence of observations was made at regular intervals (e.g., half hour during a deployment). Some of the instruments recorded instantaneous values while others internally processed instantaneous observations and recorded values that were averages over a user determined sampling interval.

Satellite imagery was obtained from Ocean Imaging of San Diego and processed at SAIC, Raleigh, NC.

### 2.2.2 Data Processing - Time Series

All oceanographic and meteorological data were processed using tested and verified procedures and algorithms. A key step in all processing was thorough quality control procedures which assure that all data have been thoroughly examined and evaluated by several oceanographers prior to being included in the program data base. After the QA steps, all data were entered into a physical oceanographic data management and analysis system for further processing. This data base system, interactively linked analysis, and graphics routines form the basis for all subsequent ocean data analysis and presentation.

Because currents often tend to flow in the direction of the general trend of the bottom contours (along isobaths), the current velocity data used in these analyses were rotated so that the **v**-component of velocity was directed along isobath and the **u**-component of velocity was directed across or normal to the isobaths. The magnitude of this rotation is indicated on the appropriate figures in the following form: "R330" which indicates that the coordinate frame was rotated 330° clockwise from north so that the positive **v**-component is directed along isobath in this direction.

Basic processing of time series data, such as components of current velocity or temperature, involved all or some of the following methods: three hour and forty hour low pass filtering, spectral analysis, and coherence and phase analysis. Three hour low pass (HLP) filters suppress fairly rapid fluctuations with periods of three hours or less. Given the time scale of processes of interest in the present study, 3-HLP time series were sampled at one-hour intervals and used as the primary data record. This resampling of 3-HLP data assured that comparisons between time series were always done at comparable times. Forty-HLP filtering suppresses fluctuations with periods less than approximately 40 hours. Hence, semi-diurnal and diurnal tidal oscillations would be eliminated from the time series. Spectral analysis divides the variance of a time series according to the frequency at which the variance occurs. Thus, spectral analysis helps resolve the relative contribution that different periodic fluctuations contribute to the measurement record. Coherence and phase analysis identifies how well fluctuations at a given period in one time series are correlated with fluctuations at that same period in another time series. If this correlation is statistically significant, then phase information quantifies what time lag may exist at a specific periodic fluctuation between two records.

A comprehensive statistical analysis was also conducted. It identified for each time series maximum and minimum values, the mean, the 3- and 40-HLP variance, and the principal axis. The latter is a quantitative method of determining a preferred orientation or direction for vector data. In addition, as discussed in subsequent sections, several special analytical methods (e.g., tidal analyses) were used to help isolate and resolve the circulation patterns and processes.

Tidal analysis was applied to the current velocity time series to help resolve fluctuations of higher frequency current fluctuations. These results provide an estimate of the amplitude and phase of all primary and interactive tidal constituents. Those constituents that contribute significantly to the observed velocity field can then be presented graphically as tidal hodographs (Figure 2.2-1).

### 2.2.3 Satellite Imagery

Two bandwidths (channels 4 and 5) of the five channel radiometer are generally used in determining sea surface temperature (SST). A third bandwidth (channel 3 (3.55–3.93 μm)) of

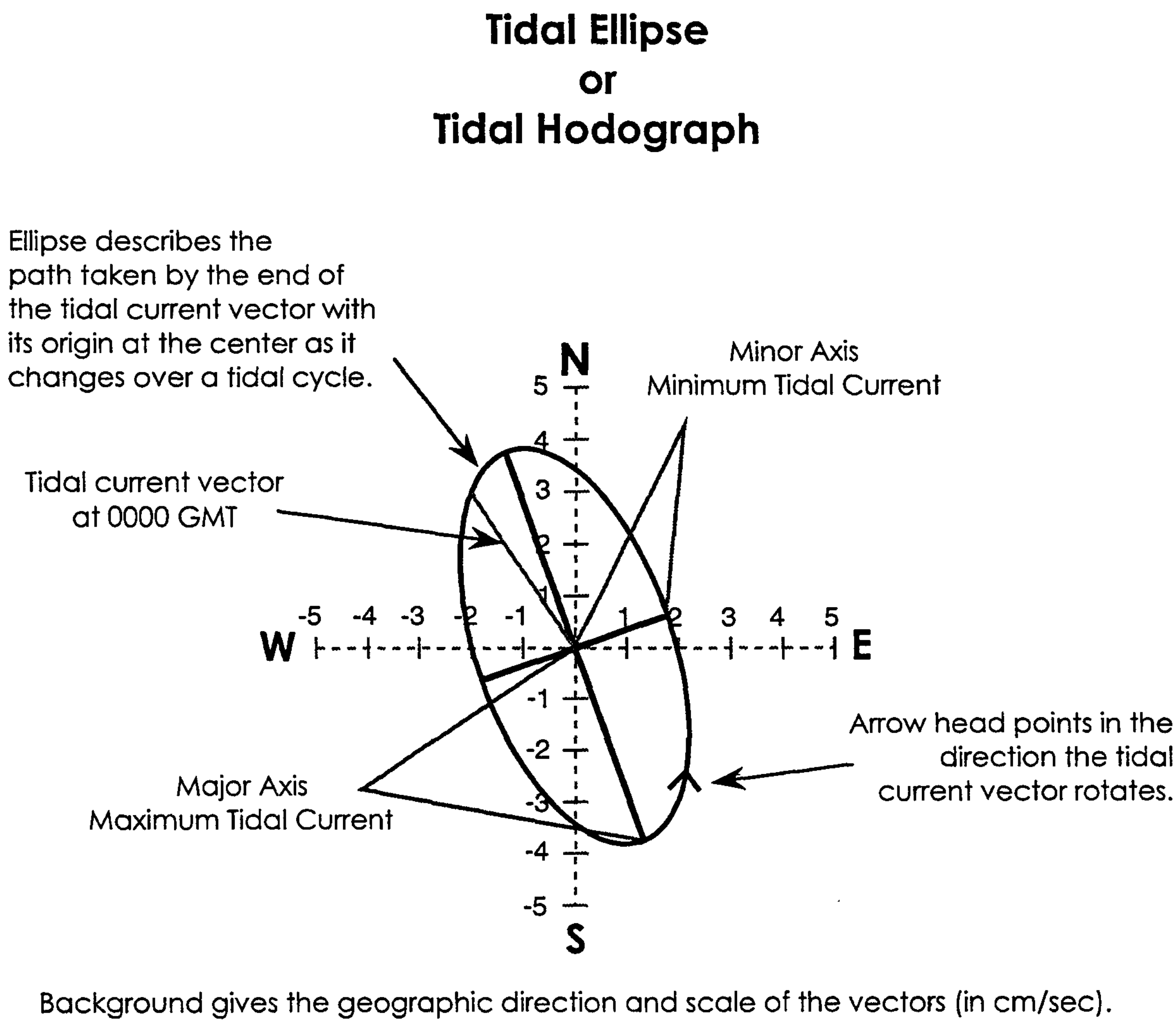



Figure 2.2-1. Example of a tidal hodograph with notation which indicates how it graphically presents a fairly complete description of a tidal constituent.

infrared data is also available but the instrument tends to be noisy and of limited usefulness (Barton 1995, Kidwell 1991). The satellite scan data were converted from radiance (counts on 10-bit scale) to temperature (8-bit scale) using an inverse of Planck's Law (Kidwell 1991).

The temperature data may be corrected for water vapor in the atmosphere (but not for clouds) if two radiometer channels are available, remapped to a user selected map projection, and displayed as color enhanced images. A single channel image provides valuable information about spatial patterns at the sea surface which can aid in understanding regional processes. The use of two channels of data to determine SST results in a more accurate temperature estimate (McClain et al. 1983; Abbott and Chelton 1991; Barton 1995).

The 1812 images acquired were separated into channel 4 and channel 5 images and converted from byte data to temperature. Navigation parameters were applied to the images to allow application of geographic data such as bathymetry, coastlines, and vectors to the images. The amount of cloud cover in each scene was noted for later use in choosing scenes to be composited as a means of cloud removal.

The image compositing routine involved a pixel by pixel comparison of two images with the warmer pixel being chosen for retention. This takes advantage of the relationship that clouds are generally cooler than the sea surface at the study area latitude, and they exibit movement. A secondary effect of the compositing process is to smear the edges of moving features such as eddies. Images were selected such that a composite included either all morning (descending) or all afternoon (ascending) passes and the time span between images was constant. Thus, two composite images of the study area (32°28.1'N to 37°31.8'N, 117°54.4'W to 124°04.8'W) were prepared from the channel 4 (10.3–11.3 μm) data during each week of the study. Daily average current and wind vectors, centered on the date and time of the corresponding composite, were overlaid on the composite images of the April 1, 1992 through April 30, 1994 period. After compositing was complete, remaining clouds were 'zeroed' by discarding values less than a value determined through visual inspection. Cloud values were generally less than 9.5–11.0° C. The composites were photographed for use in evaluating processes for the data report.

For certain cases where accurate SST was needed, a two channel correction was made to specific images using the NOAA crossed product (CPSST) algorithm (Walton 1988) for mid-latitude summer (equation 1) or winter (equation 2) conditions. The algorithm has the form (Barton 1995):

$$SST_{summer} = T_4 + 1.632*(T_4 - T_5) + 0.53 \qquad (1)$$

$$SST_{winter} = T_4 + 1.179*(T_4 - T_5) + 0.44 \qquad (2)$$

After the correction was applied the images were composited in the same sequence as the original channel 4 composite.

## 2.2.4 Particle Transport Modeling Techniques

Drilling muds are discharged from the platforms in irregular amounts on a daily basis while wells are being drilled. A description of this process is given in Coats (1994). Muds primarily consist of clay and silt sized particles with a small fraction of heavy sand sized particles. Discharge is from a pipe about 34 m (100 feet) below the surface. Since a primary interest is in the farfield dispersion of mud particles, as they slowly sink to the sea floor, the nearfield dynamics of the discharge are not considered as in Coats (1994). The focus is on dispersion caused by horizontal advection in the current field, and horizontal diffusion by oceanic turbulence. A major assumption is that the material can be split into particle size classes that can be independently tracked (as the material descends through the water column) by surrogate particles.

Tracking a surrogate particle of each size class is a good representation of the dispersal of a cloud of material as long as all scales of motion are sampled. This will be the case if sufficient numbers of particles are released over the drilling periods. The number of particles released per hour is proportioned to the daily discharge of drilling muds in barrels. Thus, the discharge rate of particles is time variable with a daily time step. The basis of the surrogate particle assumption is the theories of Batchelor (1952) and Taylor (1954) on dispersion by random movements. The main result, applicable to particle settling models, is that cloud dispersion from an ensemble mean position is given by single particle statistics (Fischer et al. 1979).

The simple particle tracking model, described below, is similar to the model of Fry and Butman (1991) which was used to estimate the footprint that would result from the dumping of municipal sludge at the deepwater 106-Mile Site, offshore of New Jersey. The Fry and Butman (1991) model is also the basis of the drilling mud disposition model used in Phase II (Coats 1994).

The model advects particles horizontally according to estimates of local current velocity at each time step. The vertical distance traveled is given by the sinking velocity. The particle's position is computed according to:

$$(x', y', z') = (x + (u + u_d)\Delta t,\ y + (v + v_d)\Delta t,\ z + w_k\Delta t) \tag{1}$$

| | | |
|---|---|---|
| where | $x', y', z'$ | is the particle's new position at time $t + \Delta t$; |
| | $x, y, z$ | is the particle's position at time t; |
| | $u, v(x,y,z,t)$ | are estimates of the local east and north velocity components; |
| | $u_d, v_d$ | are random diffusion velocity components; |
| | $w_k$ | is the sinking velocity for a particle of class k; |
| and | $\Delta t$ | is the time step. |

This equation is repeated for all active particles in the water column. To estimate u and v, all available current meter records were used from nearby moorings. For the September 1993 to June 1994 drilling periods, records were used from the Primary (P) (near Hidalgo), S5 (near

Hermosa), S6, and the SIO Santa Barbara Channel mooring SMIN. Where records are missing or short, the continuous sections of the 3-HLP records (Figure 2.1-10) are merged together using flag values. Thus, each meter position has an associated (u,v) time series covering the year-long deployment period, with flag values denoting data gaps.

At each time step, the valid velocity records at each position for all the moorings are identified. An objective method is used to find the nearest velocity position to the particle at (x,y,z). The procedure weights the nearest mooring more strongly than velocity values at similar depths to z but on moorings further away. In this manner, data gaps on a particular mooring are minimized by employing data at similar depths from other positions. The weights, $W_{ij}$, are calculated from:

$$
\begin{aligned}
R_j &= \max(r_j, r_{min}), \\
R_{min} &= \min(R_j, j=1, n), \text{where n is the number of moorings} \\
\Delta Z_{ij} &= \max(|\Delta z_{ij}|, \Delta z_{min}), \\
\text{and} \quad W_{ij} &= R_j \, \Delta Z_{ij} / (R_{min} \, \Delta z_{min}),
\end{aligned}
\tag{2}
$$

where $r_j$ is the horizontal distance between mooring j and the particle at (x,y);
$r_{min}$ is a minimum radius (1000 m);
$\Delta z_{ij}$ is the vertical distance between meter i on mooring j and the particle at depth z;
and $\Delta z_{min}$ is a minimum depth difference (50m).

The (i,j) record selected has the minimum $W_{ij}$ of all valid positions.

Linear interpolation between velocity positions on the selected mooring is used to find u and v at depth z, where appropriate. In this manner, the model attempts to account for the vertical and horizontal spatial variability of the current field seen by a particle as it moves away from the disposal site. Some scales of motion, such as tidal variability, will only be partially captured because of the limited vertical and horizontal distribution of the current measurements. Data gaps also cause a deterioration in the quality of the local interpolated velocities. However, over many realizations of particle tracks, the stochastic behavior of dispersing particles should be well captured on average. The larger scale variability of the poleward flow should also be captured, in its essentials, by using an array of moored instruments rather than just a single mooring, as is more usual in particle tracking models.

The random dispersion velocities are used to account for dispersion caused by small scale turbulence and motions not well resolved by the moored array. The velocity components are randomly selected from the range [-p,p] at each time step. The value of p can be related (Maier-Reimer and Sundermann 1982) to a dispersion coefficient, D, by

$$D = \frac{1}{6}p^2 \ \Delta t \tag{3}$$

A dispersion coefficient of 1 $m^2/s$ is appropriate for offshore ocean environments. The results are not sensitive to values of D less than 10 $m^2/s$.

The time step, $\Delta t$, is chosen from the time for a particle to fall 50 m or the velocity time series interval of 1 hour, whichever is less. Before each execution of formula (1), the position of the particle is checked to see if it has intersected the bottom or one of the outer boundaries of the grid. If the particle has intersected the bottom, it is flagged and its position recorded. If it has exited the grid, it is flagged as "lost". At the end of the particle tracking period, the positions on the bottom where the surrogate particles have settled are accumulated onto a regular grid in terms of particles per grid cell.

The model is run for all valid size classes, and the results are reported as concentrations per square meter per kg dumped of each size class. If this is denoted as $c_k$, then the deposition is given as

$$d_k = \frac{V_k c_k Q}{1-n_k} \tag{4}$$

| | | |
|---|---|---|
| where | $d_k$ | is the deposition depth of size class k; |
| | $V_k$ | is the fractional volumetric concentration of size class k |
| | Q | is the total volume of material dumped over the time period |
| and | $n_k$ | is a function of the voids ratio, $r_k$ |

where

$$n_k = \frac{r_k}{1 + r} \tag{5}$$

Total deposition,
d, is then given by the sum over the size classes

$$d = \Sigma d_k \tag{6}$$

The percent loss is calculated for each size class and then weighted by $V_k$ to produce the percent of the total solid material dumped that is not deposited and which escapes through the boundary of the grid. This total percent loss is entirely accounted for by coarse silts and fine silts (classes 5 and 6).

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# 3.0 RESULTS

## 3.1 INTRODUCTION

Physical oceanographic field measurements were made to support both an improved understanding of local oceanographic conditions and transport modeling of drilling discharges from oil and gas platforms in the study area. Section 3.2 presents a discussion of measured current velocity and temperature profiles in conjunction with satellite sea surface temperature imagery. These data describe the sequence of circulation patterns which control currents and hence material transport in the vicinity of the platforms. Section 3.3 presents a discussion of near bottom currents at two PMA locations with a goal of understanding the processes and patterns by which sediment is transported, deposited, and resuspended. This effort incorporates a consideration of temperature, salinity, and suspended sediment load in close proximity to the bottom. Finally, Section 3.4 describes the transport and deposition of material released from local drilling platforms as estimated by a numerical sediment transport model in combination with field observations of local currents.

Each of these sections provides an improved understanding of processes or conditions which are relevant to the overall program goal of characterizing the differential impact of drilling muds and cuttings on high and low relief hard bottom sites in the Phase III study region.

## 3.2 CIRCULATION PATTERNS

### 3.2.1 Background

The primary current meter mooring was located in a transition region between poleward flowing warmer water exiting the Santa Barbara Channel, as associated with the Southern California Counter Current (Hickey 1991), and the cooler, fresher water of the southward flowing coastal California Current (Hickey 1979). In addition, Pt. Arguello is often an upwelling center in the spring (Brink and Muench 1986). The outflow from the Santa Barbara Channel is often confined to the northern side with an associated cyclonic eddy between Pt. Conception and San Miguel Island that entrains cooler California Current water into the southern half of the western entrance of the channel (Brink and Muench 1986). North of Pt. Arguello, limited current measurements indicate poleward flow near the coast in opposition to the equatorward winds which occur over most of the year. Chelton et al. (1988) reported poleward flow in spring between Purisima Point and San Francisco Bay although the majority of their current meters were deployed at 70m or deeper. They also reported that for spring 1984, the alongshore currents off Pt. Conception were poorly correlated with currents north of Purisima Point, and surface drifters deployed north of Purisima Point tended to move rapidly northward. Drifters deployed off Pt. Arguello moved both north and south, often in complex eddy-like paths. In the study area, winds are equatorward throughout the year except between December and March when winter storm activity can disrupt this normal pattern. The prevailing wind direction is approximately parallel to the coast between Pt. Arguello and Pt. Conception.

The two-and-a-half year continuous time series of current velocity and temperature at the Phase III primary mooring (P) allows investigation of seasonal signals and interannual variability of these variables. Similar long time series are available from instruments on two moorings on the 100m isobath in the western entrance to the Santa Barbara Channel. These arrays were deployed and maintained by SIO under separate contract to MMS. In this report these SIO moorings are referred to as SMIN (San Miguel Inner) and SMOF (San Miguel Outer) which will be shortened to I and O (for Inner and Outer). Time lines showing data availability are given earlier in Figure 2.1-10. Access to the data taken by SIO provides information on the coupling of the flows off Pt. Arguello with those in the western end of the Santa Barbara Channel.

### 3.2.2 Seasonal Characteristics

Based on the time series of low frequency currents at the primary mooring, a spring and a summer-winter regime can be identified each year between April 1992 and July 1994. These regimes are reasonably distinct in characteristics and are based on conditions off Pt. Arguello. Different seasonal characteristics apply elsewhere as will be shown for the Santa Barbara Channel. The 7-day low pass (7-DLP) currents and 40-HLP temperatures and subsurface pressure are given in Figure 3.2-1 for the complete Phase III records at the primary mooring (P).

Spring seasons were characterized by strongly sheared equatorward flows. The equatorward events had the largest flows at the surface and weaker and sometimes northward flows at depth. The events were interrupted by several days of weak poleward currents which correspond with temporary weakening of equatorward winds. Many of the southward events had a strong offshore component at the surface. Examination of SST satellite images shows colder upwelled coastal water from north of Pt. Arguello being directed past the mooring. Water temperatures generally cooled during the spring with minimums being reached in May or June. The spring regimes in 1992 and 1994 were quite vigorous. In 1993, the spring regime was much less well-defined and appears to have been shorter, not being established until late March (as compared to the end of January for 1994) and abruptly transitioning to the summer-winter regime in mid-June (in contrast with late July for 1992).

The summer-winter regime was characterized by an abrupt transition from the preceding spring and appears not to be influenced by local winds. This was particularly noteworthy in July 1992 where strong equatorward winds persisted through the transition. Currents were poleward, often with maximum flows at mid-depth, and sometimes exceeding 50 cm/s. Bottom currents were northward and stronger than in spring (Figure 3.2-1). Water temperatures warmed until January. The source of this warm water was the Santa Barbara Channel and the Southern California Bight.

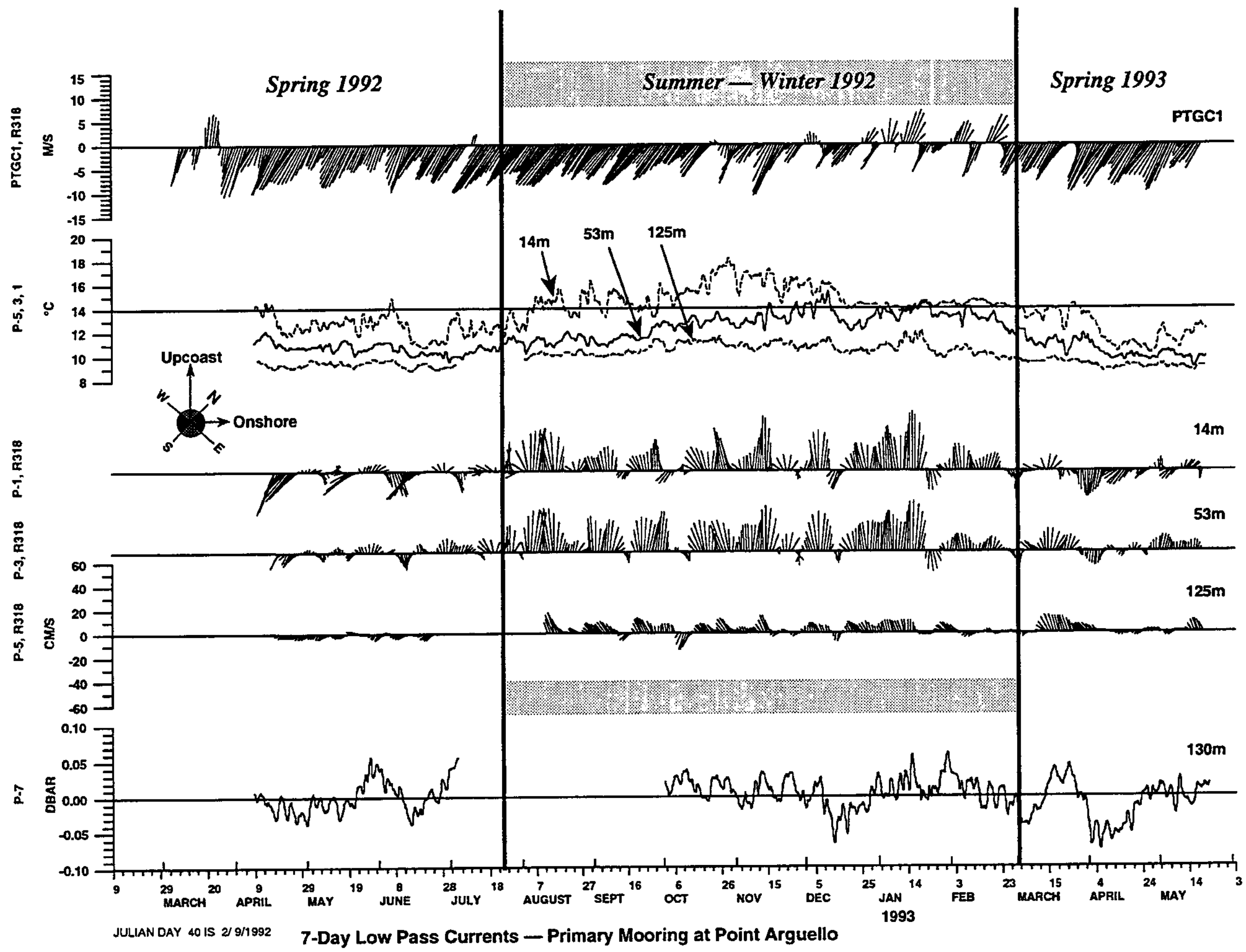



Figure 3.2-1a. 7-DLP currents and winds, and 40-HLP temperatures (mid-depth solid) and pressures for the primary mooring P.

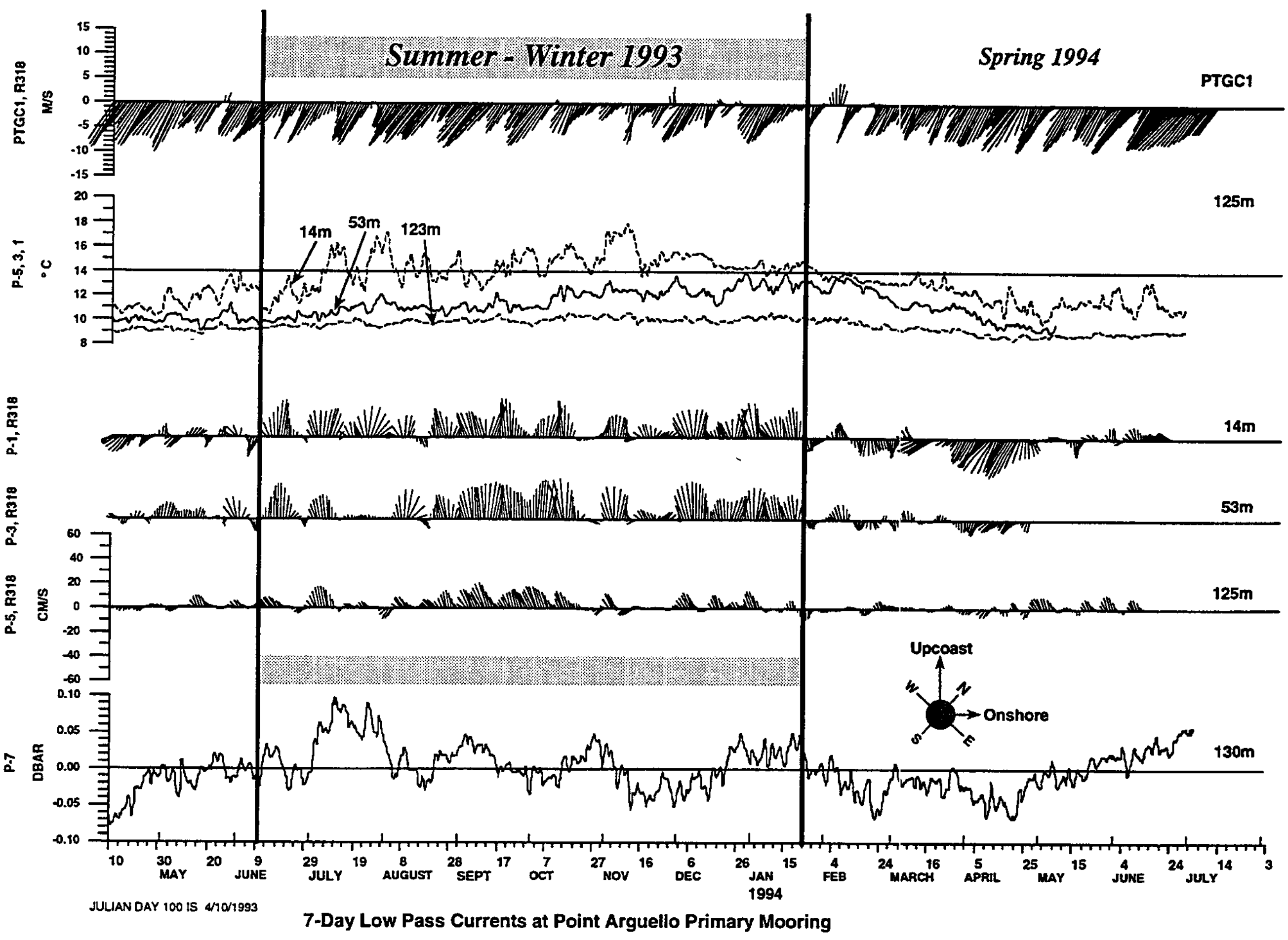



Figure 3.2-1b. 7-DLP currents and winds, and 40-HLP temperatures (mid-depth solid) and pressures for the primary mooring P.

Top-to-bottom temperature differences of 6° to 8° C occurred in late fall before the onset of winter storms which mixed and deepened the surface layer. Mixing of the surface layer occurred in January for the summer-winter 1992 period in response to a regular sequence of winter low pressure systems which moved over the west coast. Winter storms were not as prevalent in 1993–1994, resulting in the upper water column remaining stratified until February. The transition back to the spring regime was less well defined than the spring-to-summer change. The poleward flow regime had noticeable clockwise rotations of current vectors indicating that the poleward current flowing past Pt. Arguello had embedded eddies or meanders (Figure 3.2-1). The short-lived, weak equatorward reversals were associated with decreases in surface and mid-depth temperatures indicating that the front between the poleward flow and the colder offshore equatorward flow was fairly close to the mooring.

The low frequency velocity and temperature data for the Santa Barbara Channel moorings (I and O) are given in Figure 3.2-2 for the two-and-a-half year period. The same seasonal divisions as seen in records from P are evident. However, there is a much less clear cut demarcation between the different seasons, although it does correspond somewhat with data taken further north. Flows at I, on the northern side of the channel, were almost continuously to the east with only a few reversals. Flow at O was generally in the opposite direction and not as strong with evidence of considerable eddying at the surface instrument. The oppositely directed flows at P and O could be considered as part of the cyclonic eddy in the western entrance to the channel (Brink and Muench 1986).

The summer-winter periods had the greatest similarity with data from mooring P, with strong westward flows at I having a cyclonic rotary component. Clearly, these westward events and the poleward events at P correspond. The differences are that the maximum currents at I tended to occur at the surface though there was little shear between the 5 m and 45 m levels. Presumably, I is more sheltered from the opposing winds, which would tend to retard poleward surface currents at P. The spring periods did have some changes in character, though the timing was different. February to May in 1993 and 1994 had periods of weaker westward flows (at I) with marked anticyclonic rotations of the current vectors. In April 1993, flow at the 5 m level at O was northward towards I. The cause of this event is unknown. The reversals to eastward directed currents that occurred at I were associated with both strong equatorward events at P and weak reversals to the west at O (e.g., ~ June 8, 1992, ~ December 7, 1992, and ~ October 13, 1993).

Although there was less of a seasonal current signal in the channel, temperature records showed great similarities with those at P. There was cooling in spring with a minimum at depth in May or June, then warming until December. A deep mixed layer developed in winter with the onset of the winter storms. Differences are that there was weaker and stronger stratification in the lower and upper column (50 to 100 m and 0 to 50 m, respectively) than at P. Surface temperatures were also generally warmer at I than P in most periods and warmer at O than P in the summer-winter periods.

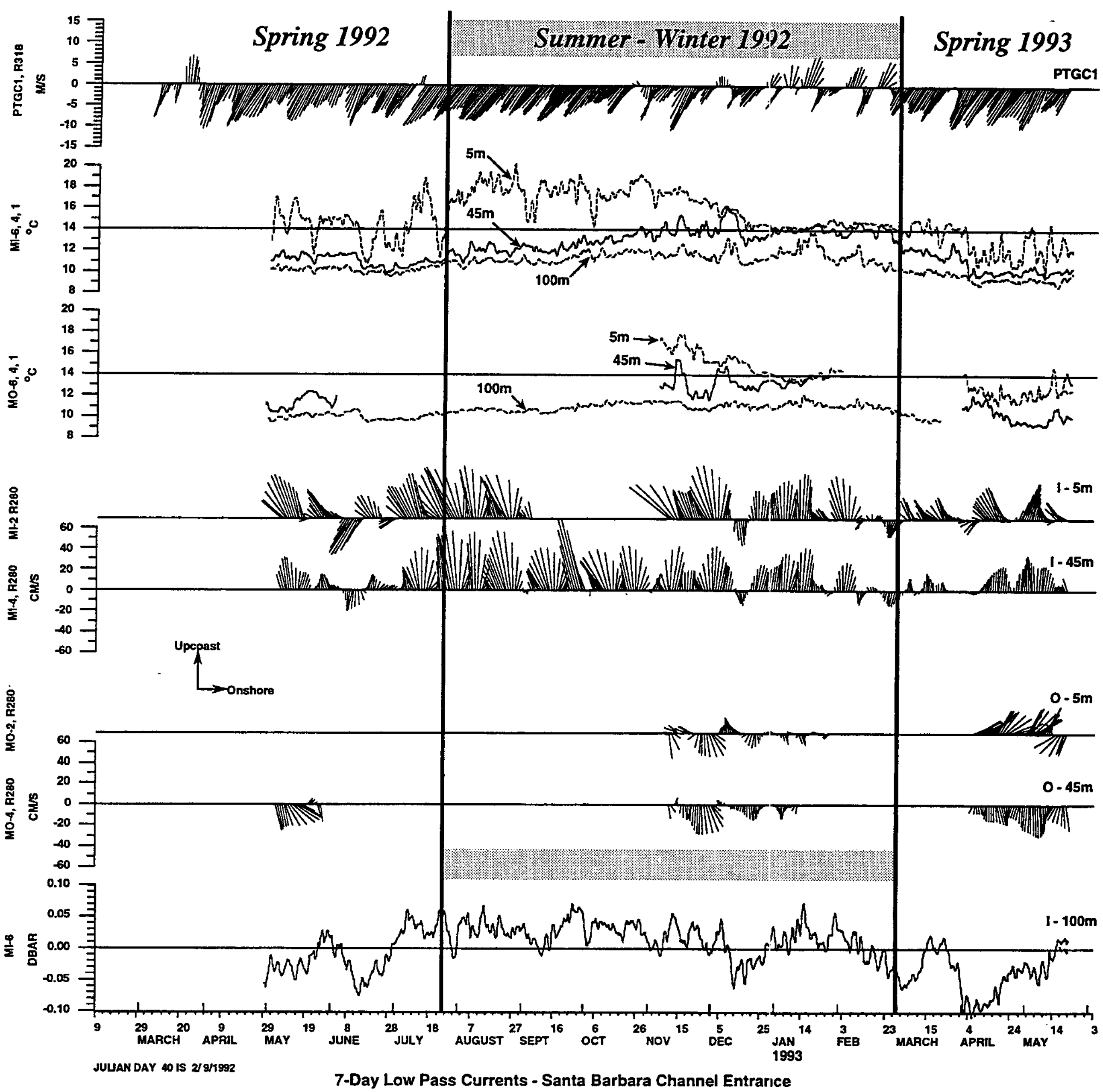



Figure 3.2-2a. 7-DLP currents and winds, and 40-HLP temperatures (mid-depth solid) and pressures (dashed MO-6) for moorings I and O in the Santa Barbara Channel.

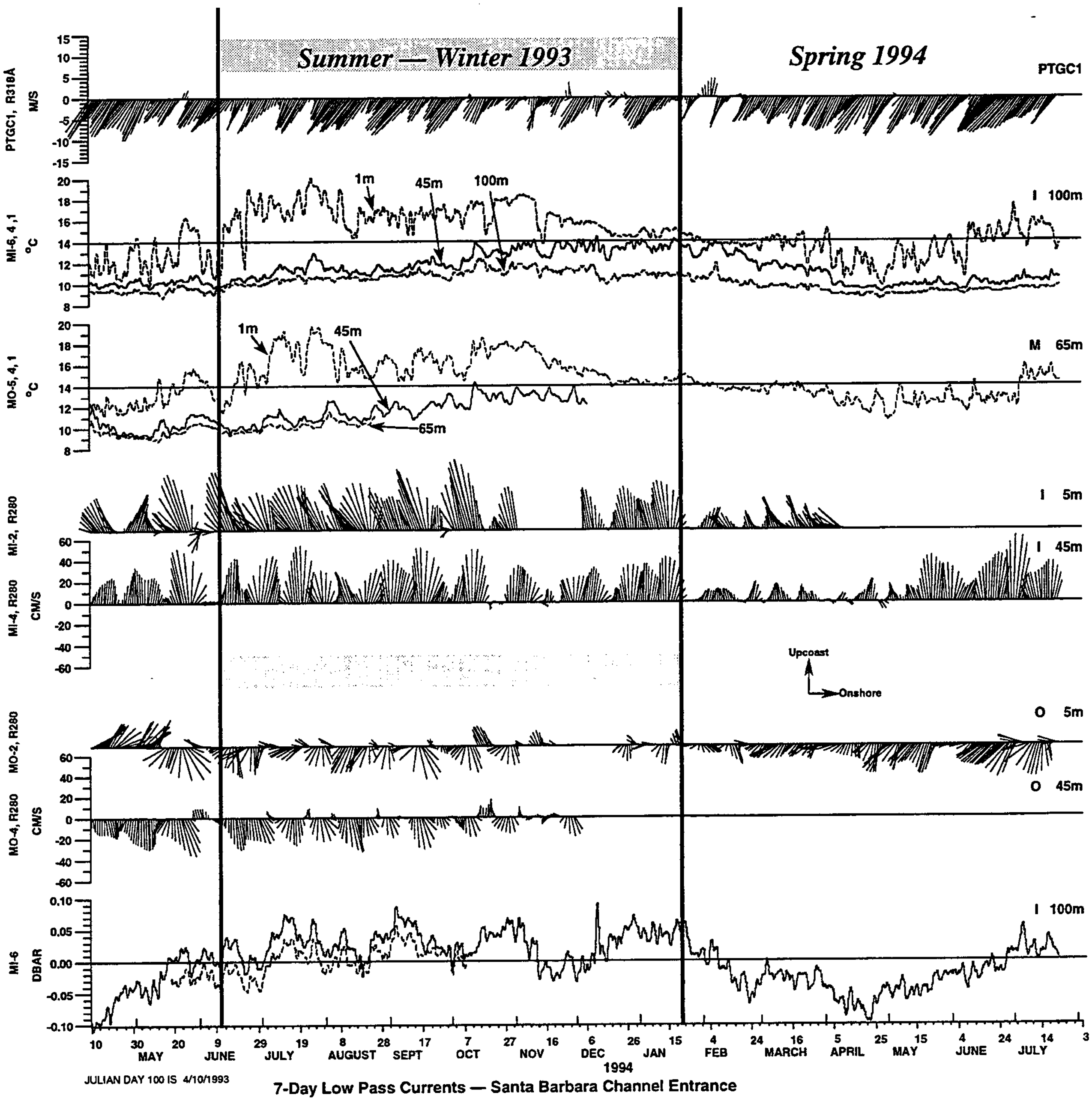



Figure 3.2-2b. 7-DLP currents and winds, and 40-HLP temperatures (mid-depth solid) and pressures (dashed MO-6) for moorings I and O in the Santa Barbara Channel.

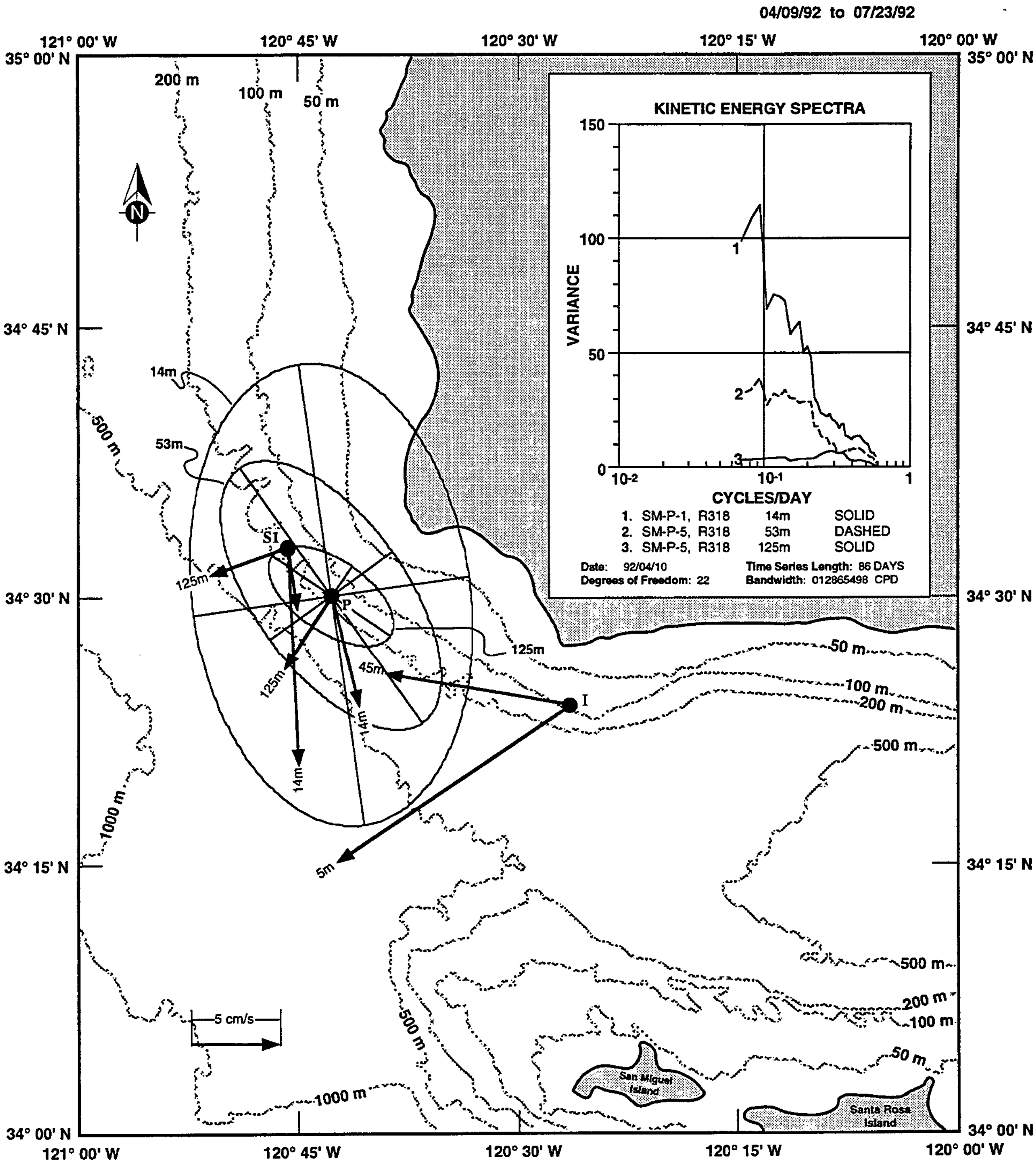
## 3.2.3 Statistics, Spectra, and Coherence

### 3.2.3.1 Spring 1992

The means and variances for the available records in spring 1992 are shown in Figure 3.2-3. The kinetic energy spectra for the primary mooring are given as an inset and show that most of the kinetic energy was at periods longer than 10 days and decreased markedly with increasing depth. This is reflected in the standard deviation ellipses which show a large anticlockwise rotation of the principal axes with depth. The rotation is consistent with upwelling and downwelling. Thus, a southward relative fluctuation at the surface had an offshore component; at mid-depths, the major principal axis was parallel to the isobaths; and at the bottom there was an onshore component. Surface and bottom onshore-offshore fluctuations reversed for northward fluctuations. In contrast, the mean currents at P and S1 all had offshore components. The S1 record is quite similar to P except for larger southward means. Thus, it appears that the southward mean flow at P and S1 was being deflected offshore by the outflow from the channel. At I, the surface mean flow was deflected southwestward, but the mid-depth was parallel to the isobath and opposed the weak 50m southward mean currents at P and S1. This convergence may account for the relatively large (~ 5 cm/s) offshore directed means at the bottom instruments at P and S1.

Figure 3.2-4 shows the 40-HLP current vectors at I, P, and S1 along with the surface temperature records. It is clear that strong westward events at I caused a reduction in the southward flows at P and S1. Conversely, strong southward events (e.g., June 6–15, 1992) could move cold water into the channel and reverse the flow there. These two situations are illustrated by the composite satellite images for the weeks of April 26 and June 7, respectively (Figure 3.2-5). The former shows Santa Barbara Channel water moving out into a band of cold water that extended down the central California coast and south of the Channel Islands. The June 7–13 image shows the cold water extending across the entrance and along the south side of the channel.

The coherence squared and phase differences for the records shown in Figure 3.2-4 are given in Figure 3.2-6. It can be seen that the near surface longshore current was well correlated with the mid-depth current, but the mid-depth current had little correlation with bottom currents. Longshore wind fluctuations were also not coherent with the surface current fluctuations at P1. This is in contrast to current measurements made north of Purisima Point in the spring of 1984 (Chelton et. al. 1988), where fluctuations of longshore wind were related to near coast current fluctuations despite the northward mean current opposing the mean equatorward winds. Coherence squared between the surface longshore current fluctuations at I, P, and S1 are quite high for periods longer than 5 days. Currents at the 5 m and 45 m levels at I were more highly correlated than the 45 m and 53 m levels at P and S1. The signal at I occured prior to that of P, and P before that of S1, for coherent frequencies. This indicates the possible presence of northward propagating shelf waves, as discussed by Chelton et. al. (1988) and Hickey (1992).




**40-HLP Means and Variances, Spring 1992**

Figure 3.2-3. Spring 1992 40-HLP means and variances (P only). Inset: Kinetic Energy spectra in variance preserving form for P.

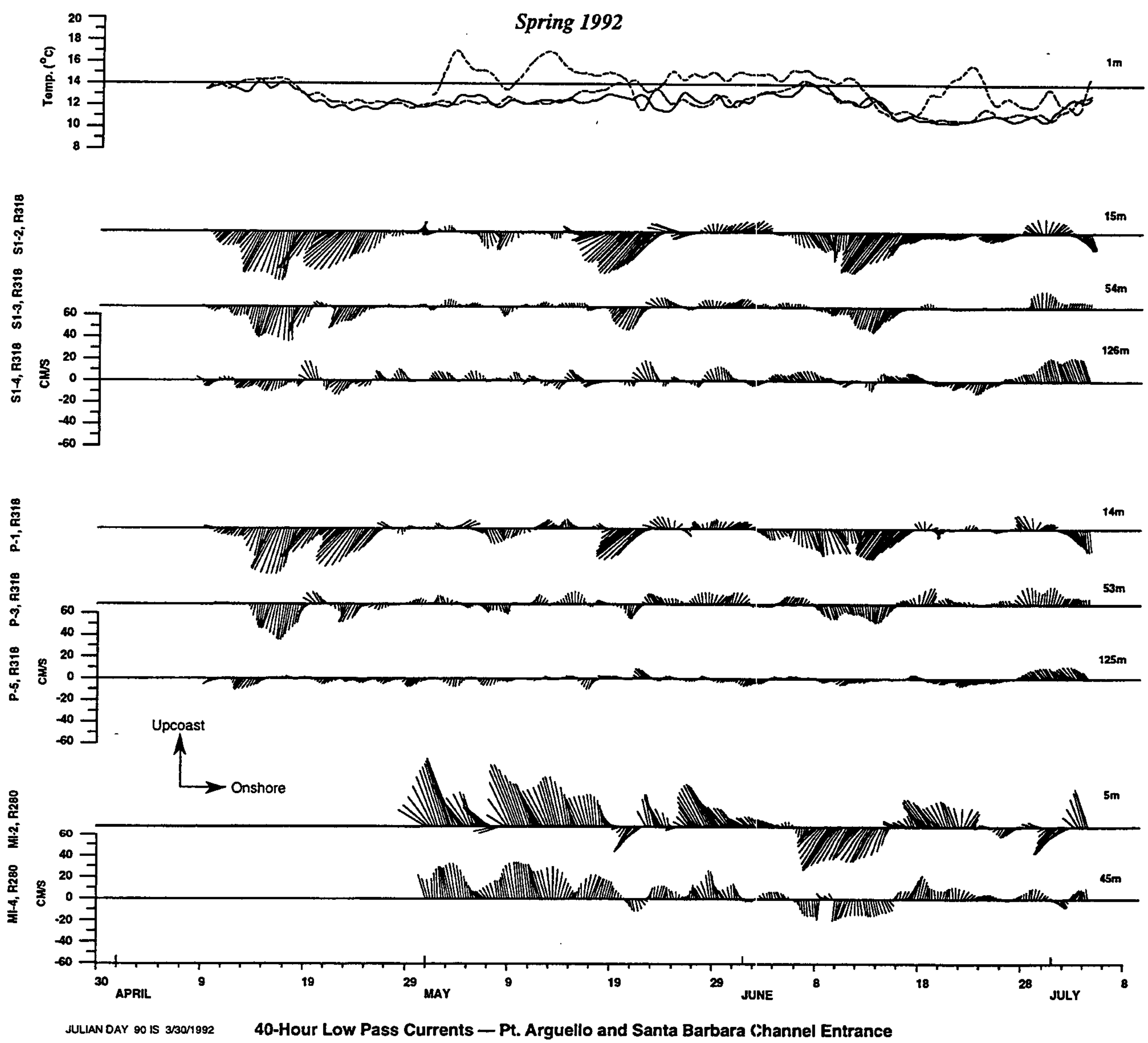



Figure 3.2-4. 40-HLP currents and near-surface temperatures (dashed – 1 m level at I and 15 m level at S1, solid – 14 m level at P) for moorings I, P, and S1.


Figure 3.2-5a. Composite NOAA-11 AVHRR image for 26 April - 2 May 1992. Daily averaged 40-HLP current and wind vectors for the center of the period are overlayed on the image. Vector and temperature scales are shown in the land area. Note difference in wind and current scales. Temperature has not been atmospherically corrected.

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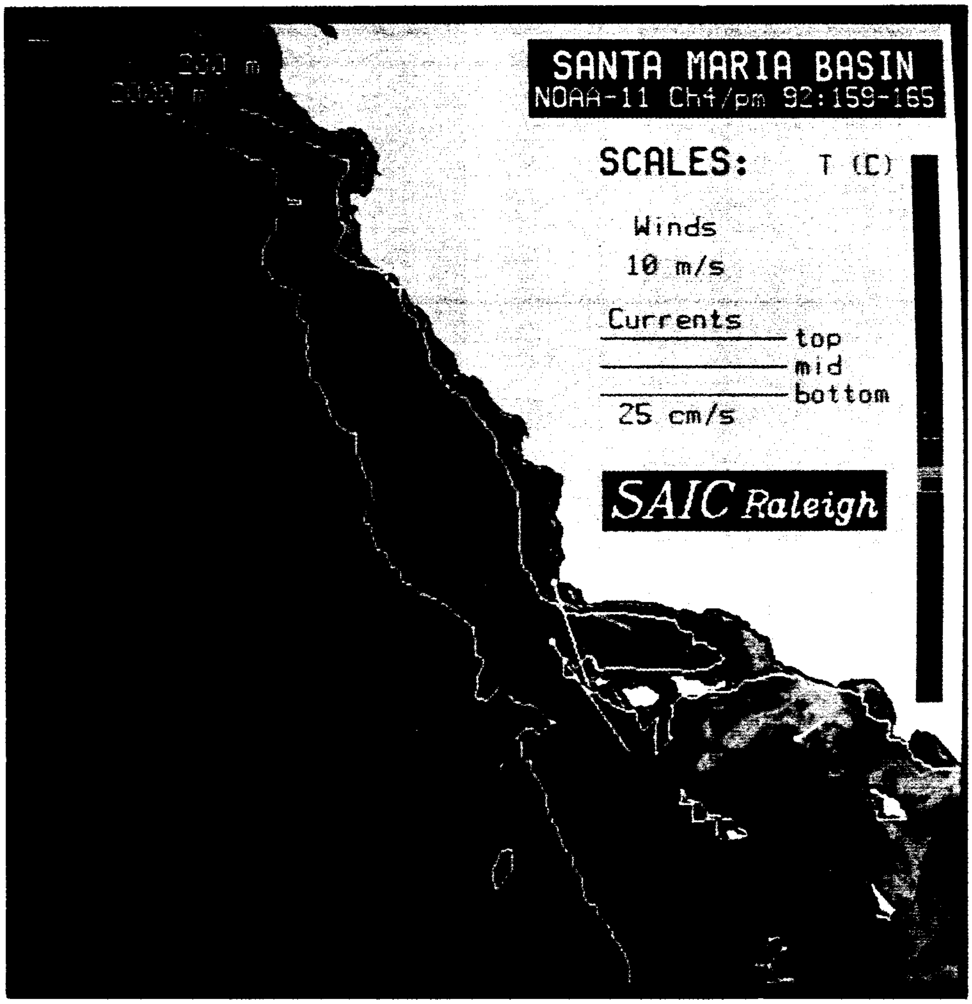


Figure 3.2-5b. Composite NOAA-11 AVHRR image for 7-13 June 1992. Annotated as in Figure 3.2-5a.

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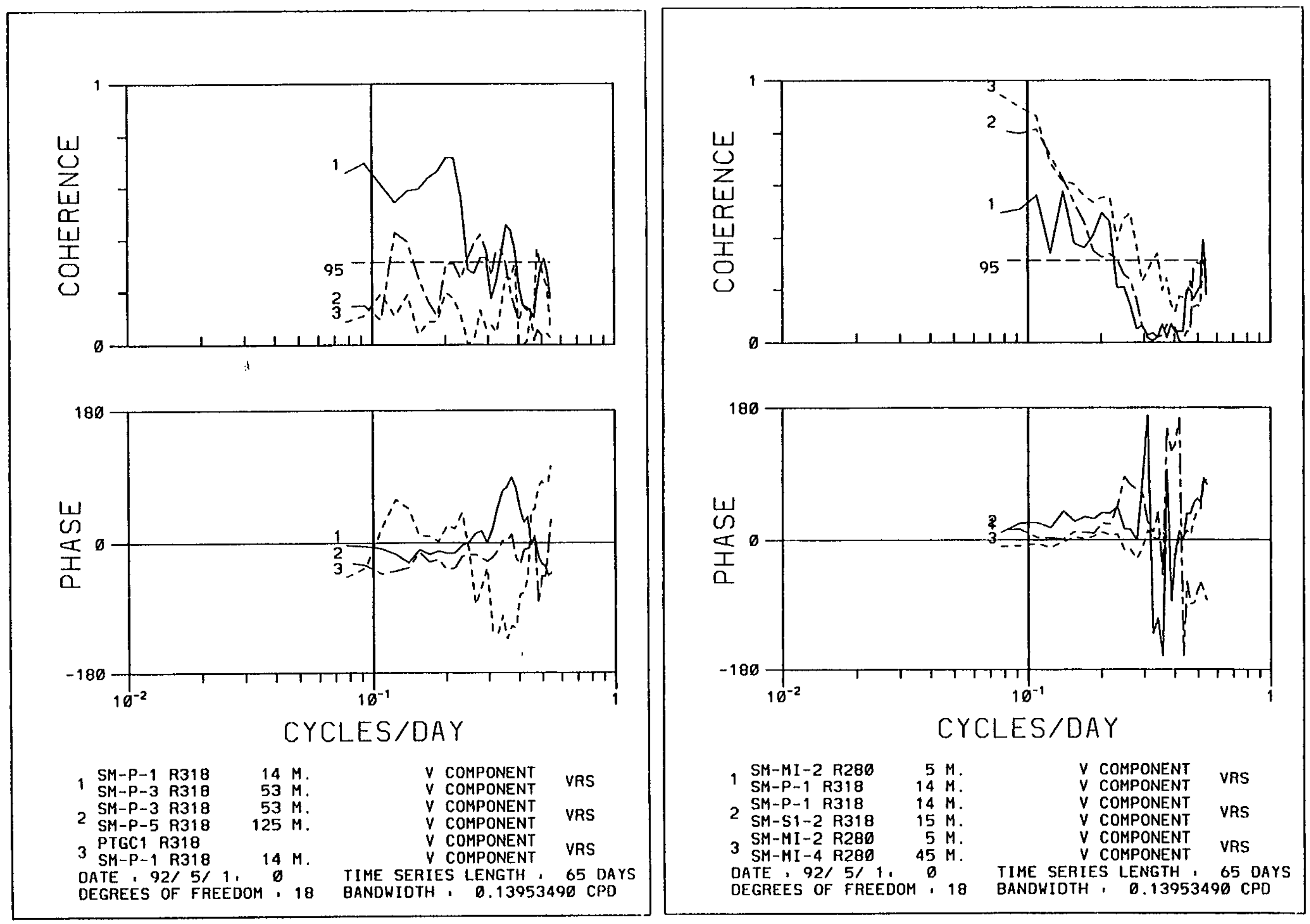


Figure 3.2-6. Coherence squared and phase differences for the indicated wind, P, I, and S1 records for Spring 1992.

### 3.2.3.2 Summer-Winter 1992

Statistics for the summer-winter 1992 poleward flow season are shown in Figure 3.2-7. Mean currents were poleward off Pt. Arguello, and the westward means at I strengthened. At P, the mid-depth mean current exceeded that of the surface, and the current variances were virtually the same. The bottom standard deviation ellipse is larger than its spring counterpart, and the mean current at 125 m had a northward component as well as the offshore component seen previously. Currents at the S3 mooring (deployed October 1992 – January 1993) in 90 m water depth, inshore of P, also experienced strong northward means. The 54 m levels had a strong onshore component, perhaps being indicative of persistent upwelling off Pt. Arguello during the fall and early winter. Instruments on mooring O recorded eastward directed flows with a larger mean at depth. These were oppositely directed to and weaker than the means at I. Spectra show the dominant energy was at 20 days but with subsidiary higher frequency peaks at 7 and 4–5 days (Figure 3.2-7).

The 40-HLP time series of currents and surface temperatures are shown in Figure 3.2-8. Surface temperatures at I were 4–6° C warmer than at P for most of the summer except when short-lived current reversals occurred. By November, temperatures at P had warmed to those at I and O. This pattern, in conjunction with the persistent poleward directed currents, indicates that warm water from the channel was being advected northward past Pt. Arguello. The frequent rotary motions of the current vectors are evidence of eddies and meanders in this current field. The SST image for the week of November 8, 1992 (JD 313) clearly shows (Figure 3.2-9) that warm water from the channel moved north around Pt. Arguello while a tongue of cooler water moved eastward along the north shore of San Miguel Island. Note the evidence of a cyclonic eddy off Pt. Arguello. It appears that when westward currents at I reversed (e.g., ~ December 5), the surface currents at O also reversed, indicating that intrusions of northern waters may not have moved far into the channel but rather exited on the southern side.

The coherences between alongshore velocity components on mooring P (Figure 3.2-10) are quite different from those in spring. During summer-winter 1992, upper level currents were highly coherent, and even the bottom currents showed moderate to high coherence squared with those at the 53 m level. Between I and P, coherences were now poor with some barely significant peaks between 5- and 10-day periods. Alongshore winds were slightly more coherent with currents at 14 m at P than in the spring, but again it was confined to about 5-day period motions. The implications are that the northward flows at P were more decoupled from the flows out of the channel than in the spring.

### 3.2.3.3 Spring 1993

As discussed above, the spring regime during February to June 1993 was quite short and not well developed. The statistics (Figure 3.2-11) show similarities with the spring of 1992. Mean

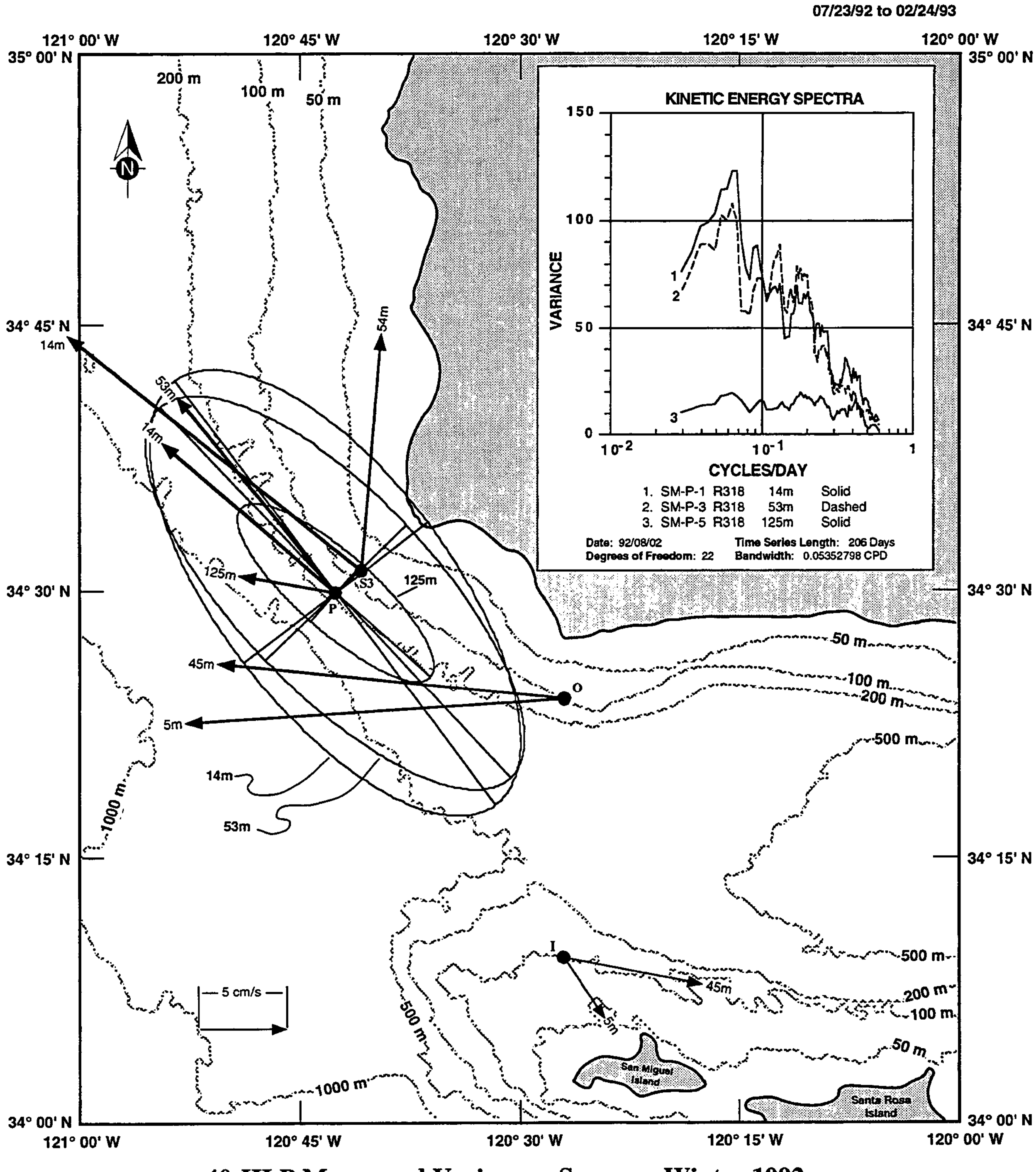


Figure 3.2-7. Summer-Winter 1992 40-HLP means and variances (P only). Inset: Kinetic Energy spectra in variance preserving form for P.

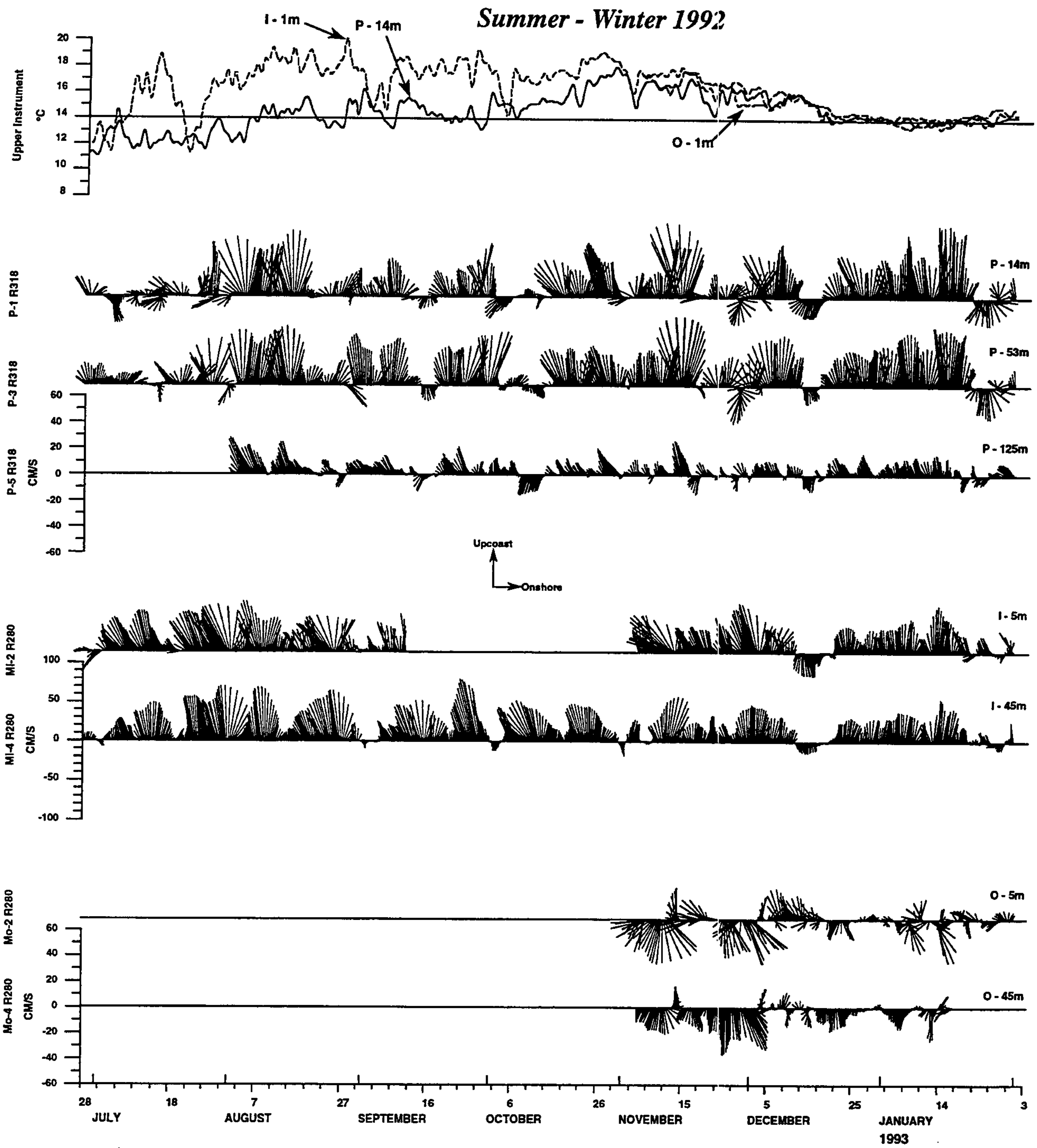


Figure 3.2-8. 40-HLP currents and near-surface temperatures (dashed – 1 m level at I and O, solid – 14 m level at P) for moorings I, O, and P.

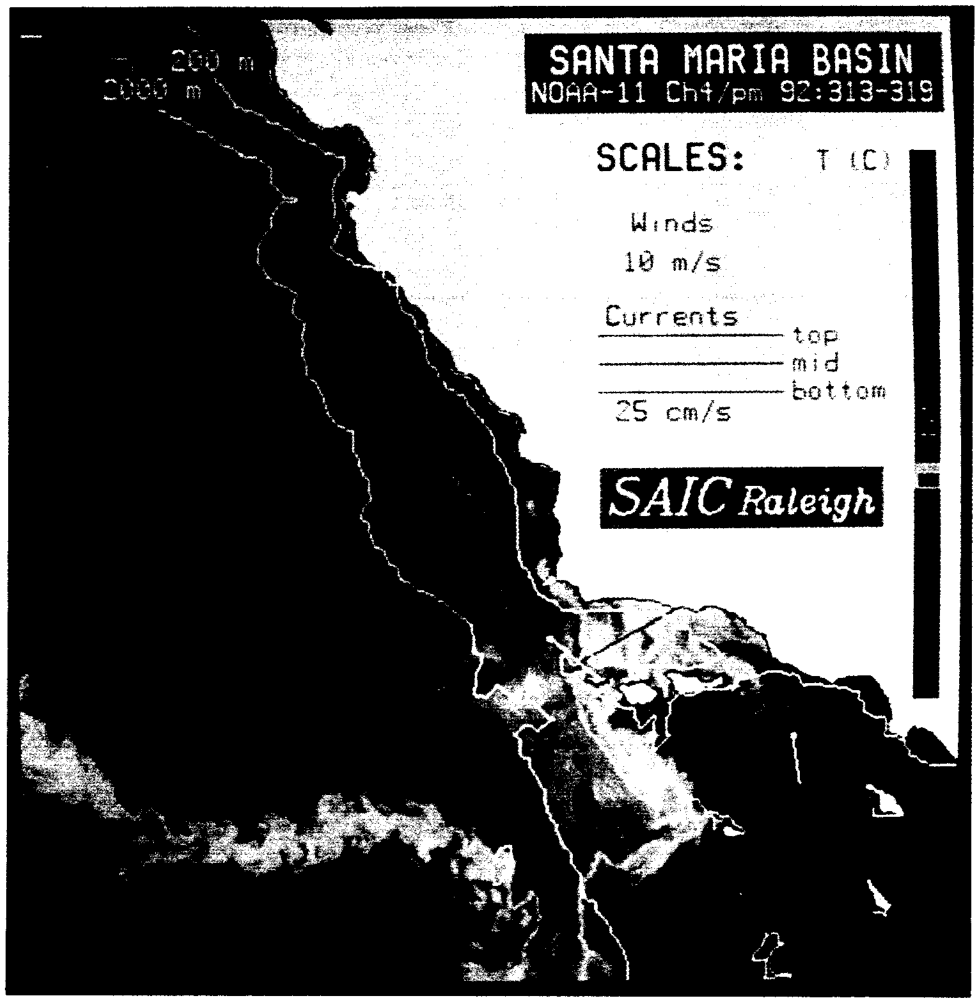


Figure 3.2-9. Composite satellite images for 8-14 November 1992. Daily averaged 40-HLP current vectors for the center of the period are overlayed on the image.

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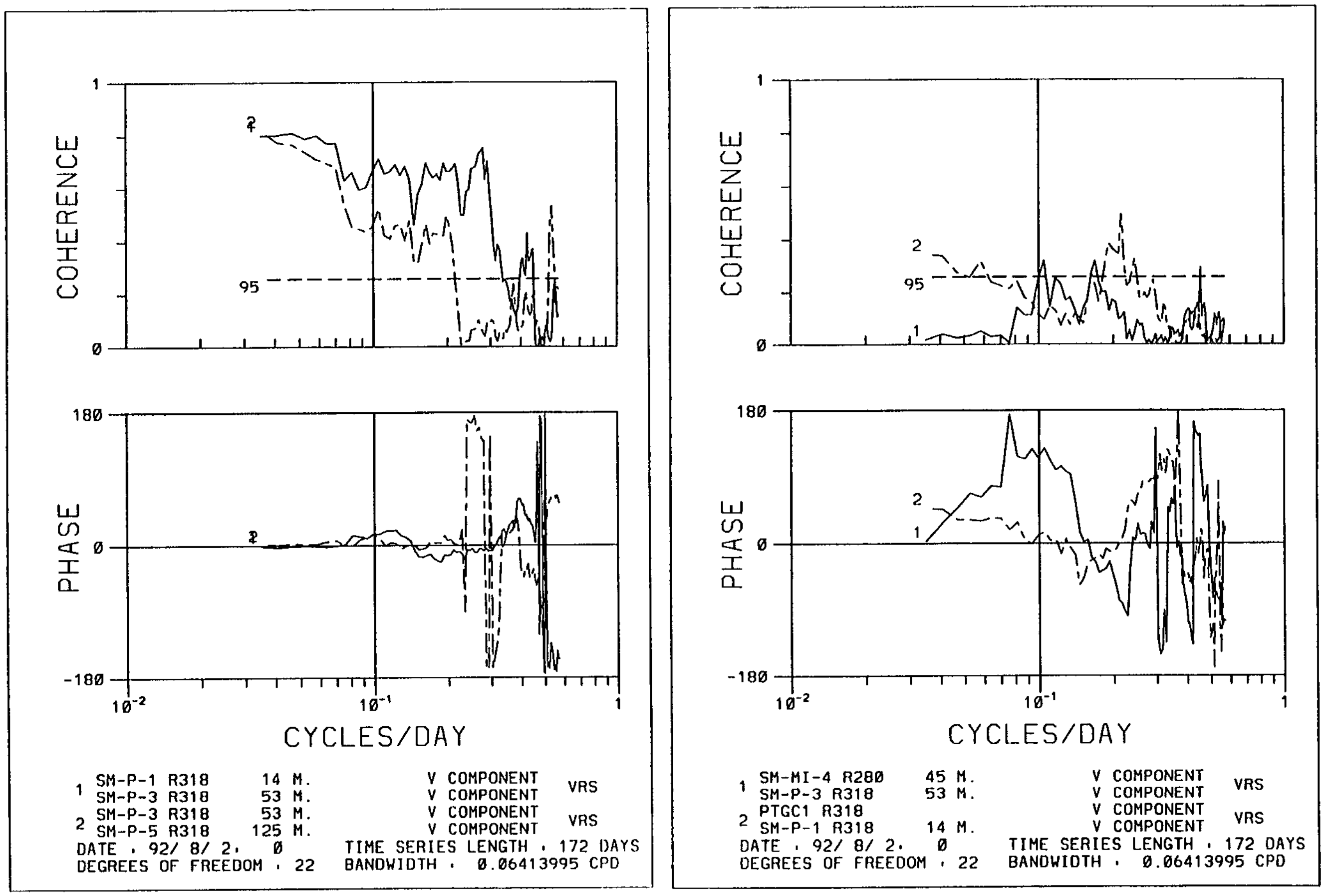
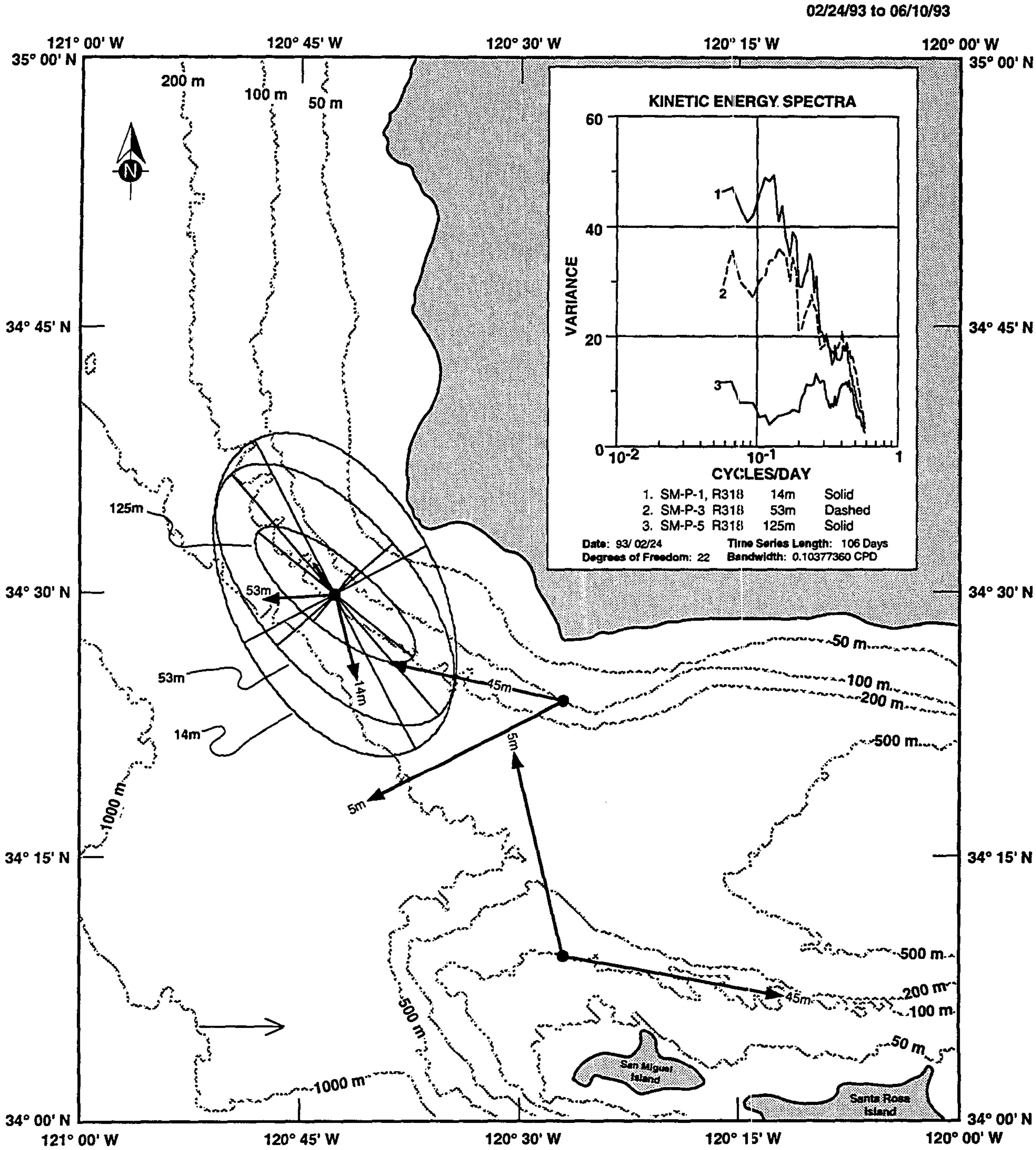



Figure 3.2-10. Coherence squared and phase differences for the indicated wind, P, and I records for Summer-Winter 1992.




**40-HLP Means and Variances, Spring 1993**

Figure 3.2-11. Spring 1993 40-HLP means and variances (P only). Inset: Kinetic Energy spectra in variance preserving form for P.

currents were not as large and offshore flow took place at mid-depth rather than the bottom at P. Mooring I had a southward component of the near surface mean, probably caused by the southward surface flow at Pt. Arguello as before. Currents at mooring O had eastward means at 45m but northward nearer the surface. This was caused by a remarkable episode in April and May (Figure 3.2-12) where flows were northward or westward at 5 m but eastward at 45 m. An SST image from this period is shown in Figure 3.2-13 (May 2–8, 1993). A surface patch of cold water which seemed to cause a cyclonic rotation of the surface currents was just west of San Miguel Island . The 50 m currents were more as expected, being eastward at O and northward at P. The spectra show a peak at about seven days (Figure 3.2-11) and generally the fluctuations had shorter periods and were more variable in direction than during the comparable period in 1992.

The secondary moorings S2, S3, and S4 were deployed inshore of P between June 1992 and July 1993. S2 and S3 were 3.5 km and S4 was 1.5 km from P, and, as might be expected, the records at equivalent depths were essentially the same as at P (not shown).

#### 3.2.3.4 Summer-Winter 1993

The summer and winter of 1993 were much closer to their 1992 counterparts than to the respective springs. The main difference was somewhat lower energy levels, although the spectral peaks at 20, 7, and 5 days are similar (Figure 3.2-14). Mean currents were at a maximum at mid-depth and the surface at P and I, respectively. Currents at I were somewhat more sustained than measured previously (Figure 3.2-15). Beginning in June, surface temperatures increased most rapidly at I and slowest at P. It is noted that there were some events in the channel where both I and O were flowing westward (e.g., October 11–19, 1993).

Coherence squared and phase differences for the summer 1993 alongshore velocities and wind are given in Figure 3.2-16. Currents at the three levels at P were again moderately coherent at periods longer than 5 days. The wind velocity was moderately coherent with the alongshore surface current velocity at about 5- to 7-day periods. This response is a little stronger than the 5-day coherence the previous summer. As before, the flows at I (45 m) were poorly correlated with those at P (53 m); however, there was moderate coherence with O (45 m) between 20- and 5-day periods. Phase differences were 120° to 180° which indicates that fluctuations at O and I were opposed. Surface and mid-depth, along-channel velocity components at O were highly correlated as they were for I in Figure 3.2-6. Thus, again, there appears to have been a disconnect between the channel and Pt. Arguello flows in summer although there was clearly a strong relation between inflows and outflows on the south (O) and north (I) sides of the channel, respectively.

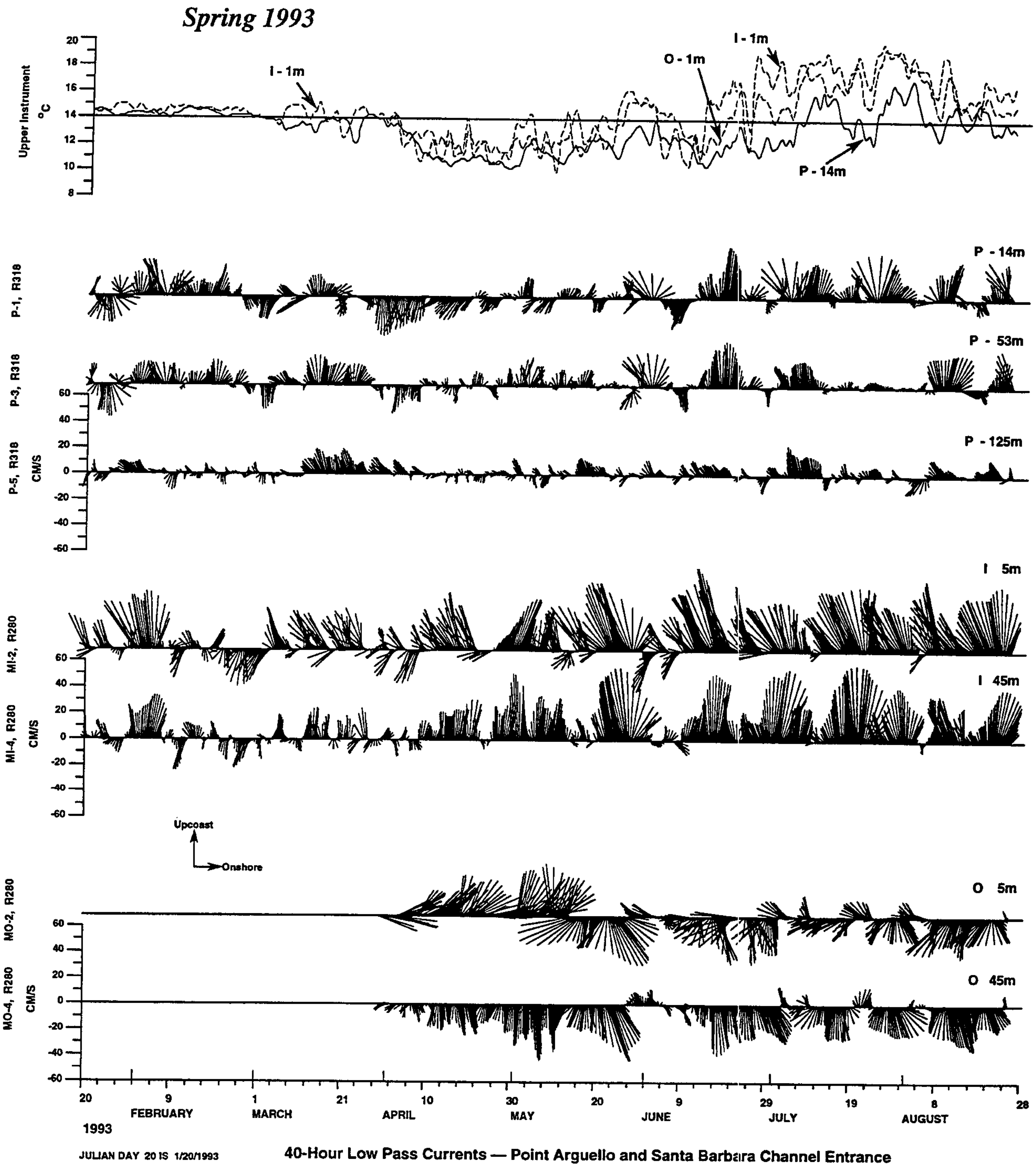
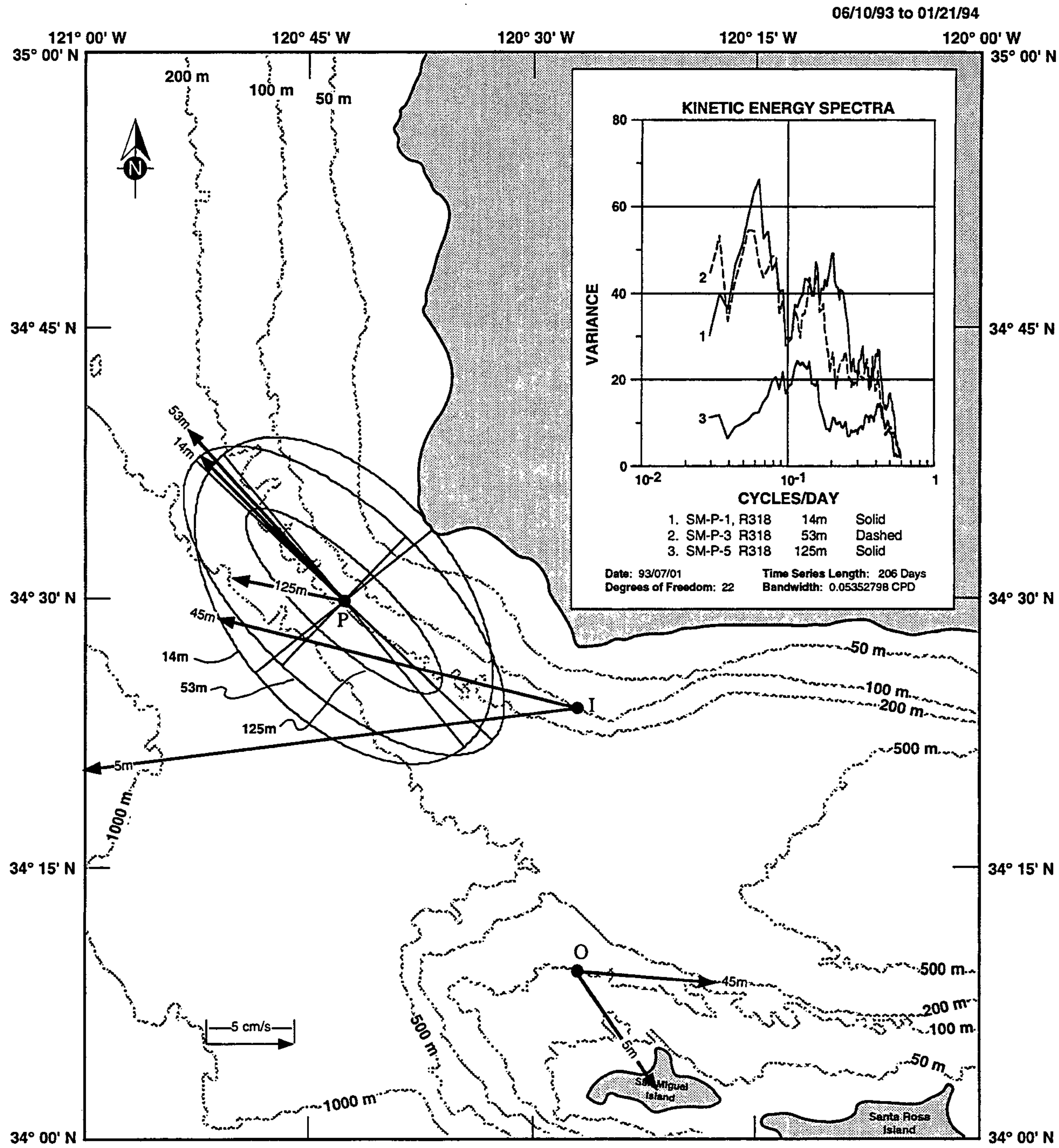



Figure 3.2-12. 40-HLP currents and near-surface temperatures (dashed – 1 m level at I and O, solid – 14 m level at P) for moorings I, O, and P.




**40-HLP Means and Variances, Summer-Winter 1993**

Figure 3.2-14. Summer-Winter 1993 40-HLP means and variances (P only). <u>Inset</u>: Kinetic Energy spectra in variance preserving form for P.

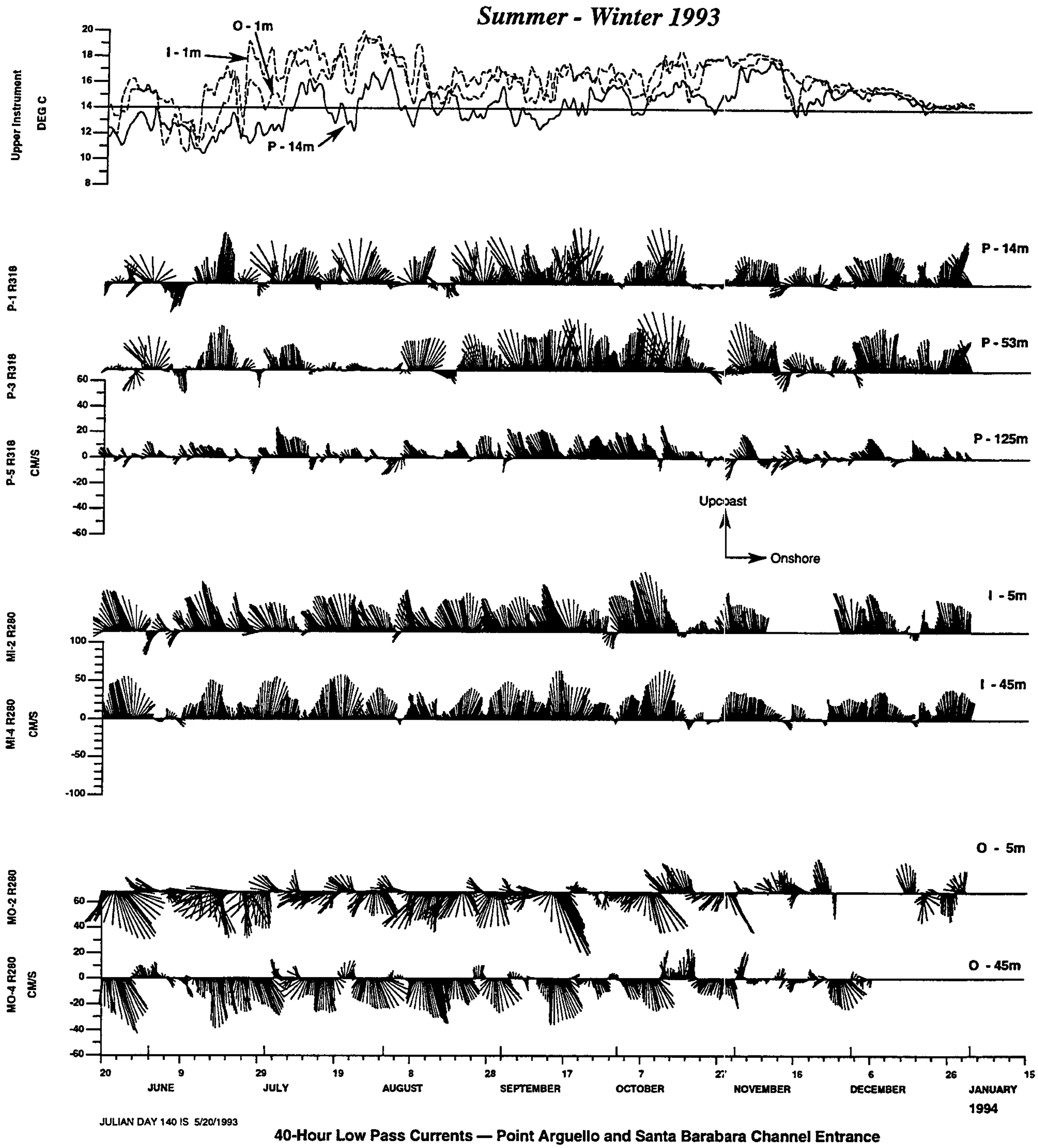



Figure 3.2-15. 40-HLP currents and near-surface temperatures (dashed – 1 m level at I and O, solid – 14 m level at P) for moorings I, O, and P.

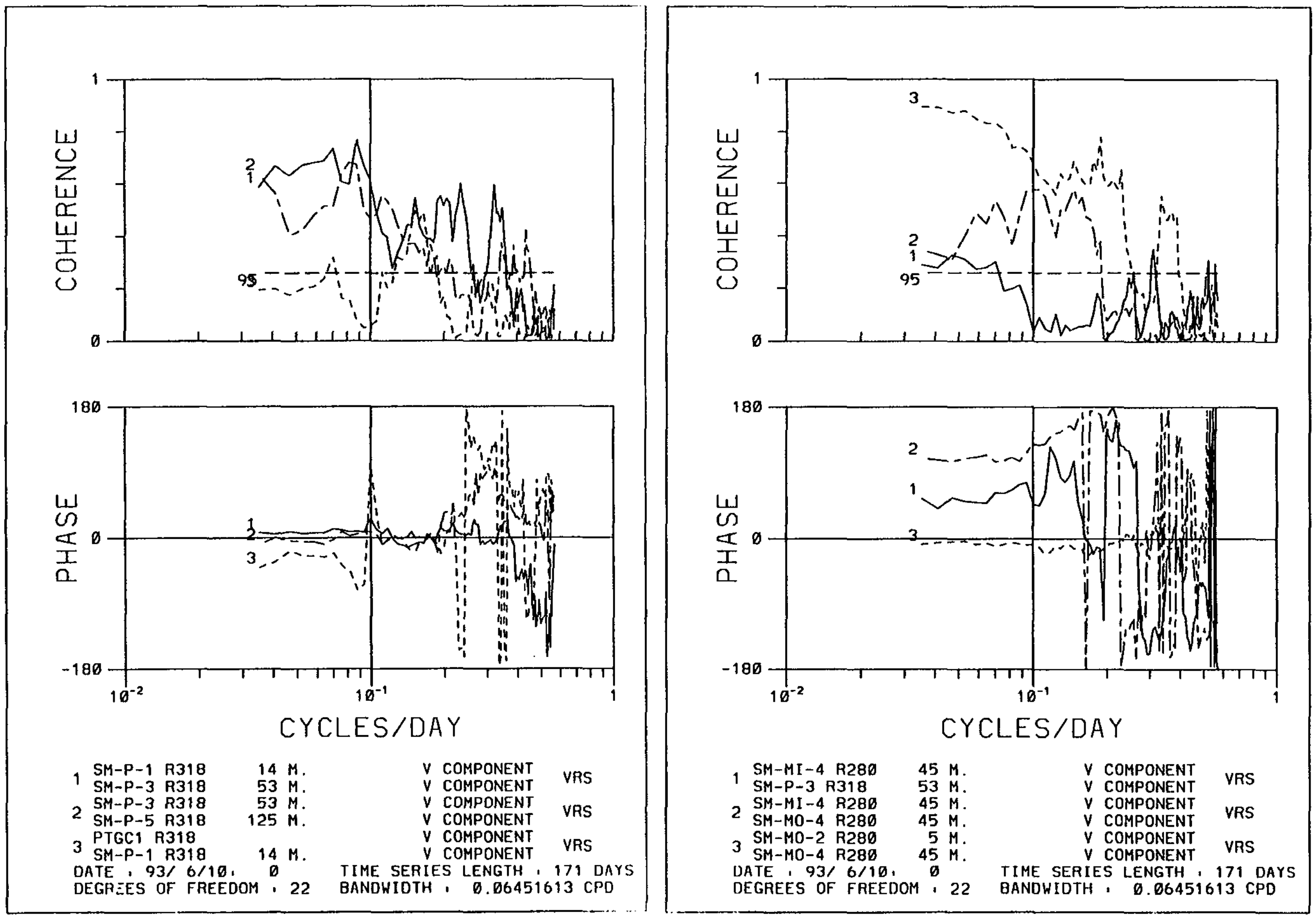


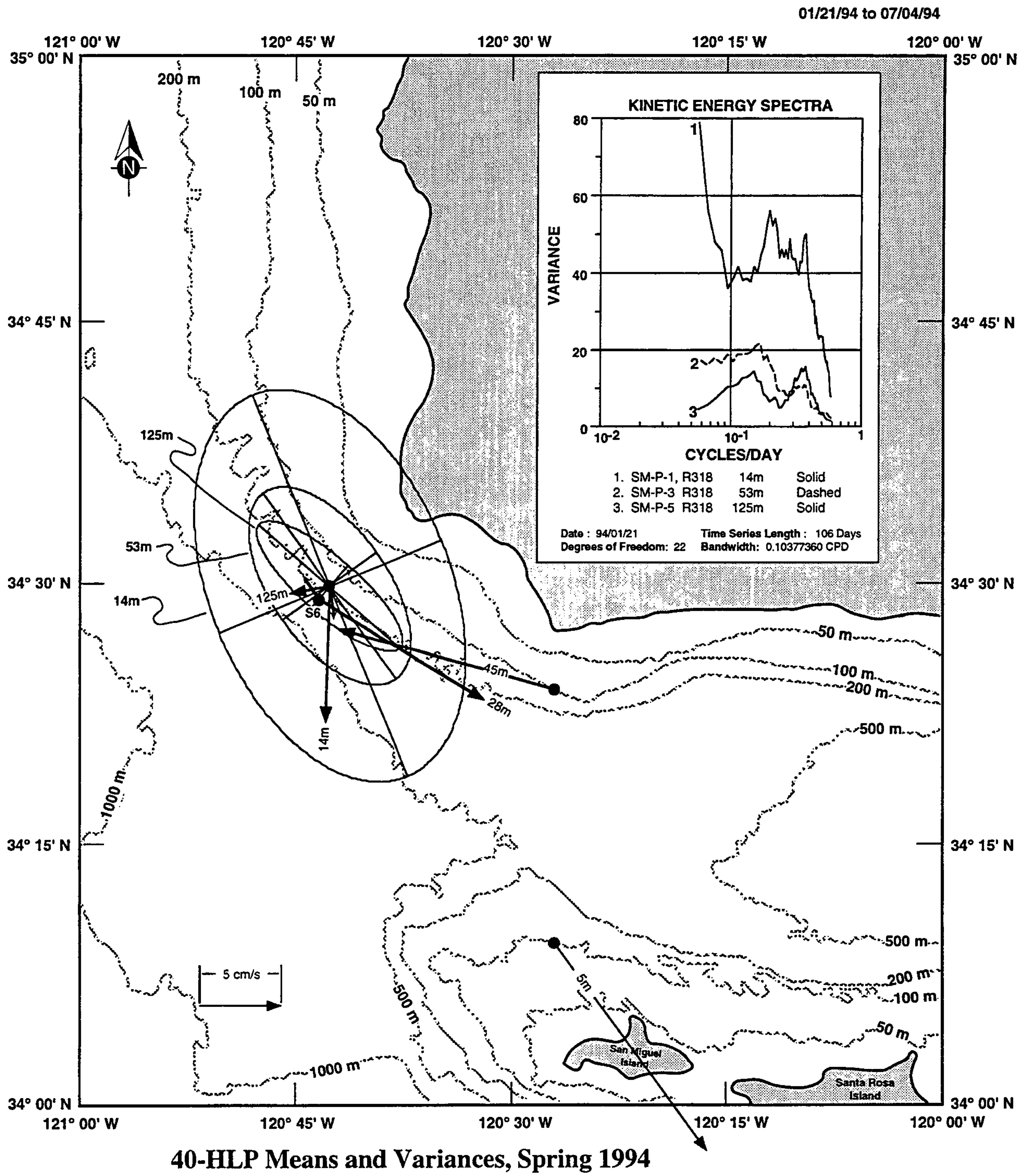

Figure 3.2-16. Coherence squared and phase differences for the indicated wind, P, I, and O records for Summer-Winter 1993.

### 3.2.3.5 Spring 1994

The spring 1994 season had strong similarities to spring 1992. The means, variances, and spectra are shown in Figure 3.2-17. The mean flow was convergent between I and P with strongest southward currents at the surface. The secondary mooring, S6 in 250 m water depth and only 2 km further offshore than P, had upper layer (28 m) currents that were much more parallel to local isobaths than at P. This implies further convergences between Pt. Arguello and Pt. Conception. Examination shows that the time series of current vectors (Figure 3.2-18) have some similarities between the 14 m and 28 m levels on P and S6, respectively, particularly for the large southward event in April. However, even during this event, occasional large offshore flows at P occurred which were not seen in the southward flows at S6. Also noteworthy is the general tendency of the 28 m flows at S6 to have been southward more often.

In the first part of January, before the start of the spring 1994 season at P, flows were southward at S6 and northward at P. This is a good indication that flow characteristics changed rapidly with distance offshore of Pt. Arguello, and that the transition between southward flowing and northward flowing water can occur over a very short distance. This result also implies that the determination of the length of the seasons based on current characteristics (as done for P) may be dependent on the location of the mooring. This is noted in the discussions of the currents at moorings I and O. A distinct spring regime was noted at I and to a lesser extent at O in 1994 (Figure 3.2-19). It began around January 21, as at P, and was characterized by weaker and more variable flow than in the summer. However, it only lasted until mid-May when strong westward flows became established at I, with P still having weak variable currents.

This variability is reflected in the spectra (Figure 3.2-17) which show most of the energy at periods of less than 10 days. The coherence squared and phase differences between the various alongshore current components are given in Figure 3.2-20. The upper level records at P and S6 are not significantly coherent except at long periods (>20 days). However, the 125 m level records are highly coherent at all frequencies. This is a further indication that the surface layer flows changed characteristics between P and S6. Longshore winds were moderately coherent with P1 at periods between 2.5 and 7 days which is similar to the previous springs. The relationship of the Pt. Arguello alongshore currents to those in the channel also had similarities. P and I were moderately coherent at periods shorter than 10 days. Moorings I and S6, and I and O were not significantly coherent except at isolated frequencies (Figure 3.2-20). Mooring O also was not coherent with S6 except for an isolated peak at 5-day periods (not shown). Thus, again it was evident that there was a relationship between the reduction of southward flows at P with outflows from the channel at I during the spring regime. Surface flow at S6, only a little further offshore, was not part of this regime.




**40-HLP Means and Variances, Spring 1994**

Figure 3.2-17. Spring 1994 40-HLP means and variances (P only). Inset: Kinetic Energy spectra in variance preserving form for P.

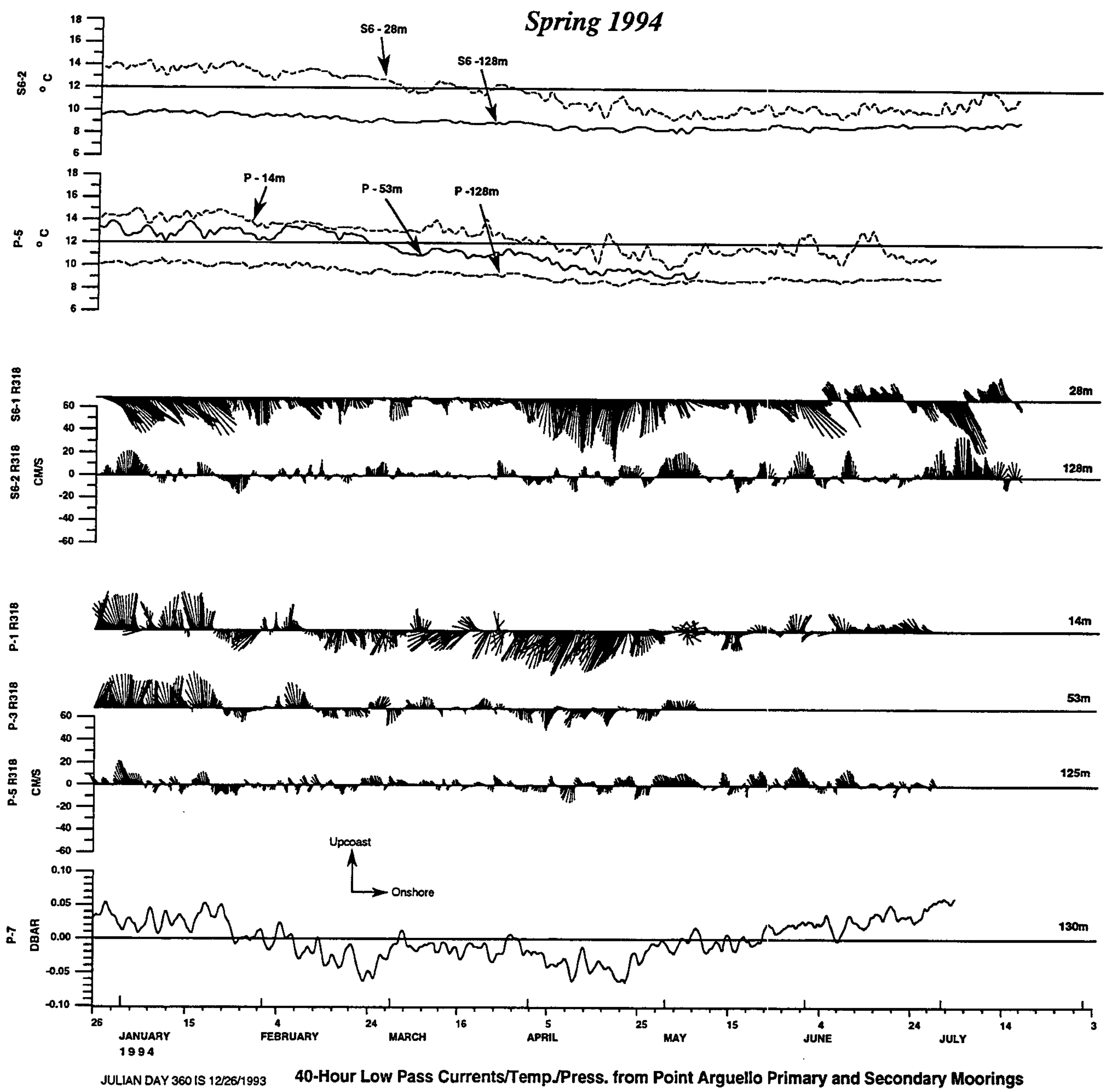



Figure 3.2-18. 40-HLP currents, temperatures (solid – 53 m level at P and 128 m level at S6) and pressure for moorings P and S6.

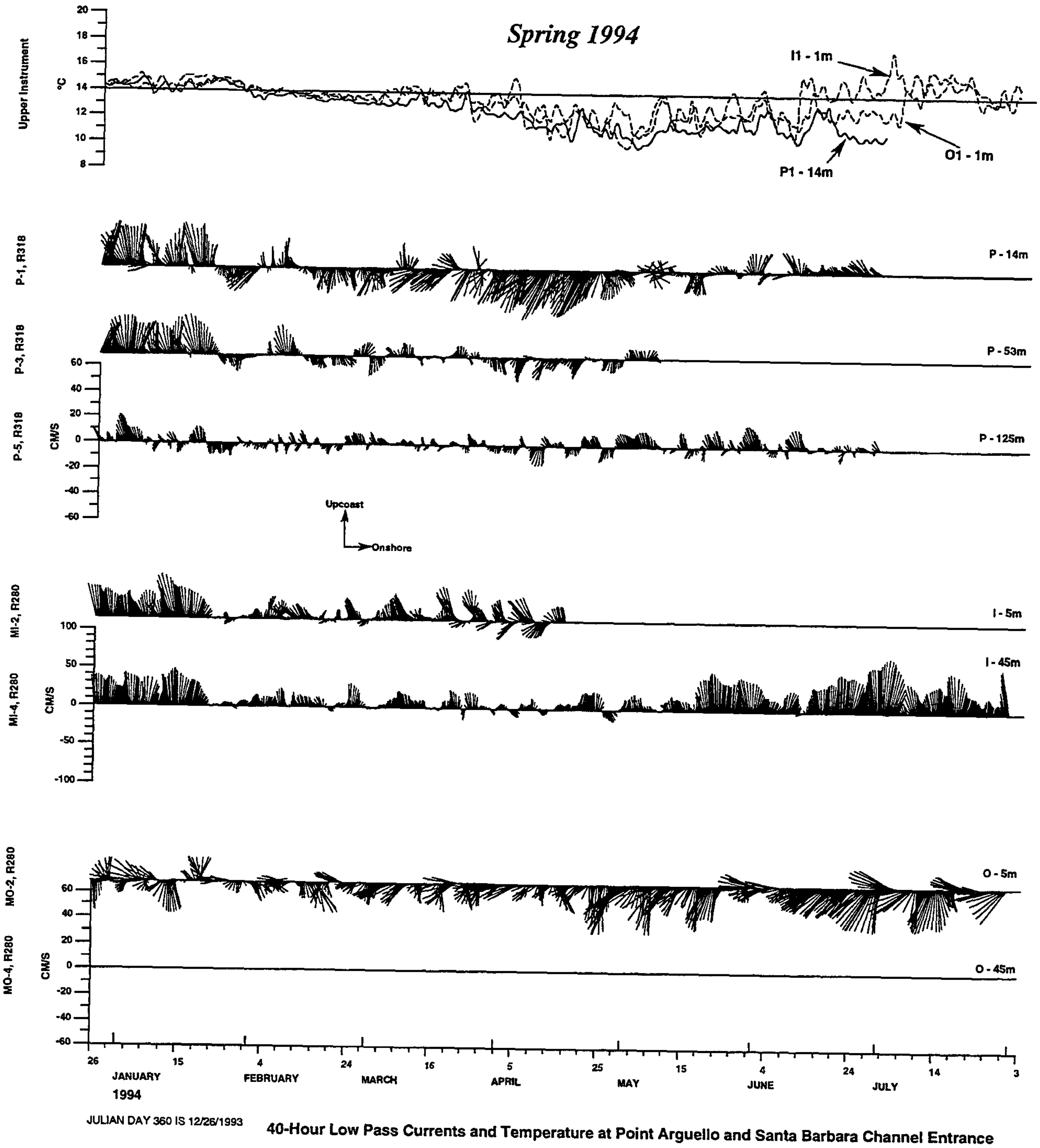



Figure 3.2-19. 40-HLP currents and near-surface temperatures (dashed – 1 m level at I and O, solid – 14 m level at P) for moorings I, O, and P.

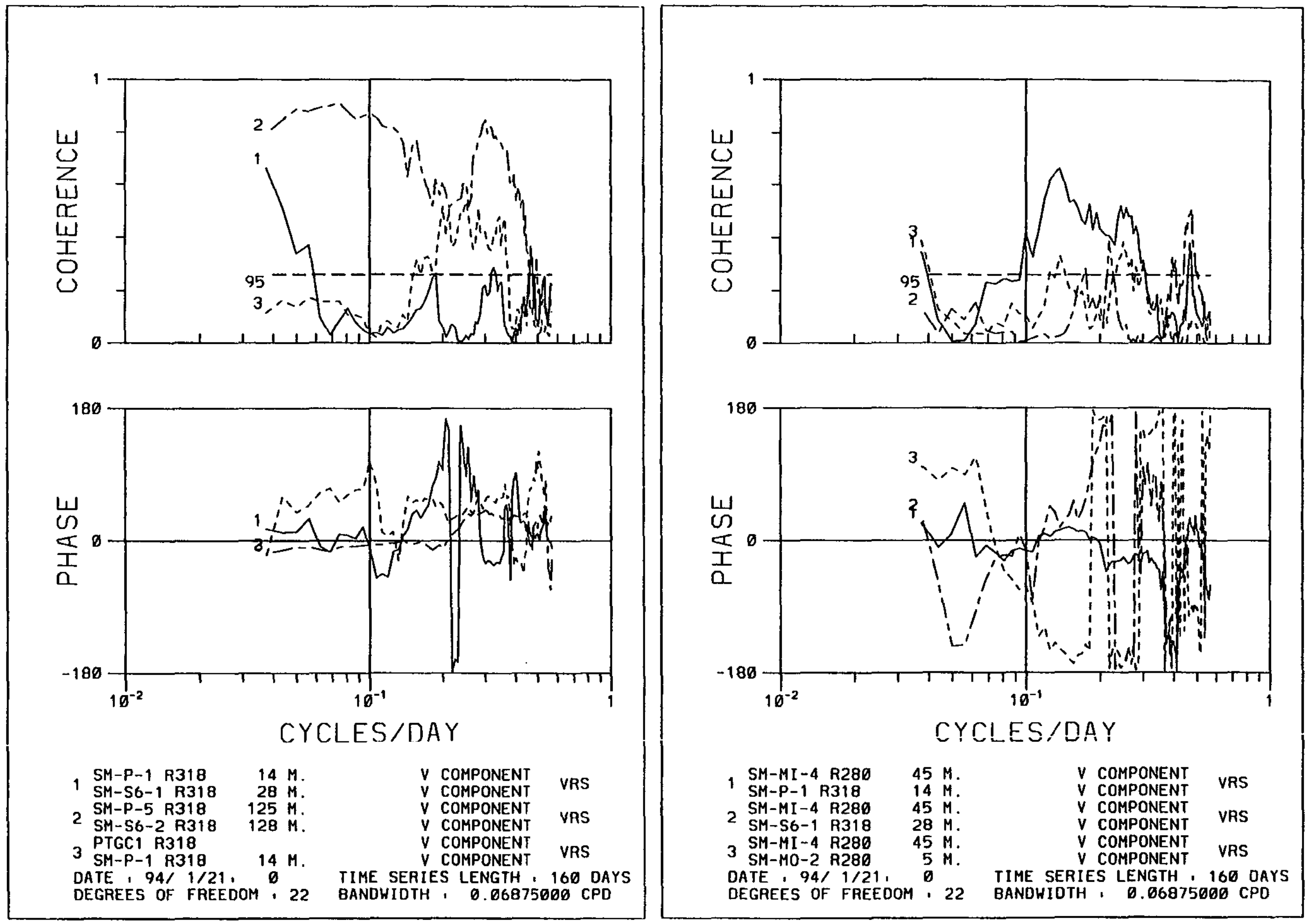



Figure 3.2-20. Coherence squared and phase differences for the indicated wind, P, S6, I, and O records for Spring 1994.

### 3.2.3.6 Total Statistics

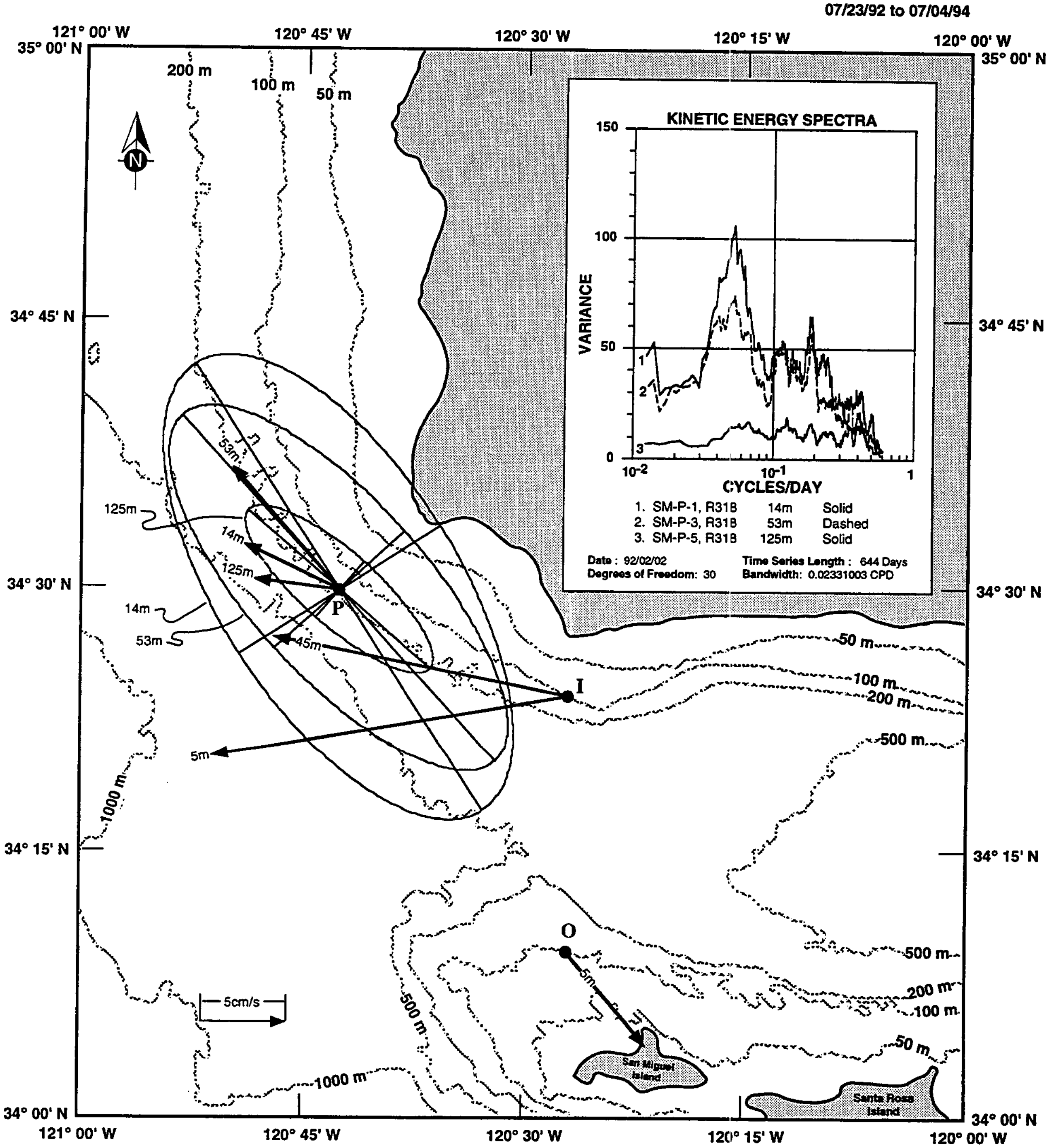
Statistics for the two year interval from July 1992 to July 1994 and incorporating two spring and two summer-winter regimes, are dominated by the summer-winter results because of the vigor of the poleward flows and the longer length of this season as compared to spring (Figure 3.2-21). The spectra clearly show a dominant peak at 20 days that has also been identified in the Southern California Bight (Hickey 1992) and a band of energetic frequencies between 4 and 10 days.

Results of coherence analysis for the various periods and moorings indicate that currents measured on moorings onshore of P (S2, S3, and S4) were highly coherent with records at the same depths. The one offshore mooring, S6, showed no coherence for the upper level but high coherence for the lower level. This, however, may only apply in spring and the results may be different for summer and winter. On the same isobath, P and S1 (7 km to the northwest) and S5 (5 km to the southeast) were also highly coherent in both seasons (S1 in spring, S5 in winter). However, at 28 km from P, I showed moderate coherence in spring at periods shorter than 7 to 10 days and poor coherence for the summer-winter regime.

Coherence squared and phase differences for the longest common records from P and I, including pressure from P7 and I6 are shown in Figure 3.2-22. The pressure records were highly coherent at all frequencies with phase differences not significantly different from zero. Longshore winds were moderately coherent with pressure and surface longshore currents at P. Apart from a very low frequency coherence, peak coherences were similar with the 20-, 7-, and 5-day periods being noteworthy. Currents at I (45 m) were much less coherent with the pressure record except at very low frequencies (>60-day period). However, P and I currents did show moderate coherence at periods longer than 20 days and 7 days with I leading P at all coherent frequencies. This is consistent with the poleward propagation of continental shelf waves. This result indicates that there were complex connections between Pt. Arguello and the outflow from the channel, but these were restricted to specific frequency bands.

## 3.2.4 Tides

Tidal analysis of the pressure gauge record from the primary and Inner SBC moorings indicated mixed diurnal and semi-diurnal features that are characteristic of the west coast. The amplitudes and phases of the principal constituents are summarized in Table 3.2-1. These data indicate that the $M_2$ and $K_1/O_1$ constituents had very similar amplitudes and that there is little difference in amplitudes and phases between moorings I and P. The constituents at I lead slightly over P which is consistent with northwards propagation of the tidal waves along the continental margin. Tidal analyses of the $M_2$ and $K_1$ currents are presented in the form of hodographs (ellipses) in Figures 3.2-23 and 3.2-24, respectively. The ellipses trace out the end of the tidal current vector




**40-HLP Means and Variances, 1992 - 1994**

Figure 3.2-21. 1992-1994 40-HLP means and variances (P only). Inset: Kinetic Energy spectra in variance preserving form for P.

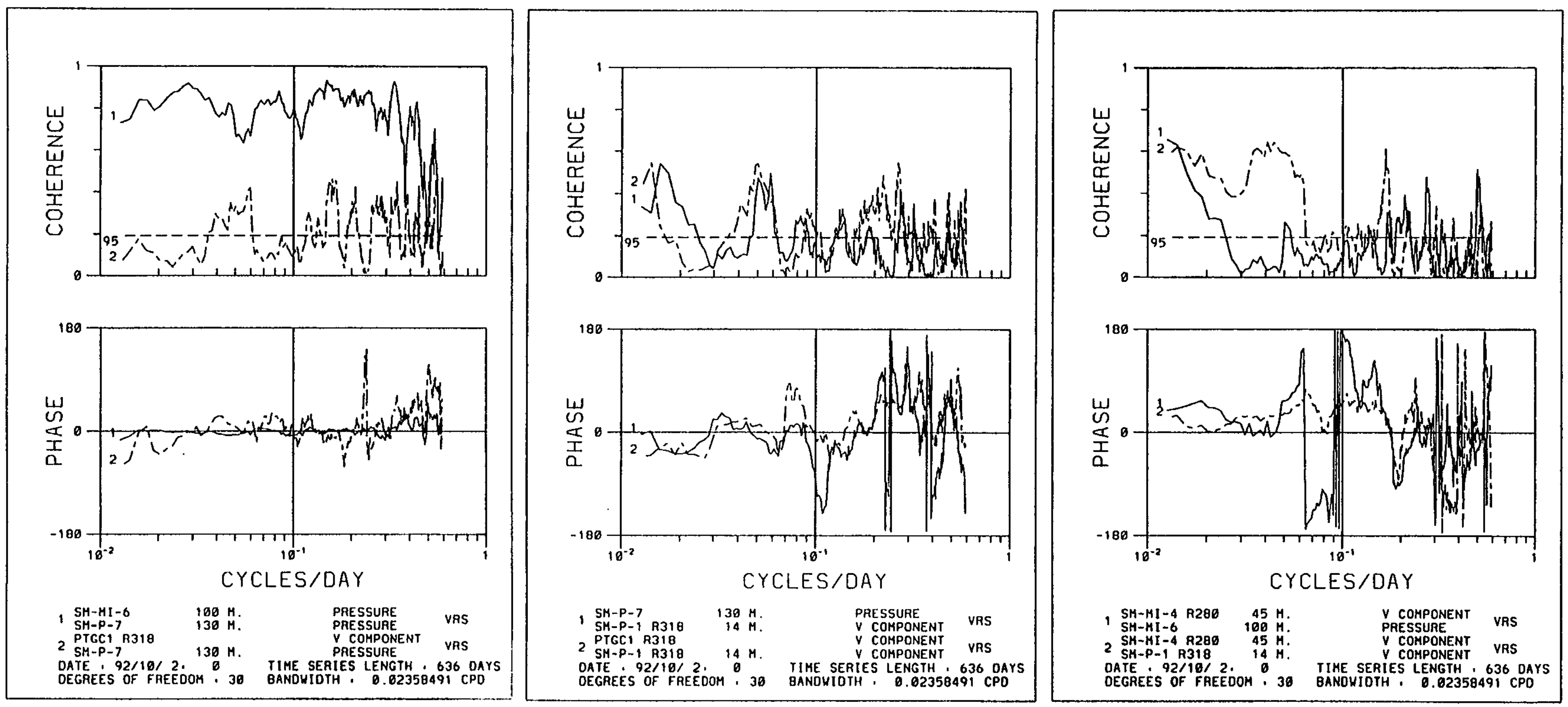



Figure 3.2-22. Coherence squared and phase differences for the indicated pressure, alongshore current (V) and wind records from P and I for 1992-1994.

Table 3.2-1. Tidal height analysis of the pressure gauge record at the Primary mooring (P7) and SBC (I6) locations, October 1, 1992 through October 1, 1993.

| Constituent | Period (hours) | Amplitude (cm) | | Greenwich Phase | |
|---|---|---|---|---|---|
| | | P7 | I6 | P7 | I6 |
| $M_2$ | 12.421 | 46.0 | 48.0 | 158° | 159° |
| $N_2$ | 12.658 | 10.7 | 11.2 | 131° | 134° |
| $S_2$ | 12.000 | 15.6 | 16.6 | 153° | 154° |
| $K_1$ | 23.934 | 34.8 | 34.9 | 211° | 212° |
| $P_1$ | 24.066 | 11.0 | 11.0 | 207° | 209° |
| $O_1$ | 25.819 | 21.8 | 22.1 | 196° | 197° |

through the specified tidal period. The $M_2$ ellipses at P had amplitudes of approximately 3 cm/s, were rectilinear, and were directed at slight angles to the isobaths. The tidal currents were in-phase through the depth range and with the tidal heights. Thus, the $M_2$ tide at the primary mooring had the characteristics of a pure barotropic progressive wave. In contrast, at the secondary mooring, during the first deployment, the amplitudes were larger at the surface and bottom, and there was a 90° phase shift between the amplified (~7 cm/s) bottom $M_2$ tidal currents and mid-depth. The inclination of the major axes of the ellipses was also directed across the isobaths, particularly at the bottom. This implied that active internal tide generation had occurred at the secondary mooring but not at the primary mooring. A steeper bottom slope at the secondary mooring may have accounted for this pattern.

The $K_1$ ellipses (Figure 3.2-24) were not as consistent as those for $M_2$, but the currents were generally weaker (~2 cm/s) and decayed with depth. The major axes tended to be more aligned with the isobaths, and phase differences between currents and elevations suggest a mixed standing and progressive wave. Internal tides were not generated at diurnal frequencies because internal waves were not supported at periods longer than the inertial period. The $M_2$ and $K_1$ current ellipses were calculated for the upper and mid-depth instruments for the S5, S3, O, and I moorings (Figure 3.2-25). The secondary moorings have similar characteristics to the primary with no indication of any amplification or substantial phase differences with depth. At I, in the SBC, the tidal flows are larger than at P and more parallel to the isobaths. The $M_2$ flows have little depth variation between the near-surface and mid-depth. Maximum flood and ebb currents precede slightly those at P, also indicating the northward propagation of a progressive $M_2$ tidal wave. Tidal flows at O on the south side of the channel entrance are also vigorous, particularly

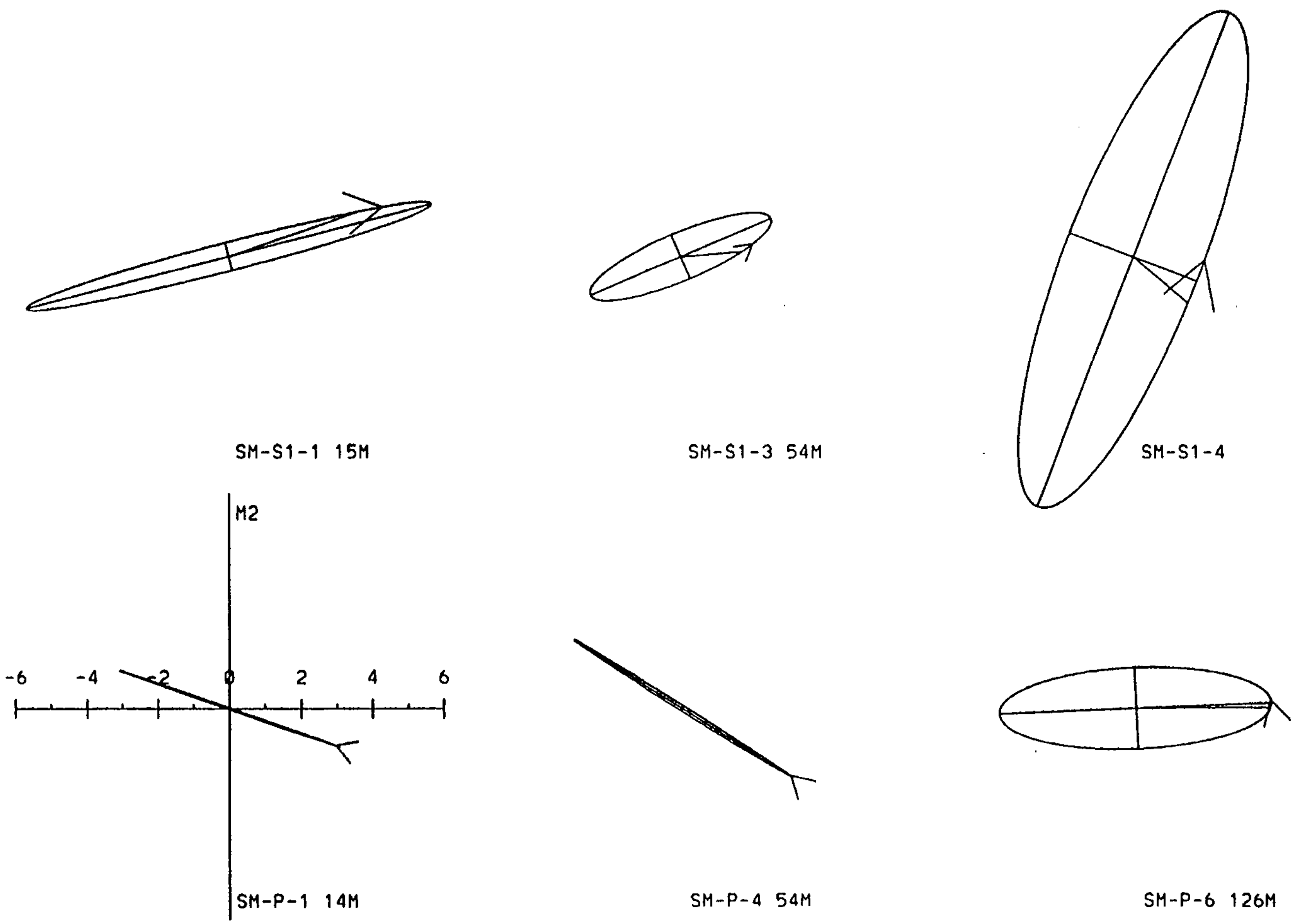



Figure 3.2-23. Tidal ellipses for the semi-diurnal lunar tide ($M_2$) for the indicated instrument locations.

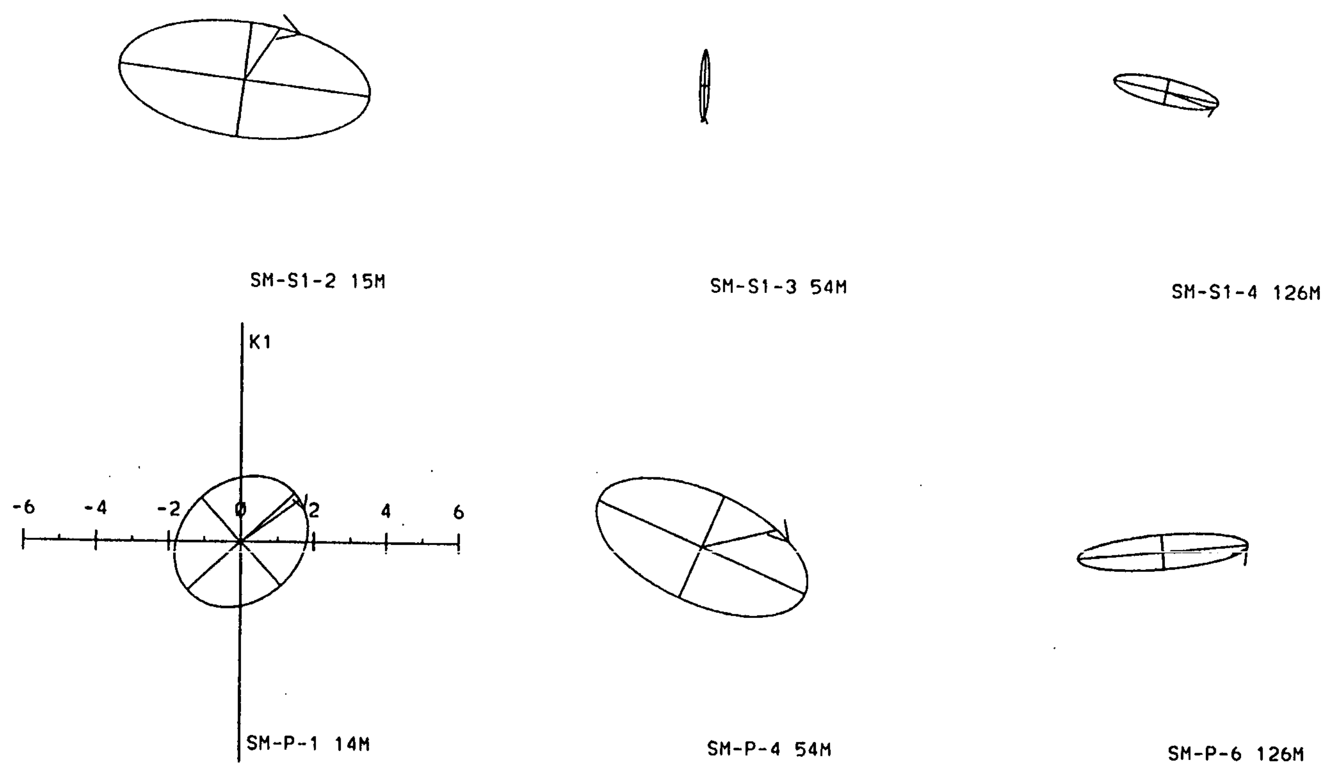



Figure 3.2-24. Tidal ellipses for the luni-solar diurnal tide ($K_1$) for the indicated instrument locations.

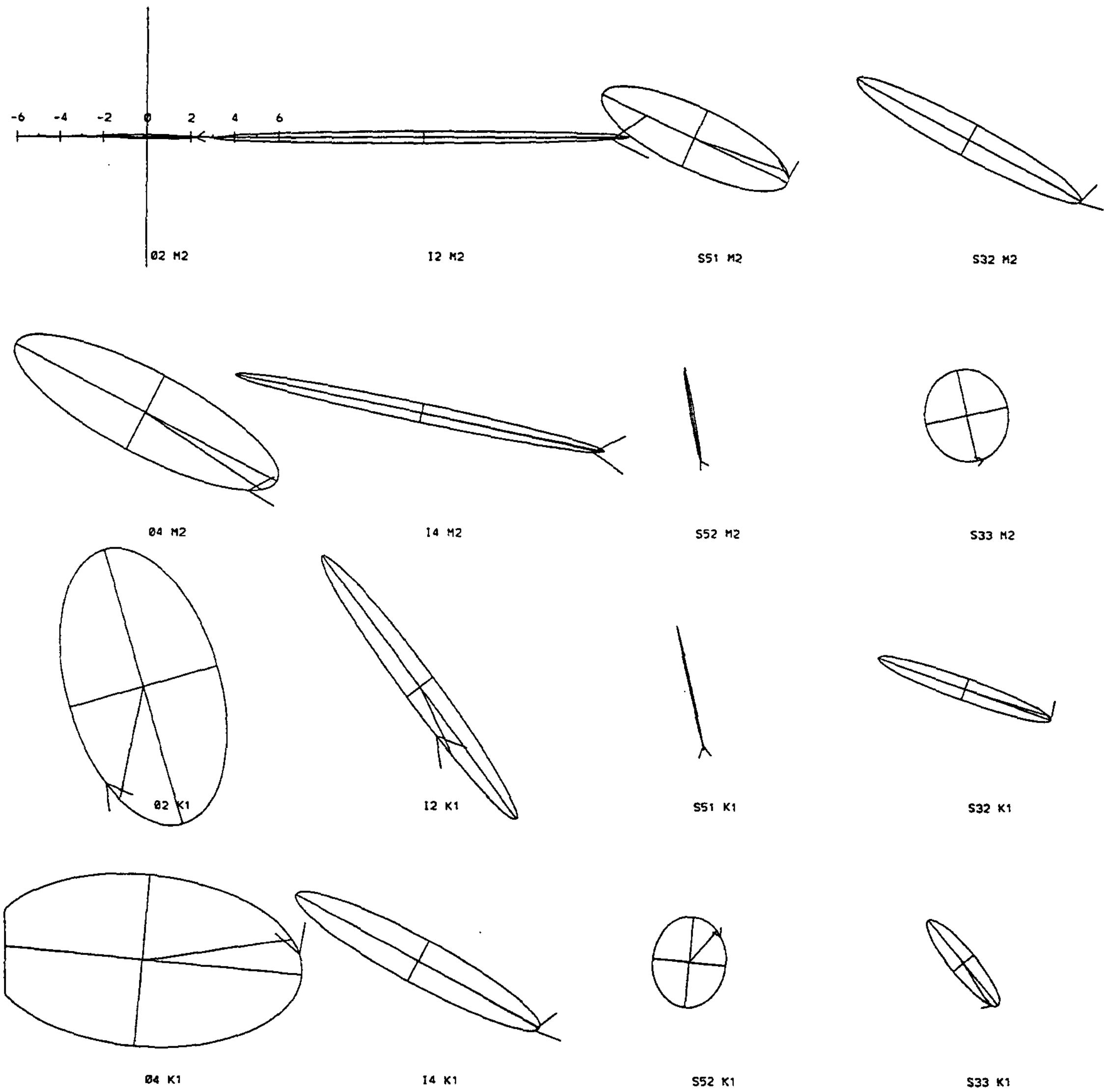



Figure 3.2-25. $M_2$ and $K_1$ tidal ellipses for moorings O, I, S5, and S3.

for the $K_1$. There is a noticeable reduction of the $M_2$ amplitudes at the near-surface compared to mid-depth. The reason for this is unclear.

# 3.3 NEAR-BOTTOM CURRENTS AND SEDIMENT DYNAMICS

## 3.3.1 Introduction

Evaluation of the influence of drilling mud discharges on the marine biological system in the Santa Maria Basin requires an understanding of the ambient sediment transport field including both average background characteristics and the effects of aperiodic storm events. Previous investigations have detailed regional surficial sedimentology and selected aspects of the suspended material field in the area (Steinhauer and Imamura 1990) but provided relatively limited time series data and essentially no field observations detailing storm response. In an effort to obtain these data, a field experimental program that placed primary emphasis on the characteristics of the near-bottom suspended material field in the vicinity of Platform Hidalgo was initiated in April 1992.

## 3.3.2 Near-Bottom Hydrographic Charateristics

### 3.3.2.1 Deployment 1 (18 April 1992 – 17 October 1992)

As noted in Section 2.1.6, there was an apparent bias in the velocity records for Deployments 1 and 2. Therefore, analysis of the near-bottom hydrographic characteristics for these deployments focuses on the tidal regime and the density field. The velocity data from these deployments are appropriate to provide qualitative evaluations of short-term perturbations, including the passage of high energy storm events or anomalously high river discharge.

The near-bottom pressure observations during Deployment 1 show periodicity in sea level at both the Nearfield and Farfield stations (Figures 3.3-1 and 3.3-2). Spectral analysis of these data indicates dominant periods of approximately 12 and 24 hours coincident with the principal semi-diurnal lunar ($M_2$) and diurnal luni-solar ($K_1$) components of the astronomical tide (Figure 3.3-3). Tidal ranges in the area display a monthly cycle with values varying from more than 2 m during spring tides to less than 1m during neap tides. In addition to these higher frequency components, the time series show longer term variability most probably associated with regional meteorological forcing and/or some large scale, Farfield effects. Reviews of the meteorological data from CMAN Station PTGC1 located near Pt. Conception indicate that the winds during Deployment 1 were predominantly from the north with average hourly maxima of approximately 15 m/s (Figures 3.3-4 and 3.3-5). The system is evidently energetic with relatively few extended

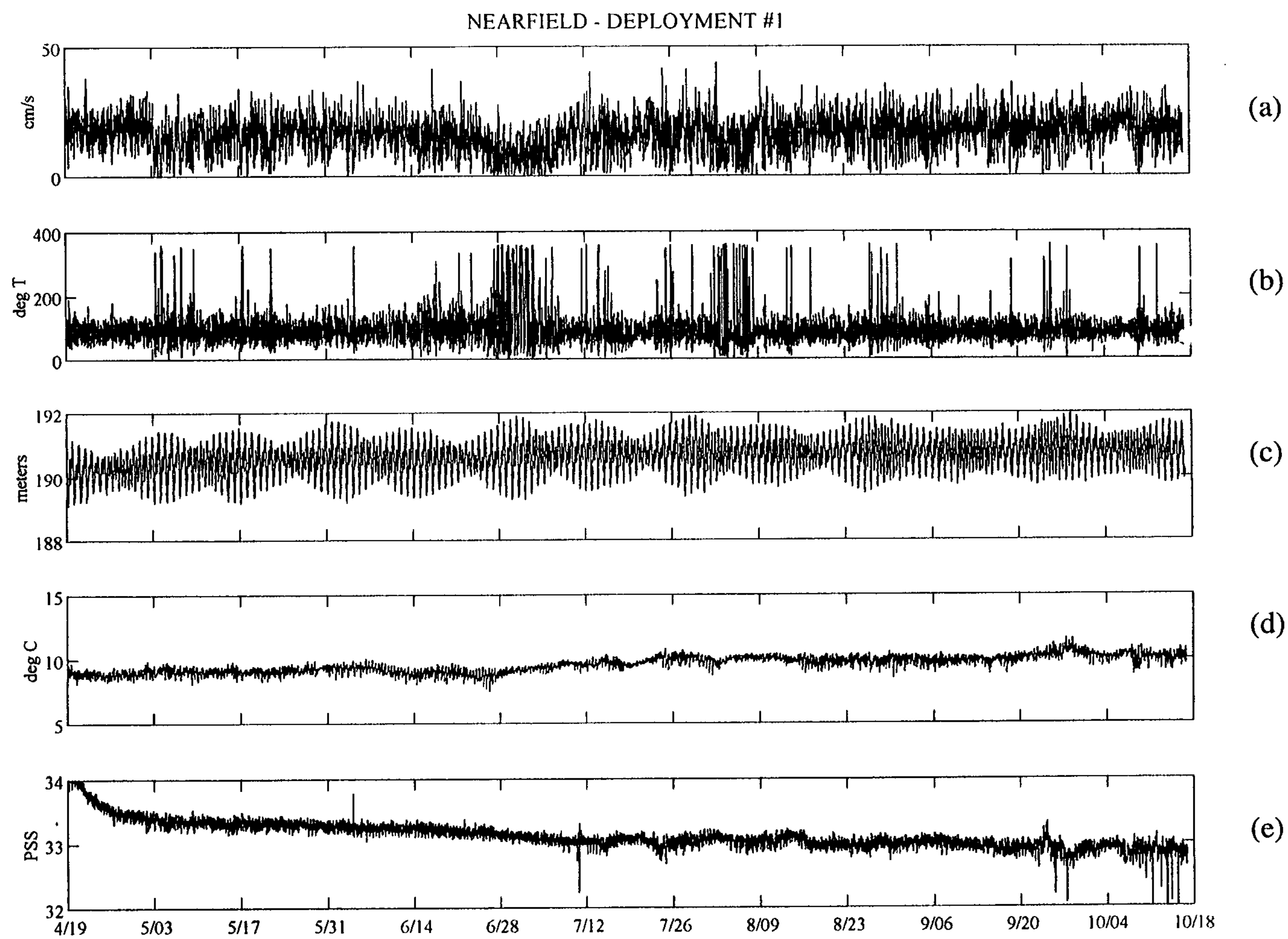



Figure 3.3-1. Time series observations from Nearfield station for Deployment 1: (a) near-bottom current speed, (b) near-bottom current direction, (c) hydrostatic pressure, (d) water temperature, and (e) salinity (practical salinity scale).

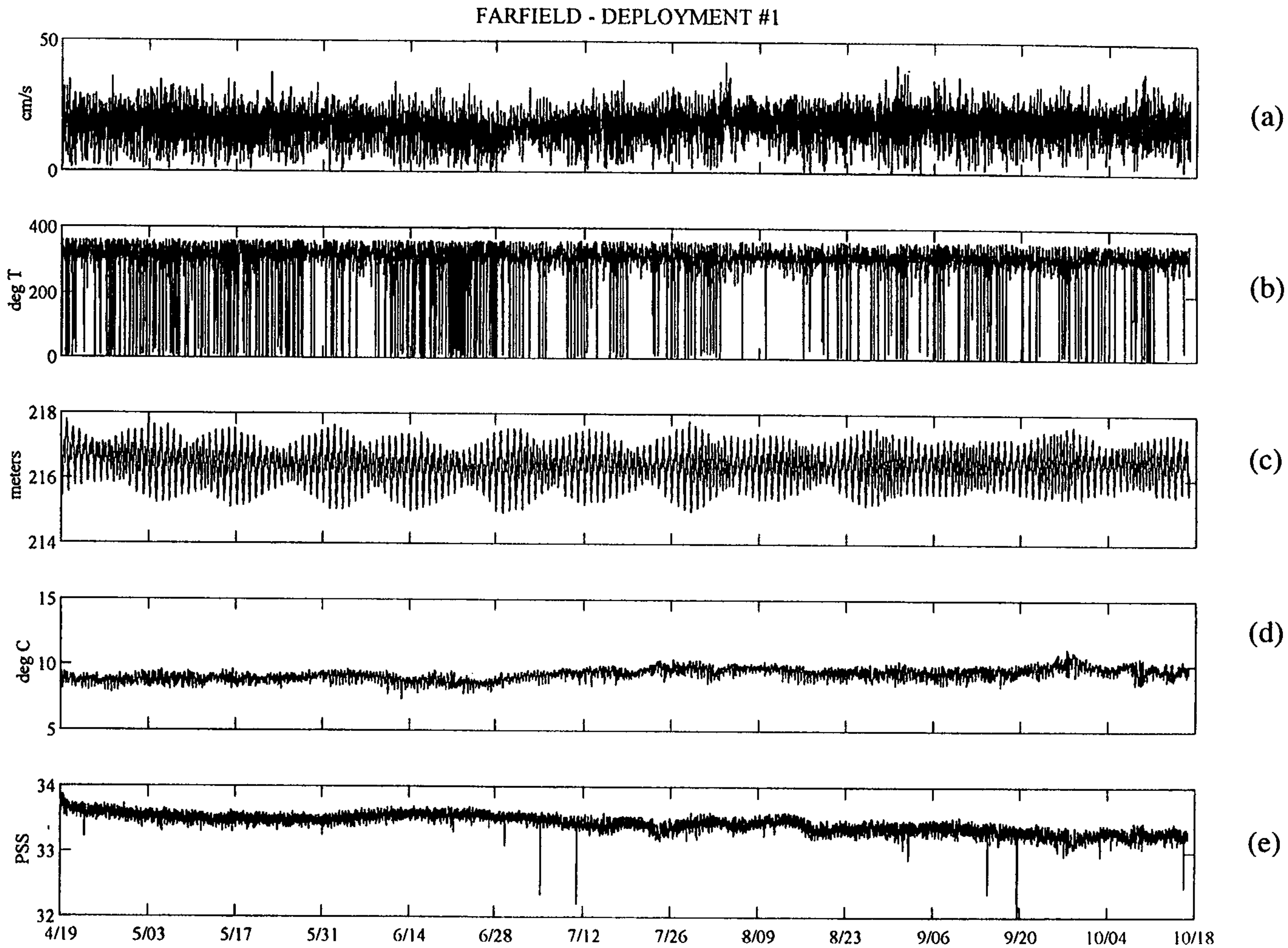
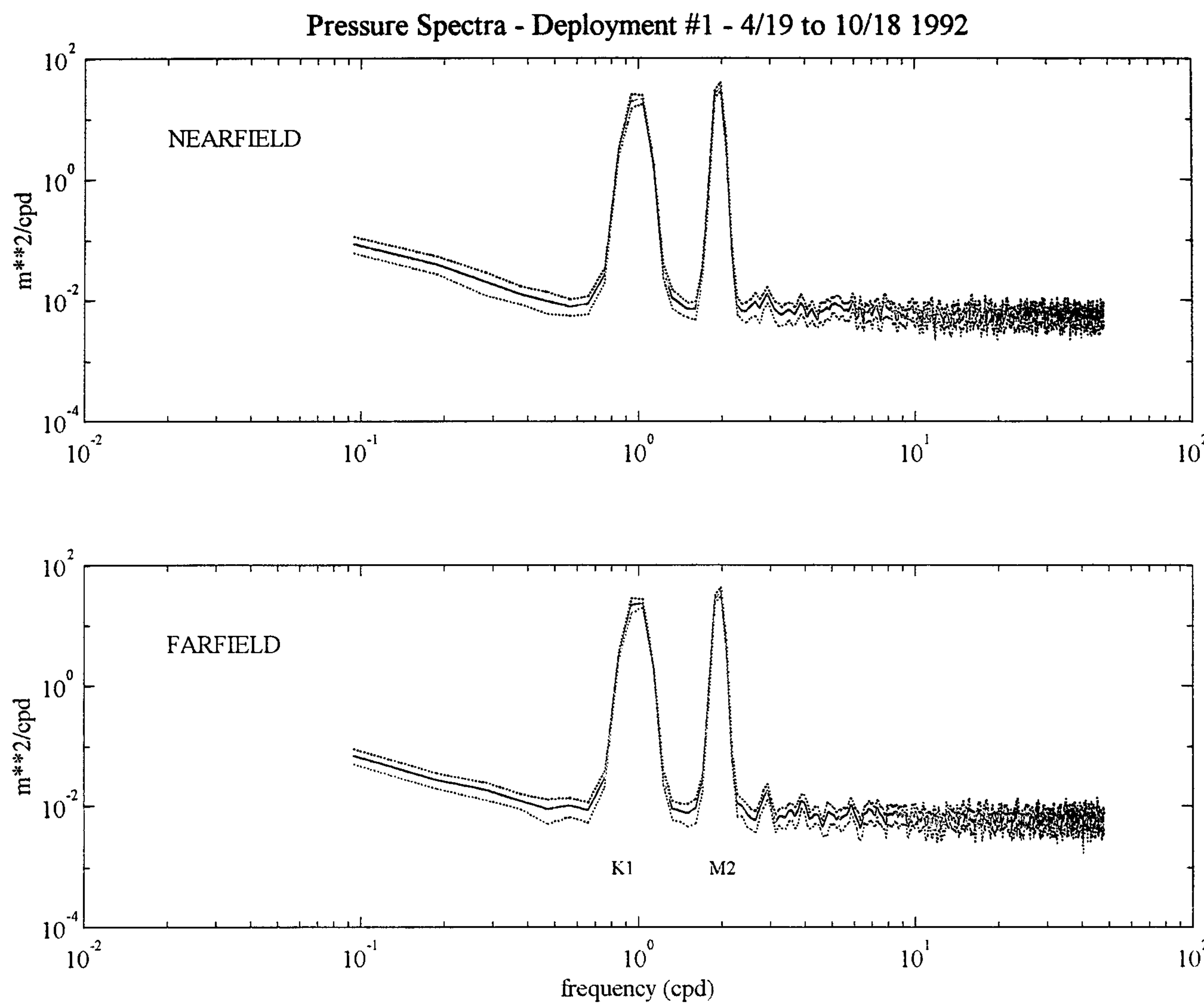



Figure 3.3-2. Time series observations from Farfield station for Deployment 1: (a) near-bottom current speed, (b) near-bottom current direction, (c) hydrostatic pressure, (d) water temperature, and (e) salinity (practical salinity scale).




dashed lines delimit the 95% confidence interval
record length = 181 days
degrees of freedom = 32
bandwidth = 0.09375 cpd

Figure 3.3-3. Spectral analysis of near-bottom hydrostatic pressure for Deployment 1.

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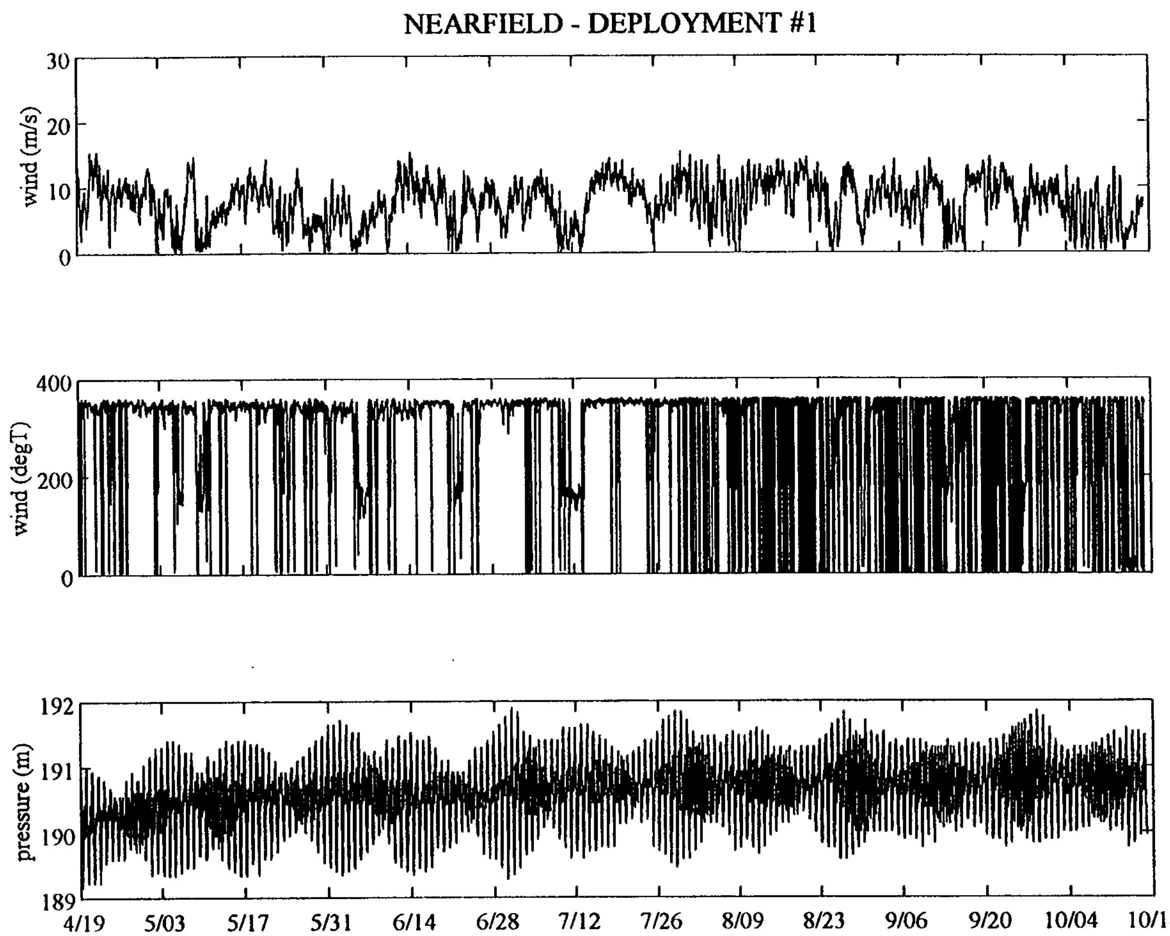


Figure 3.3-4. Meteorological observations from CMAN station PTGC1 and concurrent near-bottom hydrostatic pressure from Nearfield station for Deployment 1.

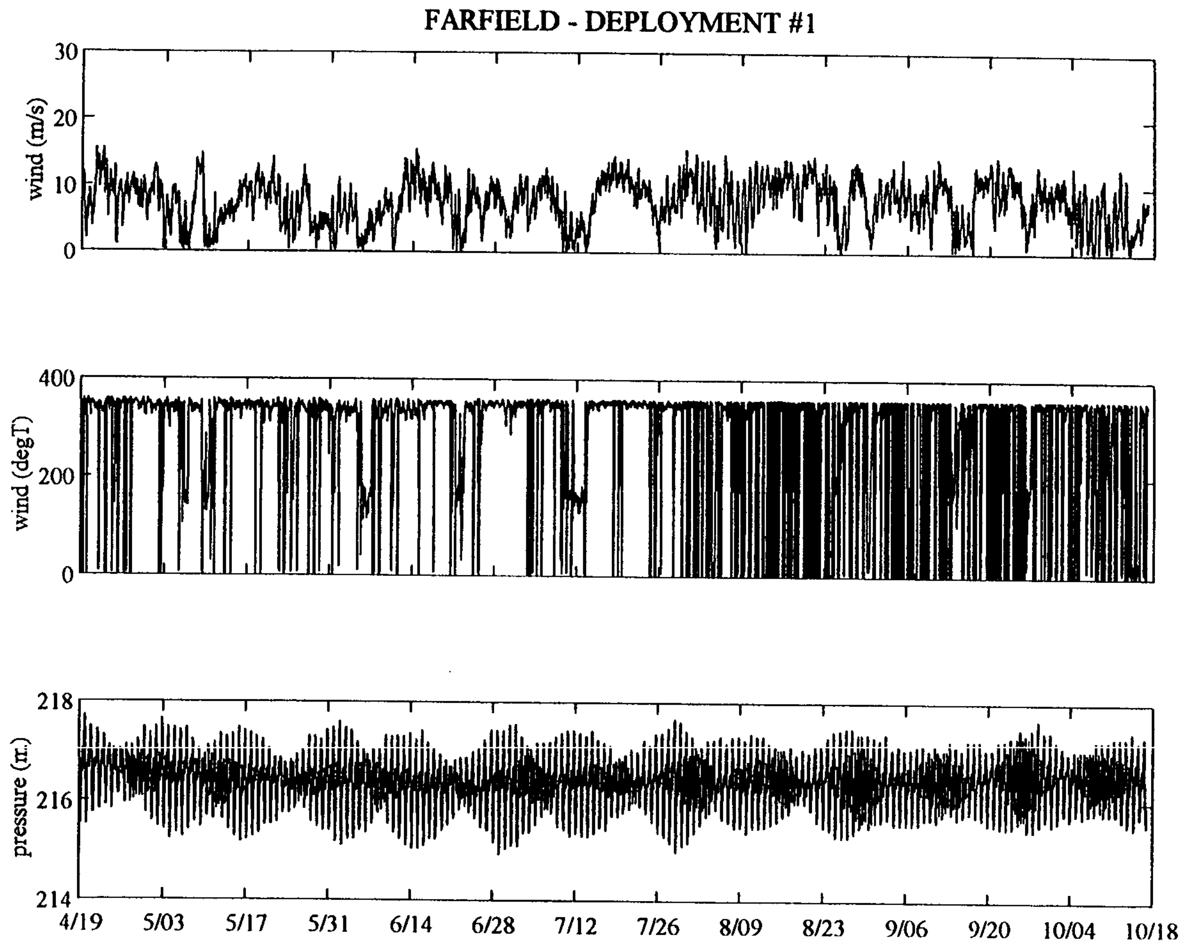


Figure 3.3-5. Meteorological observations from CMAN station PTGC1 and concurrent near-bottom hydrostatic pressure from Farfield station for Deployment 1.

periods of near calm conditions (i.e., winds less than 5 m/s). Against this persistent high energy background, short term perturbations in the wind field, such as those observed on or about May 6, 1992 and August 25, 1992, produce finite but small amplitude variations in tidal range and slight readjustments in phasing. Simple cause and effect relationships associated with these perturbations are difficult to establish due to the unconfined nature of the system and the resulting potential for influence from both local and Farfield factors.

Examination of the qualitative character of the current meter record indicates that high energy wind events may alter both flow speed and direction patterns. The event of May 6, 1992, for example, apparently resulted in a marked reduction in near-bottom speeds and a shift in dominant flow direction at the Nearfield station (Figures 3.3-1 and 3.3-4). Variations in the flow pattern are also evident around June 28 and August 9, 1992 although the correlation with wind speed conditions is less evident. The data suggest that local wind events may cause an adjustment in near-bottom circulation patterns in the vicinity of the Nearfield station.

Reviews of the Farfield flow data provide only a limited indication of wind associated perturbations. In common with the Nearfield station, variations in flow patterns are evident around June 28 and August 9, 1992. However, the character of this pattern shift differs substantially from that observed at Nearfield. At this latter station, the flow variations consisted of a reduction in speed and a shift in dominant direction. The Farfield variations consisted primarily of a reduction in flow variability with a minimal change in direction. In addition to these differences, the current meter record from Farfield displays no pattern shift on or about May 6, 1992. The cause(s) for the apparent differences in the response of the Farfield flow regime, as compared to that observed at Nearfield is unknown. It may be the result of differences in water depth or instrument artifacts associated with the frame induced bias.

In common with pressure and velocity, near-bottom water temperatures and salinities varied over a variety of temporal scales (Figures 3.3-1 and 3.3-2). Records from both stations display diurnal variations in temperature and salinity of approximately 0.5° C and 0.25 psu, respectively. These variations appear to be dominated by a combination of tidal factors and short-term variations in air temperature. The presence of these latter variations is consistent with the relatively high energy wave field in the area and suggests that the local water column was reasonably well mixed over the vertical, at least in certain seasons. Beyond these high frequency fluctuations, water temperatures and salinities at both stations displayed a variety of lower frequency variations and some slight spatial variability. Water temperatures at the Farfield station were slightly less, and salinities slightly more, than those observed at Nearfield. These differences appear to be primarily the result of the slight difference in water depths at the two stations with a possible secondary influence associated with the complex bathymetry in the vicinity of the Farfield station.

Consistent with local seasonal characteristics, average water temperatures at both stations increased progressively over the period of deployment from approximately 8.5–9.0° C in April to 10–11° C in October (Figures 3.3-1 and 3.3-2). This upward trend was interrupted on several occasions, with a particularly evident reversal occurring about June 7, 1992. Temperatures decreased progressively over a 2–3 week period before resuming their upward trend. A second perturbation, characterized by a significant short-term increase in water temperature, occurred on September 27, 1992. Salinities at both stations displayed a slow but persistent decrease of approximately 1 psu over the deployment period, apparently in response to regional streamflow characteristics (Figure 3.3-6). Variations in near-bottom salinity showed limited correlation with concurrent temperature variations, and both were weakly correlated with local wind conditions.

#### 3.3.2.2 Deployment 2 (18 October 1992 – 7 August 1993)

The pressure records obtained at the Nearfield and Farfield stations during Deployment 2 differed from those of Deployment 1 only in average depth values indicating a slight difference in station location and depth (shallower) during Deployment 2 (Figures 3.3-7 and 3.3-8). The pressure field continued to have high frequency periodicity dominated by the diurnal and semi-diurnal components of the astronomical tide (Figure 3.3-9). Tidal range was identical to that observed during the initial deployment, varying from slightly more than 2 m during spring tides to approximately 1 m on the neap tides. Again, the response of the pressure field to meteorological forcing is finite but limited with the passage of major wind events such as that of January 12–13, 1993 and/or February 9–10, 1993 producing only slight reductions in range with no evident variation in phase. The observed tidal response to these wind systems is subtle and appears to be easily obscured by the variety of factors affecting the hydrodynamics of this portion of the shelf.

The near bottom flow patterns observed during Deployment 2 were qualitatively similar to those of Deployment 1 with differences primarily associated with the directional characteristics. Qualitatively, the directional patterns are simply reversed with Farfield during Deployment 2 displaying characteristics similar to Nearfield in Deployment 1 and vice-versa. Although the cause(s) of this pattern reversal cannot be easily defined, the fact that the current meters used at each station were the same in each deployment suggests that it is the result of frame-induced interference with the magnetic compass in the current meter.

With the above limitations in mind, wind conditions during Deployment 2 (Figures 3.3-10 and 3.3-11) were essentially identical to those during Deployment 1, with only a slight increase in peak wind speeds and the percentage of southerlies in the winter months. Despite these similarities, the number of perturbations in the bottom flow record coincident with high energy wind events was substantially less than observed during Deployment 1. This lack of response may be an instrument artifact associated with frame interference or alternatively the result of alterations in the regional wind field relative to conditions observed during Deployment 1. As discussed above, high energy wind events occurring in this first deployment were predominantly northerlies. Periods of southerly winds tended to be low energy and relatively quiescent (Figures 3.3-4 and 3.3-5). During the second deployment, the high energy wind events were more commonly southerlies (140° T) (Figures 3.3-10 and 3.3-11). This shift significantly alters fetch

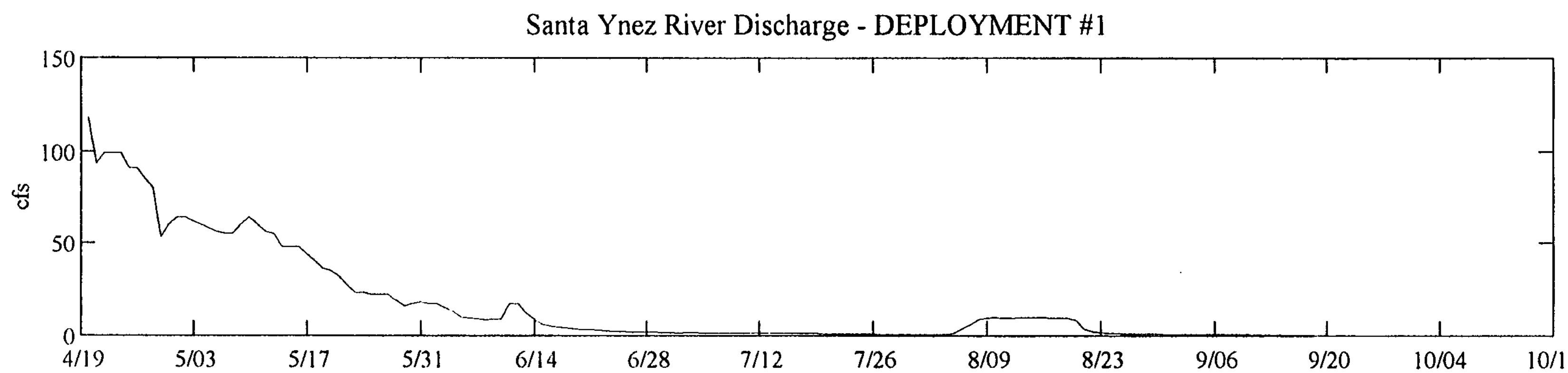


Figure 3.3-6. Average daily streamflow for the Santa Ynez River for Deployment 1 (USGS Gage Station 11123500 Santa Ynez, California).

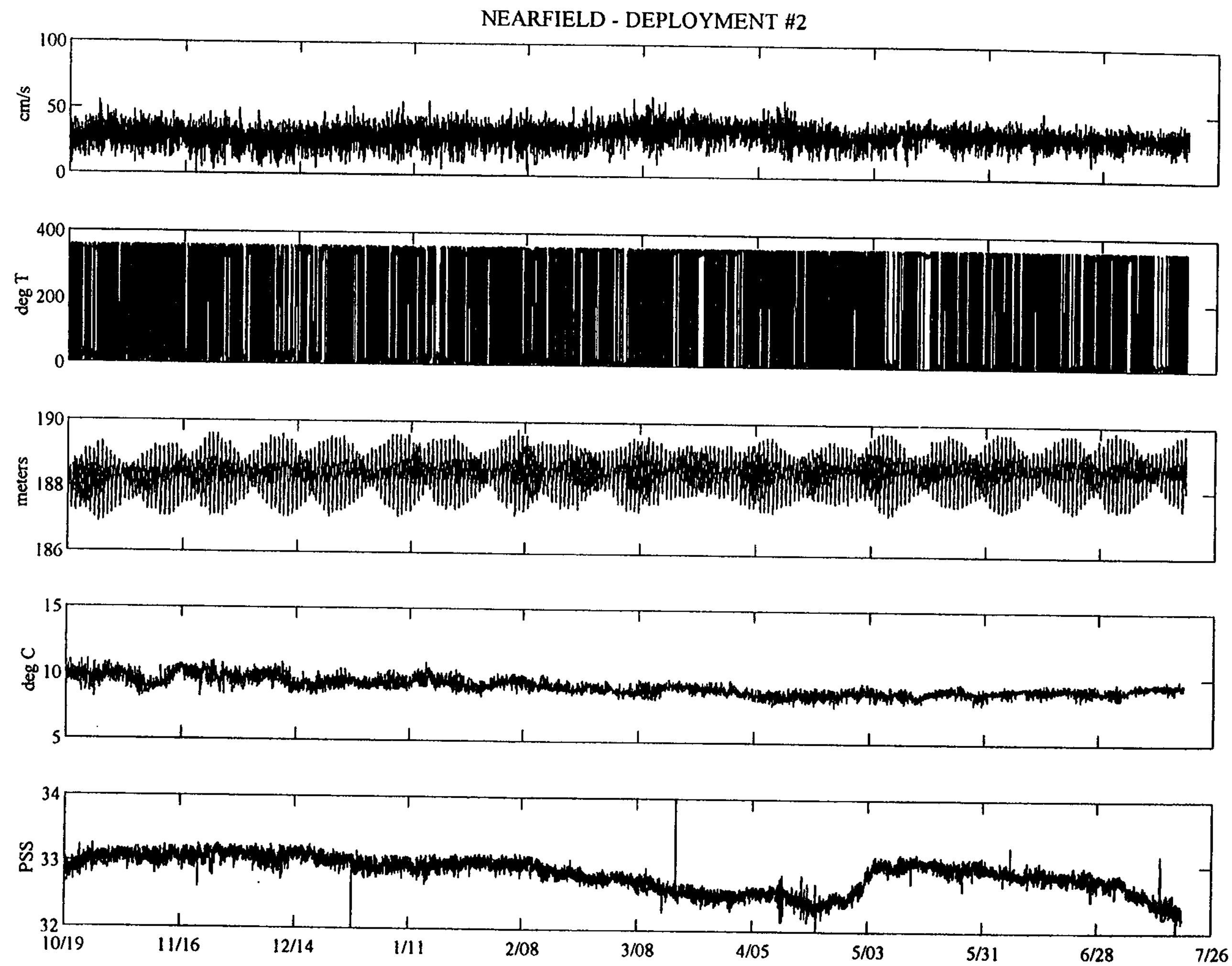


Figure 3.3-7. Time series observations from Nearfield station for Deployment 2: (a) near-bottom current speed, (b) near-bottom current direction, (c) hydrostatic pressure, (d) water temperature, and (e) salinity (practical salinity scale).

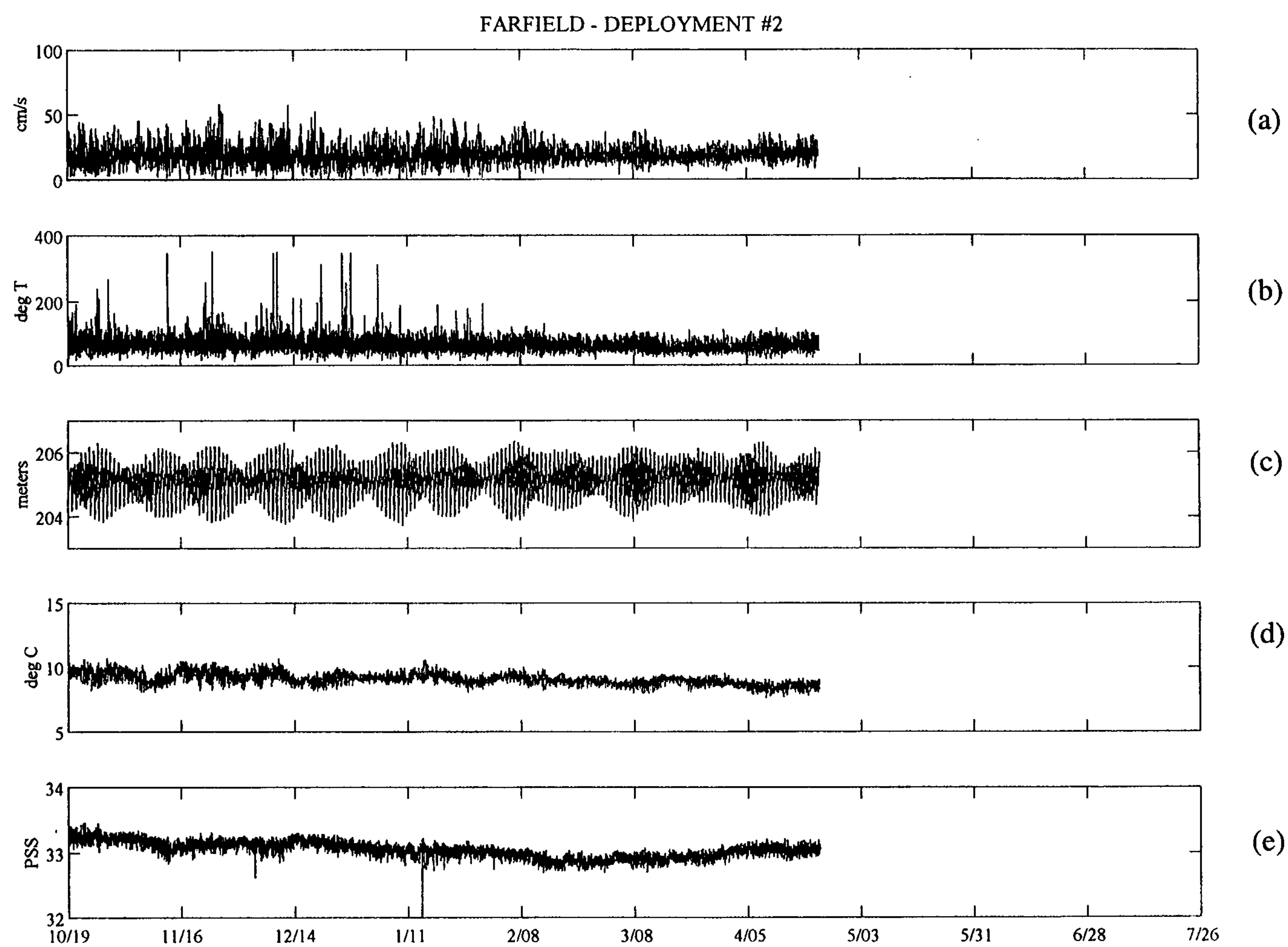


Figure 3.3-8. Time series observations from Farfield station for Deployment 2: (a) near-bottom current speed, (b) near-bottom current direction, (c) hydrostatic pressure, (d) water temperature, and (e) salinity (practical salinity scale).

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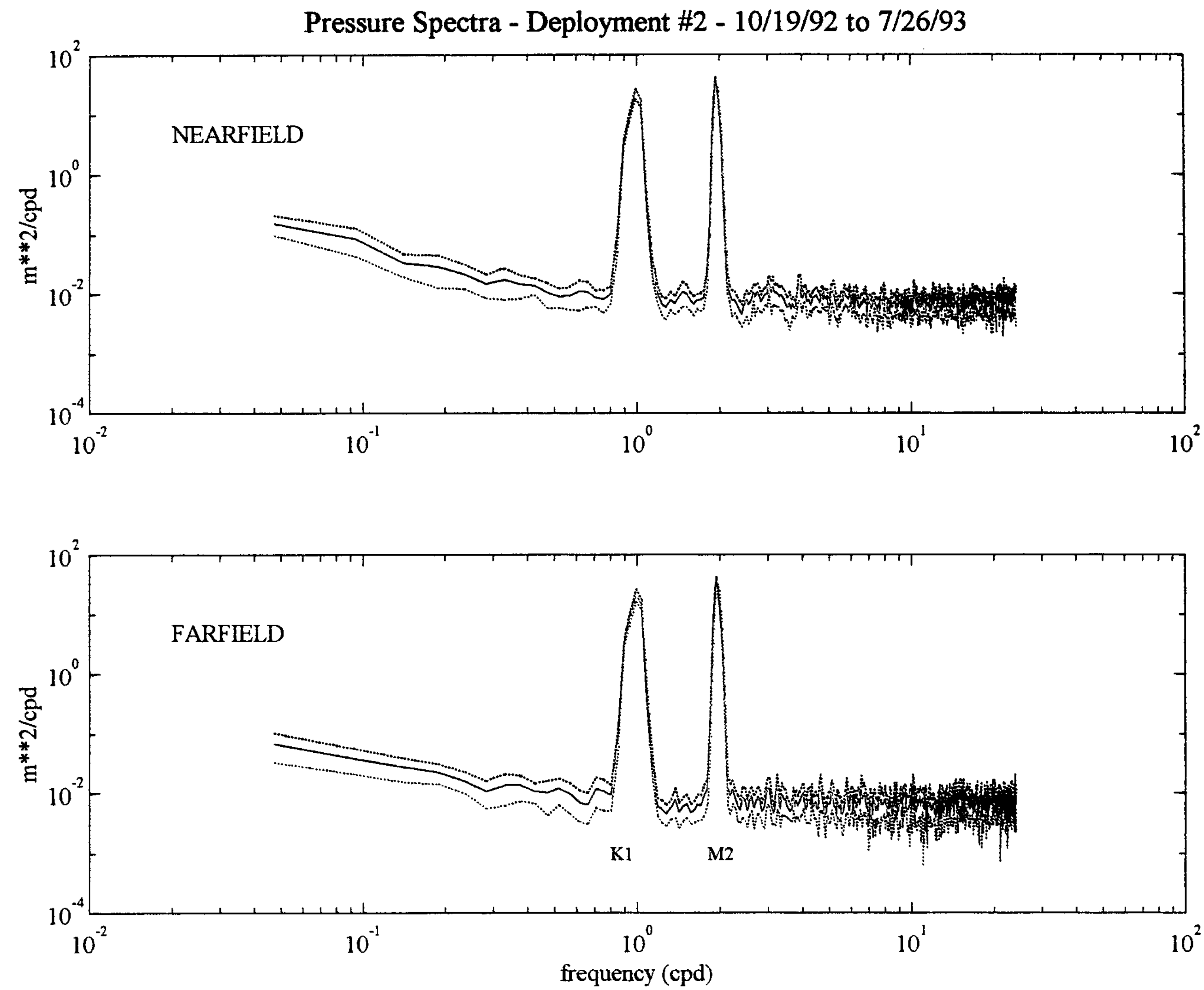


dashed lines delimit the 95% confidence interval
record length = 273 days (NF), 186 days (FF)
degrees of freedom = 24 (NF), 16 (FF)
bandwidth = 0.04687 cpd (NF & FF)

Figure 3.3-9. Spectral analysis of near-bottom hydrostatic pressure for Deployment 2.

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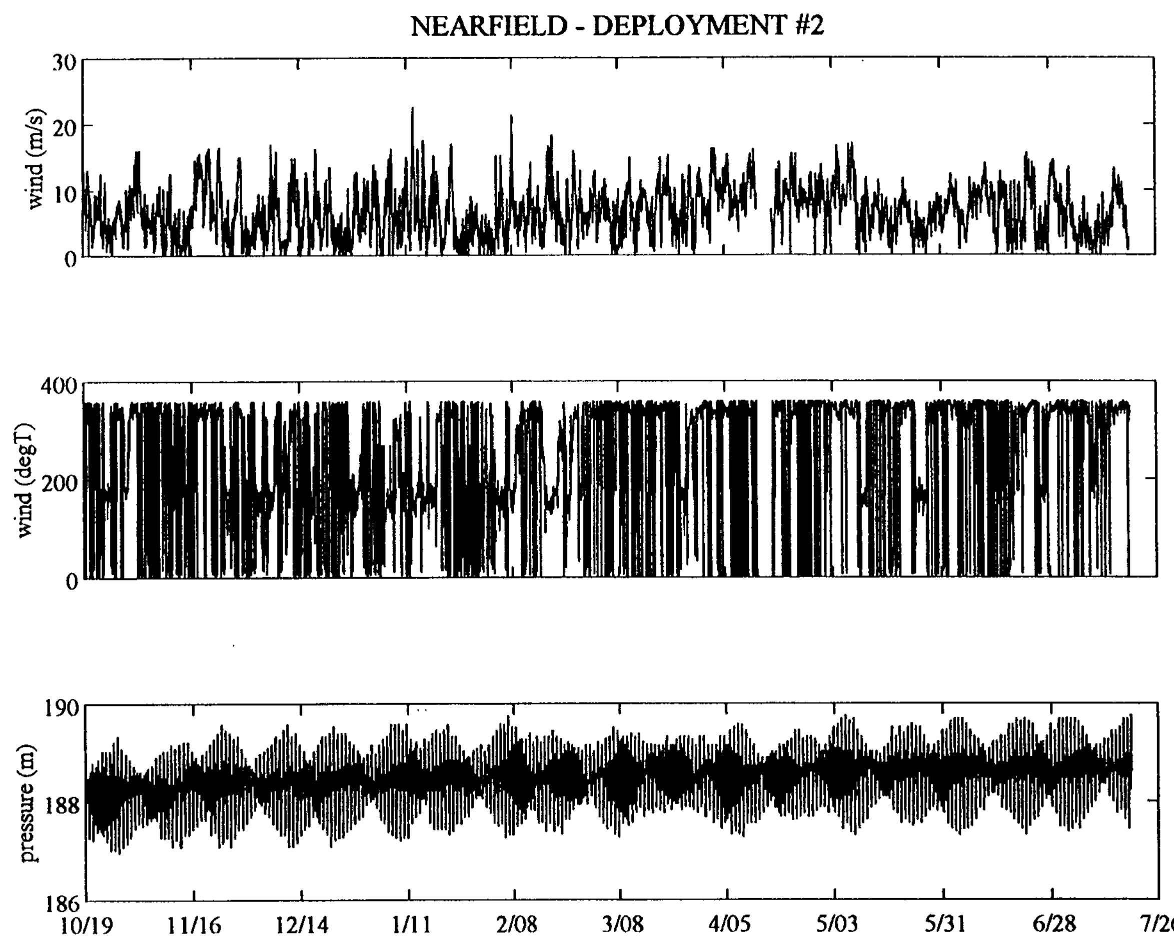



Figure 3.3-10. Meteorological observations from CMAN station PTGC1 and concurrent near-bottom hydrostatic pressure from Nearfield station for Deployment 2.

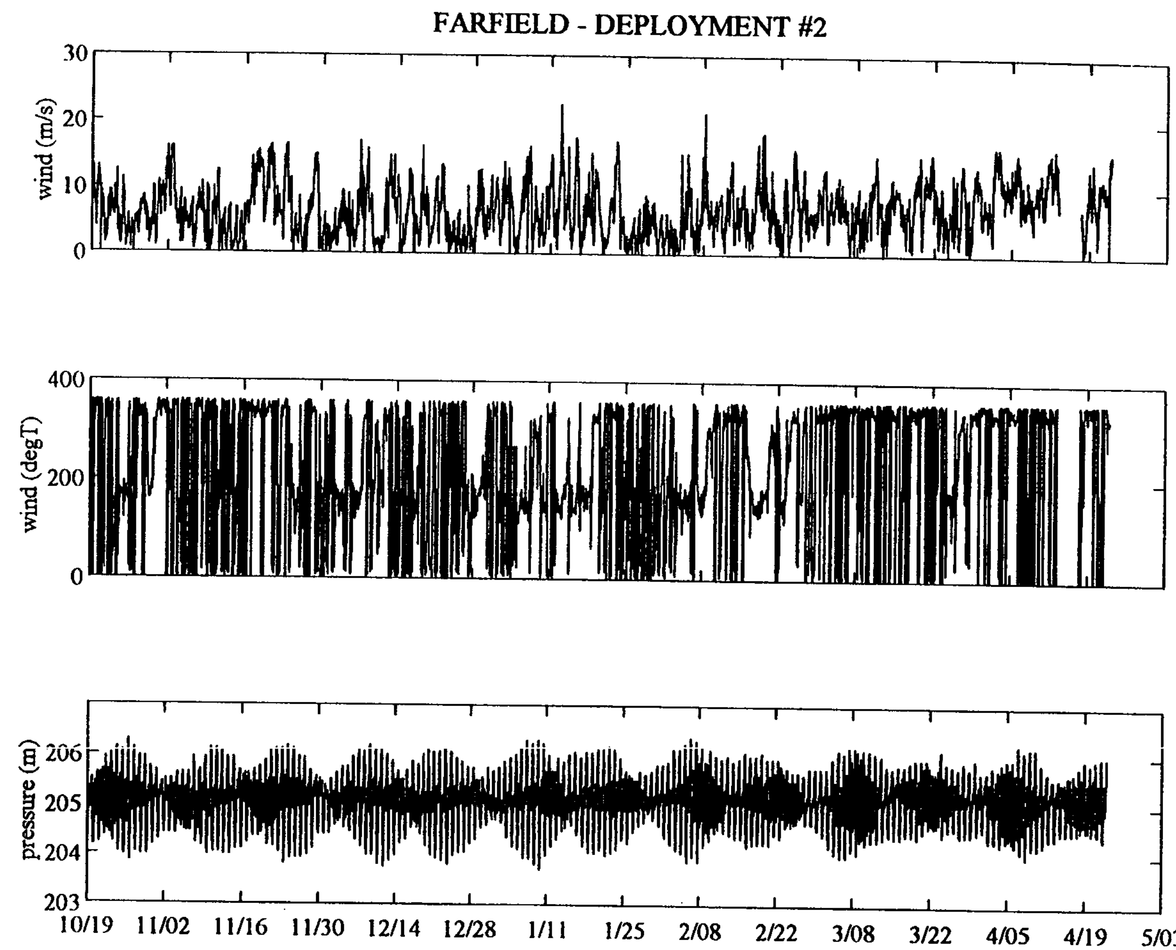



Figure 3.3-11. Meteorological observations from CMAN station PTGC1 and concurrent near-bottom hydrostatic pressure from Farfield station for Deployment 2.

conditions affecting both the surface wave field conditions and the character of the wind driven currents, thereby reducing the potential influence of the wind field on near bottom currents.

Near-bottom water temperatures during Deployment 2 decreased slightly but progressively during the late fall and winter months to a minimum in March. They then began to increase through the spring and early summer, similar in rate and magnitude to that observed during Deployment 1 (Figures 3.3-7 and 3.3-8). Short term perturbations of this long term trend often resulted in temperature variations of 1–2° C which are similar in magnitude to the long-term increase. Several of these short-term perturbations are coincident with high energy wind events, particularly during the fall-winter period. These data suggest, at least for some period of the year, that short-term, energetic wind events can and do affect the density structure of the entire water column within the study area.

On the average, near bottom salinities during Deployment 2 were lower than those observed during Deployment 1 (Figures 3.3-7 and 3.3-8). For the interval from October 19, 1992 to approximately January 11, 1993, values at both Nearfield and Farfield displayed only a slight long-term trend with high frequency variations about the mean of approximately 0.15 psu. After January 1993, average values at both stations began a progressive decline to minima in late February at Farfield and late April at Nearfield. This latter decline is approximately coincident with the gaged increase in discharge from the Santa Ynez River (Figure 3.3-12). The differences in timing and amplitude of long-term change and the seeming lack of sensitivity in Farfield salinity to local streamflow conditions suggest that these stations are located in different hydrodynamic regimes or are affected by differing components of the regional system. This possibility must be recognized in evaluations of the relative utility of the Farfield station as a reference in the scaling of the Nearfield response.

#### 3.3.2.3 Deployment 3 (9 January 1994 – 7 January 1995)

The modifications in the bottom array configuration for Deployment 3 served to remove the bias apparent in the Deployment 1 and 2 current meter data and provided a reliable current velocity time series that was consistent with data obtained from the nearby long-term moorings. During Deployment 3, near-bottom flows at both the Nearfield and Farfield stations displayed regular reversals in response to local tidal conditions (Figures 3.3-13 and 3.3-14). Spectral analysis of the near bottom pressure and current records continued to indicate the dominance of the $M_2$ and $K_1$ components of the astronomical tide (Figures 3.3-15 and 3.3-16). Currents in the vicinity of Nearfield were slightly more energetic than those at Farfield with an average speed over the observation period of approximately 14 cm/s and maxima in excess of 50 cm/s. Average speed at Farfield was approximately 11 cm/s while maxima seldom exceeded 40 cm/s. Long-term net drift at Nearfield was westerly with an average value of approximately 8 cm/s. This drift displayed moderate seasonality with a maximum of 9.3 cm/s observed during spring and a minimum of 7.1 cm/s during summer. The residual circulation at Farfield was southerly at an

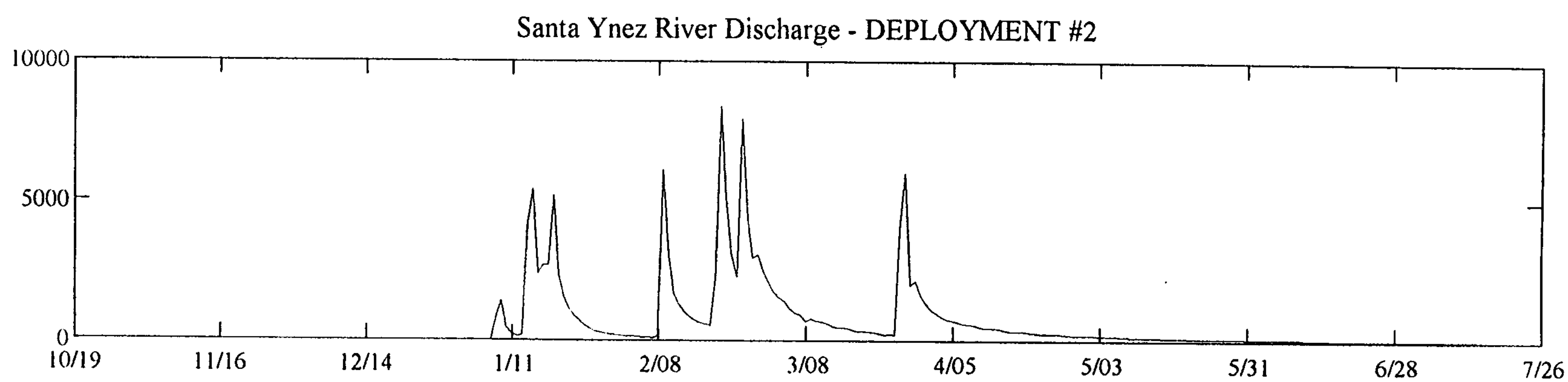



Figure 3.3-12. Average daily streamflow for the Santa Ynez River for Deployment 2 (USGS Gage Station 11123500 Santa Ynez, California).

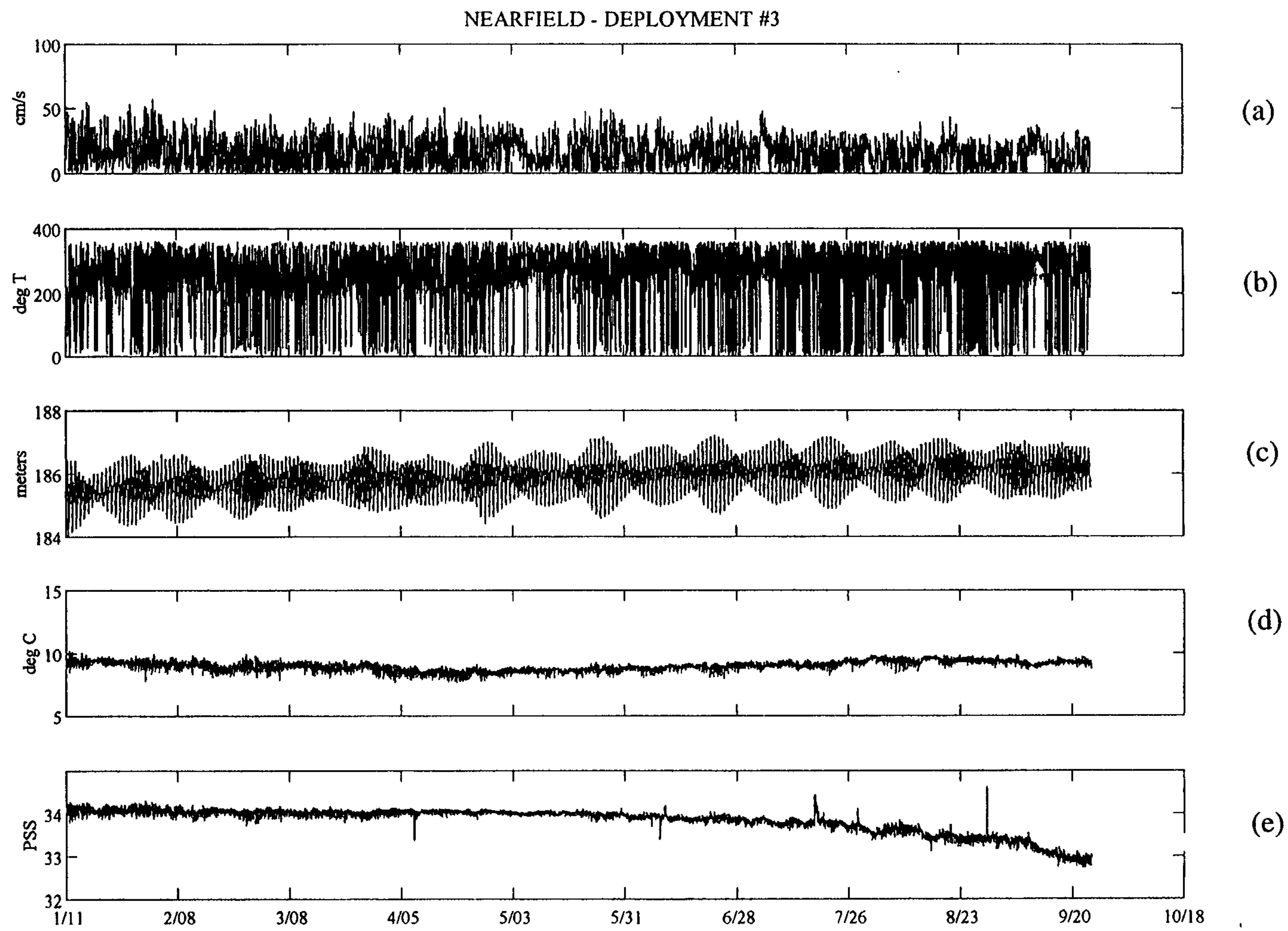



Figure 3.3-13. Time series observations from Nearfield station for Deployment 3: (a) near-bottom current speed, (b) near-bottom current direction, (c) hydrostatic pressure, (d) water temperature, and (e) salinity (practical salinity scale).

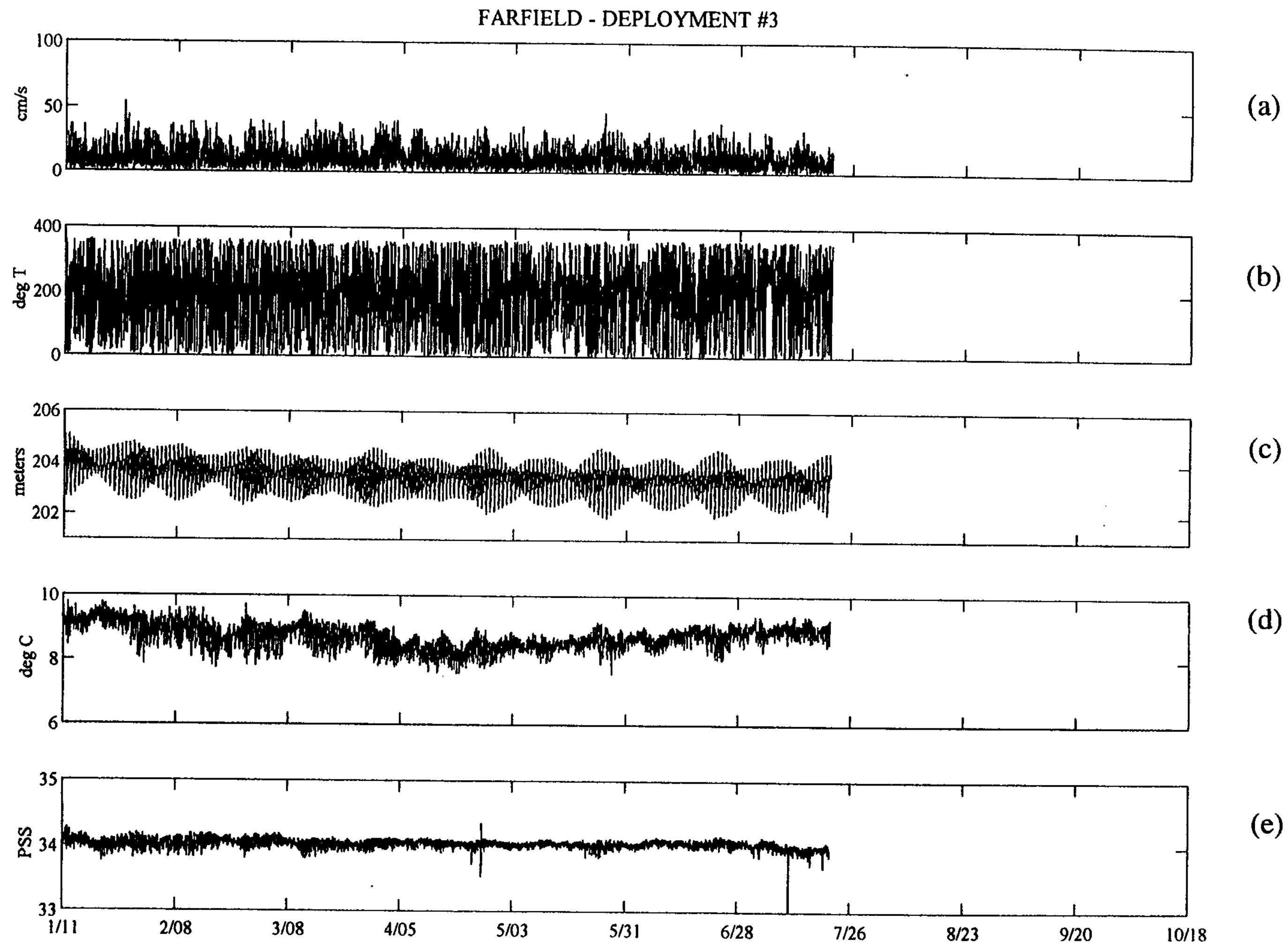
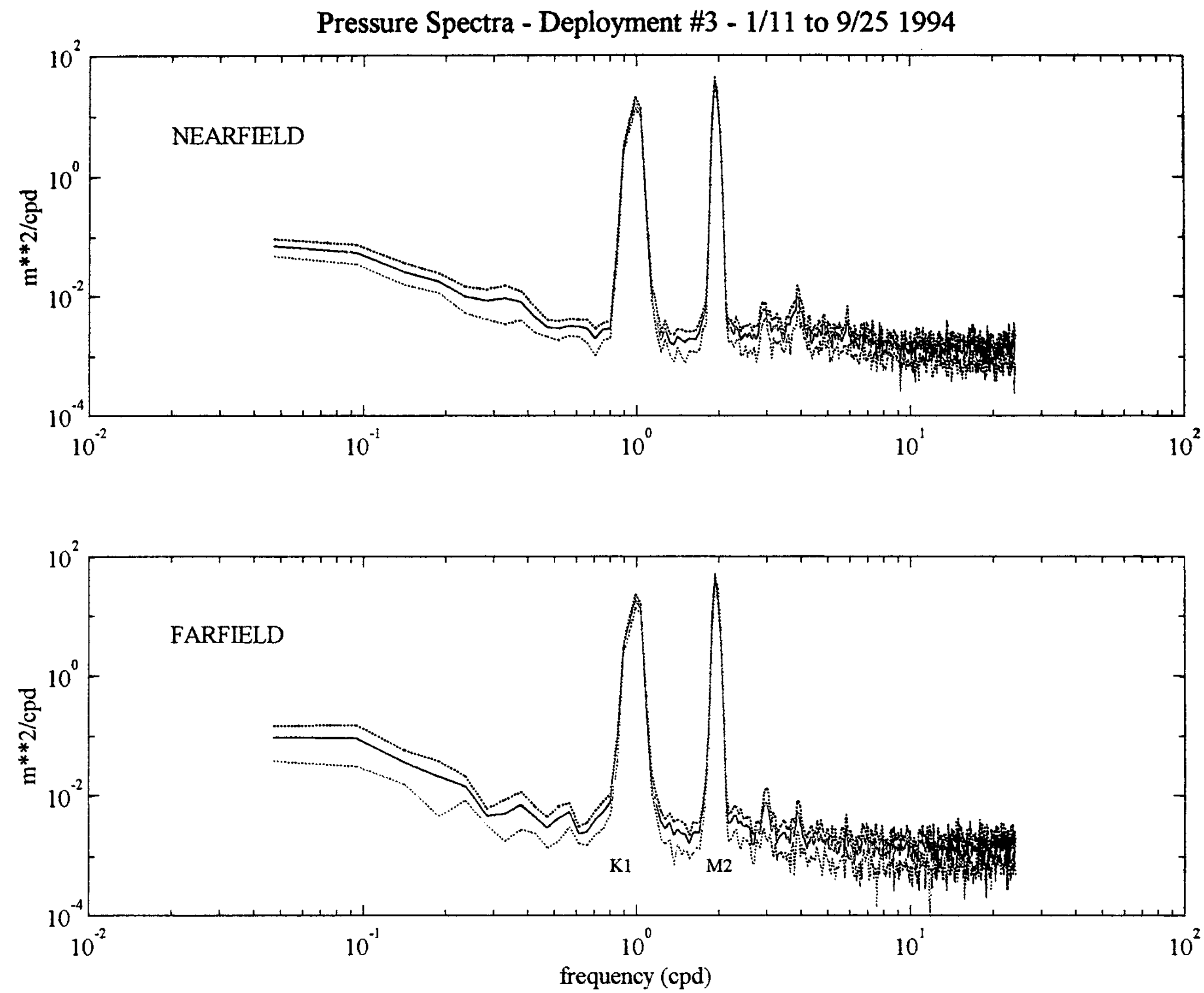



Figure 3.3-14. Time series observations from Farfield station for Deployment 3: (a) near-bottom current speed, (b) near-bottom current direction, (c) hydrostatic pressure, (d) water temperature, and (e) salinity (practical salinity scale).




dashed lines delimit the 95% confidence interval
record length = 256 days (NF), 190 days (FF)
degrees of freedom = 24 (NF), 18 (FF)
bandwidth = 0.04687 cpd (NF & FF)

Figure 3.3-15. Spectral analysis of near-bottom hydrostatic pressure for Deployment 3.

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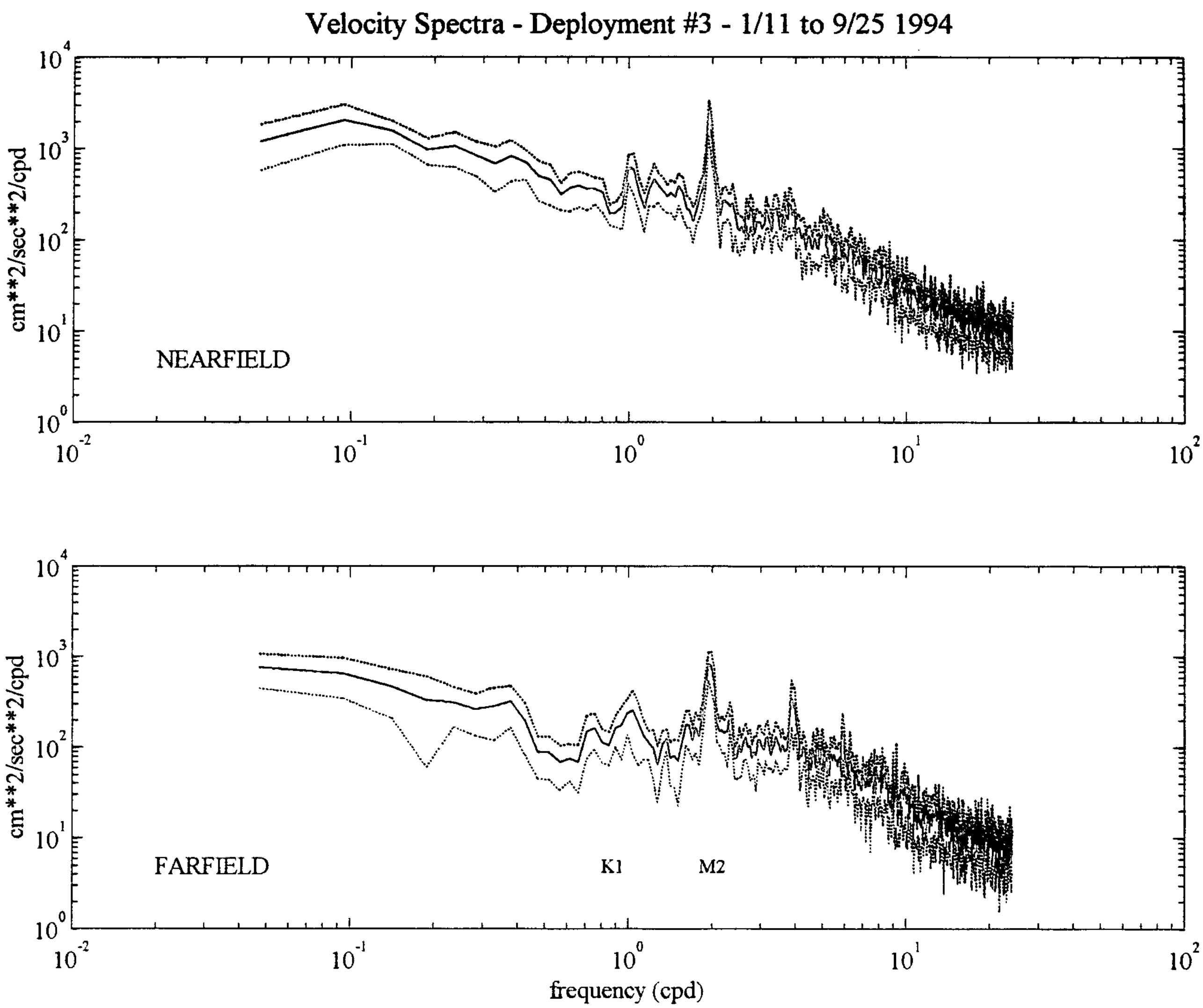


dashed lines delimit the 95% confidence interval
record length = 181 days
degrees of freedom = 32
bandwidth = 0.09375 cpd

Figure 3.3-16. Spectral analysis of near-bottom current speed for Deployment 3.

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average speed of approximately 4.5 cm/s. For this interval, maxima were observed during the winter months.

In addition to the regular tidal and low frequency long-term average conditions, both the Nearfield and Farfield current meter records displayed several high frequency perturbations, although none were temporally coincident. Perturbations in the Nearfield record were observed around the 18th of January 1994 and again near the 12th of April, 10th of May and 1st of July (Figure 3.3-13). In each event both speed and direction changed relative to pre- and post-event conditions. None of these appear in the Farfield record. The Farfield perturbations differed in timing and apparent character with the events being longer-lived and more nearly periodic. The cause for these differences cannot be specified beyond those already discussed for water depth and hydrodynamic regime.

Review of the meteorological data for the deployment period provide little indication that alterations in near-bottom flow characteristics at either station were directly associated with the surface wind field (Figures 3.3-17 and 3.3-18). Winds during Deployment 3 were similar in character to those observed during Deployments 1 and 2 with directions dominated by northerlies and maxima approaching 20 m/s. Quiescent periods tended to be dominated by southerly winds. However, in contrast to the earlier deployments, maxima during Deployment 3 were less pronounced with lower peak values. Given these characteristics, the absence of clear correlation between bottom flows and surface winds in this deployment is not surprising. Under these conditions, the observed variations in near-bottom flow appear to be the result of the regional flow field, with station to station differences mediated by local bathymetry and siting.

Water temperatures at the Nearfield station during Deployment 3 were essentially identical to those observed during Deployment 2 (Figure 3.3-13) with values decreasing initially to a minimum in April and then increasing slowly to a maximum near the end of the record. In contrast, temperatures at Farfield during Deployment 3 were lower than those observed during Deployment 2 with significant high frequency variability (Figure 3.3-14). The long-term trends were similar to Nearfield with a minimum in April followed by a slow increase through the spring and summer.

Near-bottom salinities at both stations were initially higher than those observed during the previous deployments (Figures 3.3-13 and 3.3-14), with values of approximately 34 psu. Farfield values remained relatively consistent throughout the period of record ending in mid-July 1994 when the instrument array was recovered. Nearfield displayed similar characteristics but during the extended period of deployment, with data ending in late September, began to indicate a progressive decrease in salinity with values approaching 32.5 psu. The cause for this progressive decrease is generally unknown. Reviews of the local streamflow conditions, as indicated by the discharge from the Santa Ynez River, show a maximum in February followed by an extremely dry summer (Figure 3.3-19). Once again, it appears that near-bottom conditions in the study area are more commonly controlled by larger scale regional factors than smaller scale local conditions. These characteristics complicate establishing cause and effect relationships.

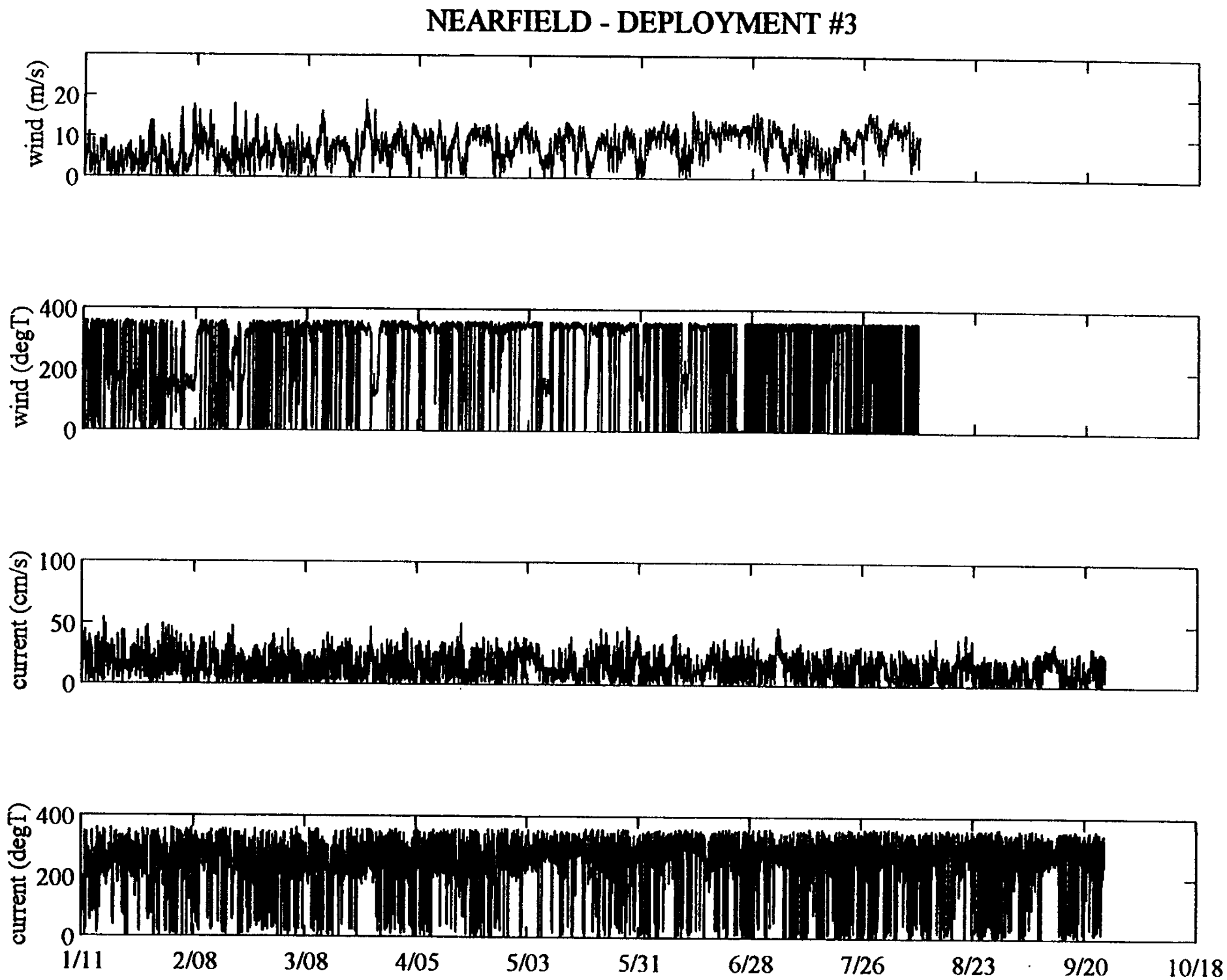


Figure 3.3-17. Meteorological observations from CMAN station PTGC1 and concurrent near-bottom velocity from Nearfield station for Deployment 3.

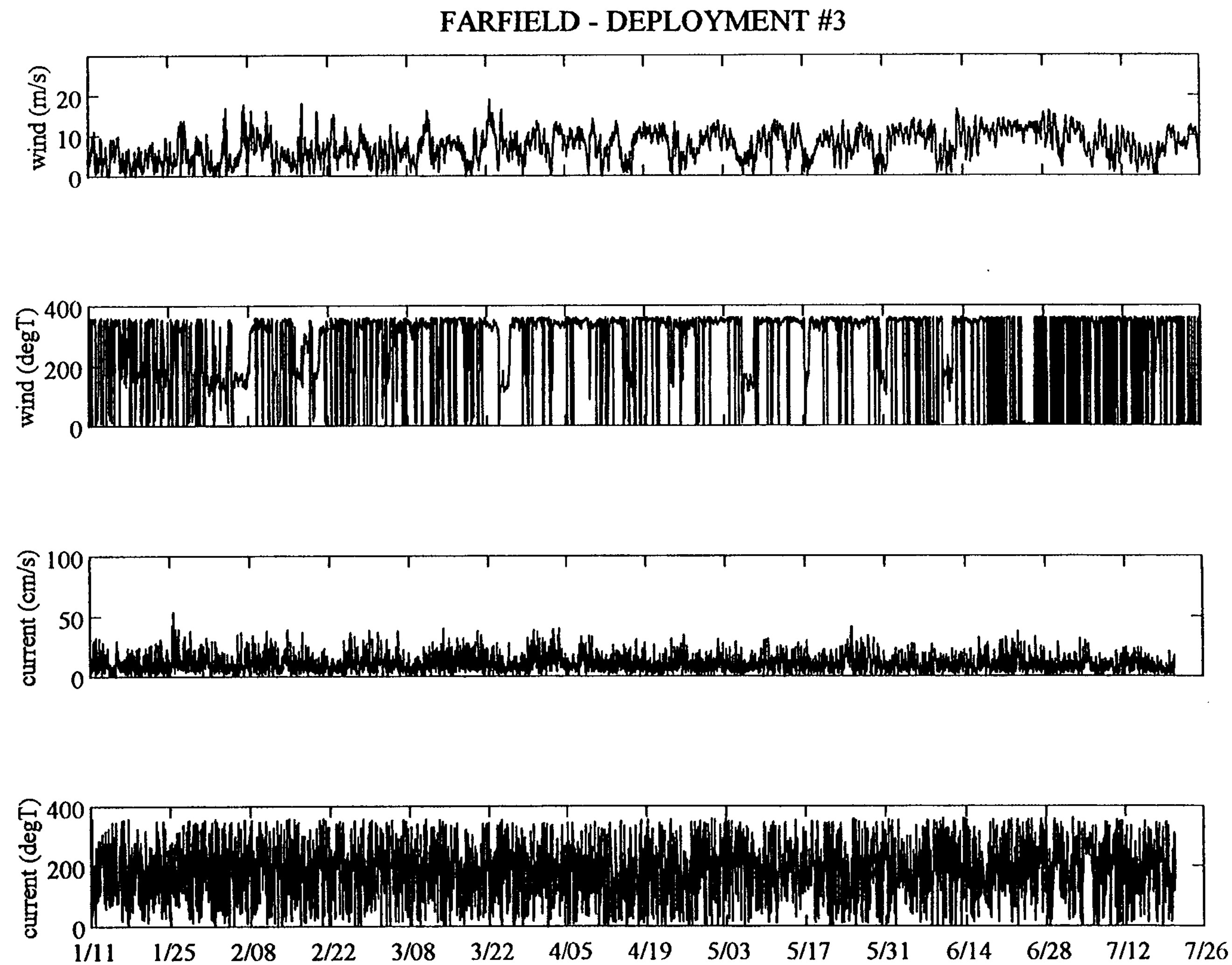


Figure 3.3-18. Meteorological observations from CMAN station PTGC1 and concurrent near-bottom velocity from Farfield station for Deployment 3.

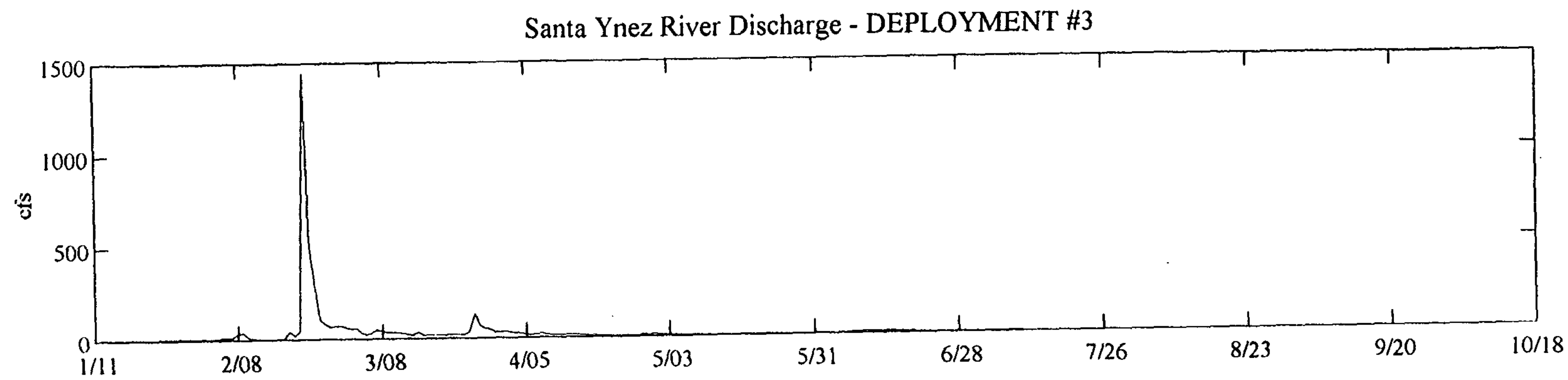


Figure 3.3-19. Average daily streamflow for the Santa Ynez River for Deployment 3 (USGS Gage Station 11123500 Santa Ynez, California).

## 3.3.3 Near-Bottom Suspended Material Field

### 3.3.3.1 Deployment 1 (18 April 1992 – 17 October 1992)

Data output from the optical sensors (OBS) indicates progressive but expected degradation of the sensor performance during each deployment period. This is most probably associated with biofouling of the vertical surface of the instrument windows. At both Nearfield and Farfield, output from the OBS began to degrade significantly within four to six weeks following deployment (Figures 3.3-20 and 3.3-21). Significant fouling of the upper sensors at Nearfield occurred within four to six weeks of deployment. The lower instruments remained operational for approximately ten weeks (Figure 3.3-20). The situation at Farfield was reversed with the lower sensors showing the higher fouling rate with significant signal degradation within approximately four to five weeks after deployment (Figure 3.3-21). The upper sensors remained operational for nearly ten weeks. Following the onset of significant fouling, the data provided by the optical sensors are invalid.

OBS data indicate that Deployment 1 near-bottom concentrations of suspended material at both the Nearfield and Farfield stations were generally low with average values ranging between 1 and 10 mg/1 (Figures 3.3-20 and 3.3-21). Water samples obtained on April 18, 1992, just following the deployment of the arrays, show initial concentrations ranging between 0.85 and 1.35 mg/1. Both OBS records display significant high frequency variability with the standard deviation at Nearfield exceeding that observed at Farfield. Overall, the timing of these high frequency perturbations is rather haphazard with spectral analysis of each of the suspended material records providing no evidence of tidal harmonic signatures (Figures 3.3-22 and 3.3-23). None of the records display visual correlation between suspended material concentrations and instantaneous speed. Examination of the suspended material distributions and speeds during the first week of the deployment, when bias due to biofouling was minimal, shows variations proceeding over a variety of time scales consistent with the spectral analysis (Figures 3.3-24 and 3.3-25). This response appears representative of a turbulent debris flow in which velocities serve primarily to transport and disperse suspended materials introduced from a variety of sources. In such a system, erosion from the local sediment-water interface is a rare event and near-bottom transport is dominated by recycling of the materials moving as a suspension in the turbulent flow. The immediate sediment-water interface in such a system tends to be dominated by relatively high water content materials that can be easily displaced by mechanical agitation. Views of the bottom in the vicinity of the Nearfield and Farfield stations provided by the ROV systems, during PMA recovery operations, indicate a dominance of such material throughout the study area.

Despite the relatively unconsolidated nature of the sediment-water interface in the study area, the array observations provide little indication of significant aperiodic resuspension associated with the passage of meteorological events. Analysis of the pressure records indicates that several systems passed by the study area during the deployment period which were sufficient to produce a significant increase in surface wind wave energy. Four events were observed on April 22, May

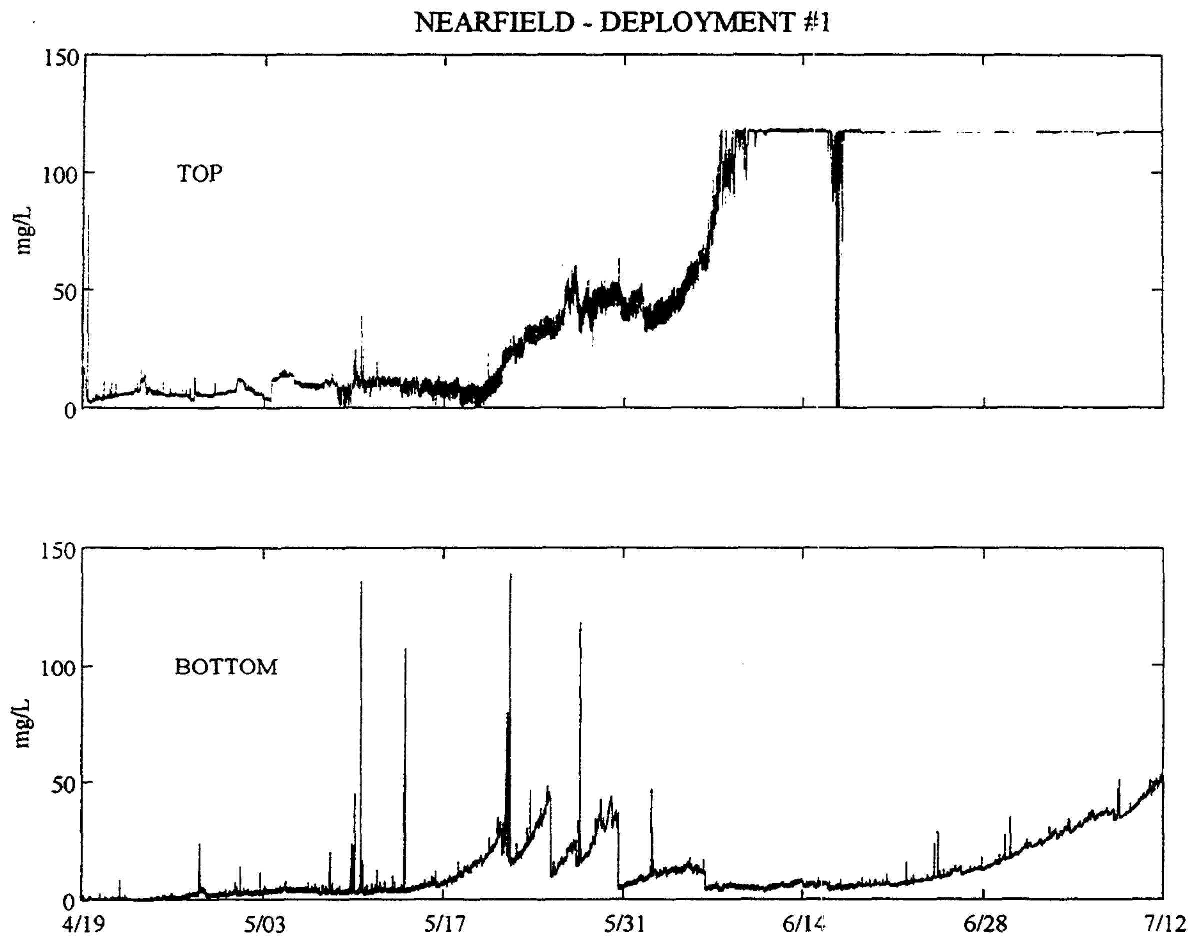


Figure 3.3-20. Near-bottom suspended material concentrations from Nearfield station for Deployment 1.

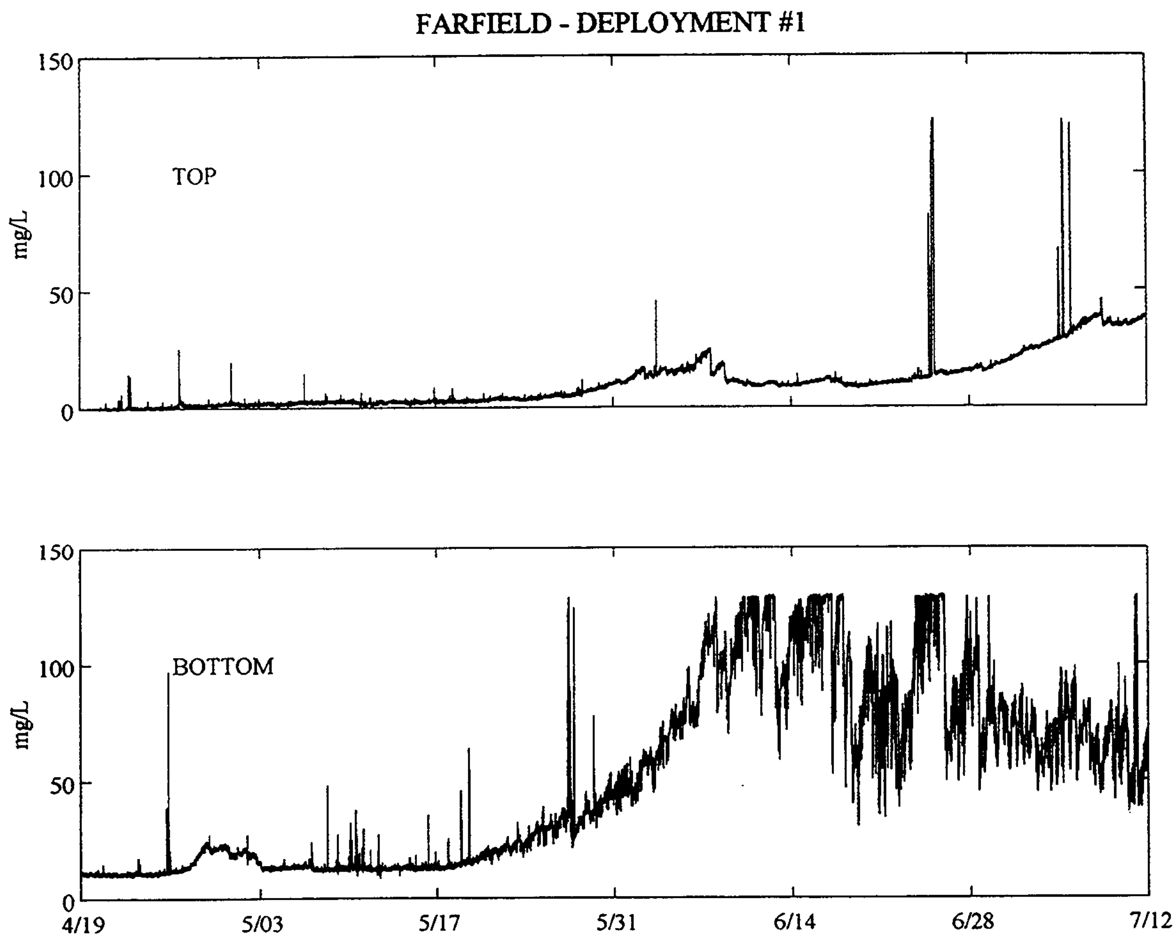


Figure 3.3-21. Near-bottom suspended material concentrations from Farfield station for Deployment 1.

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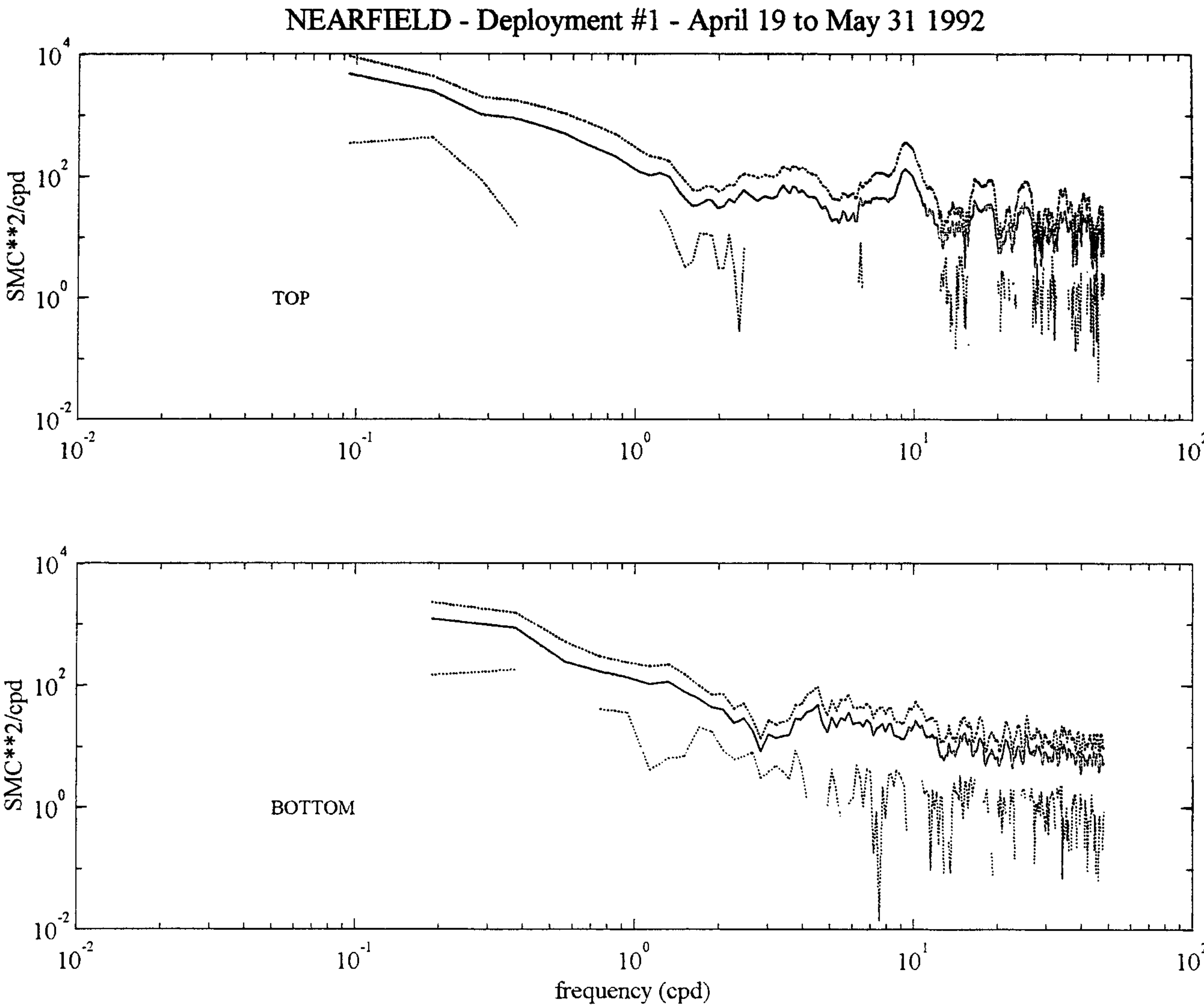


Figure 3.3-22. Spectral analysis of near-bottom suspended material concentrations from Nearfield station for Deployment 1. Dashed lines delimit the 95% confidence interval.

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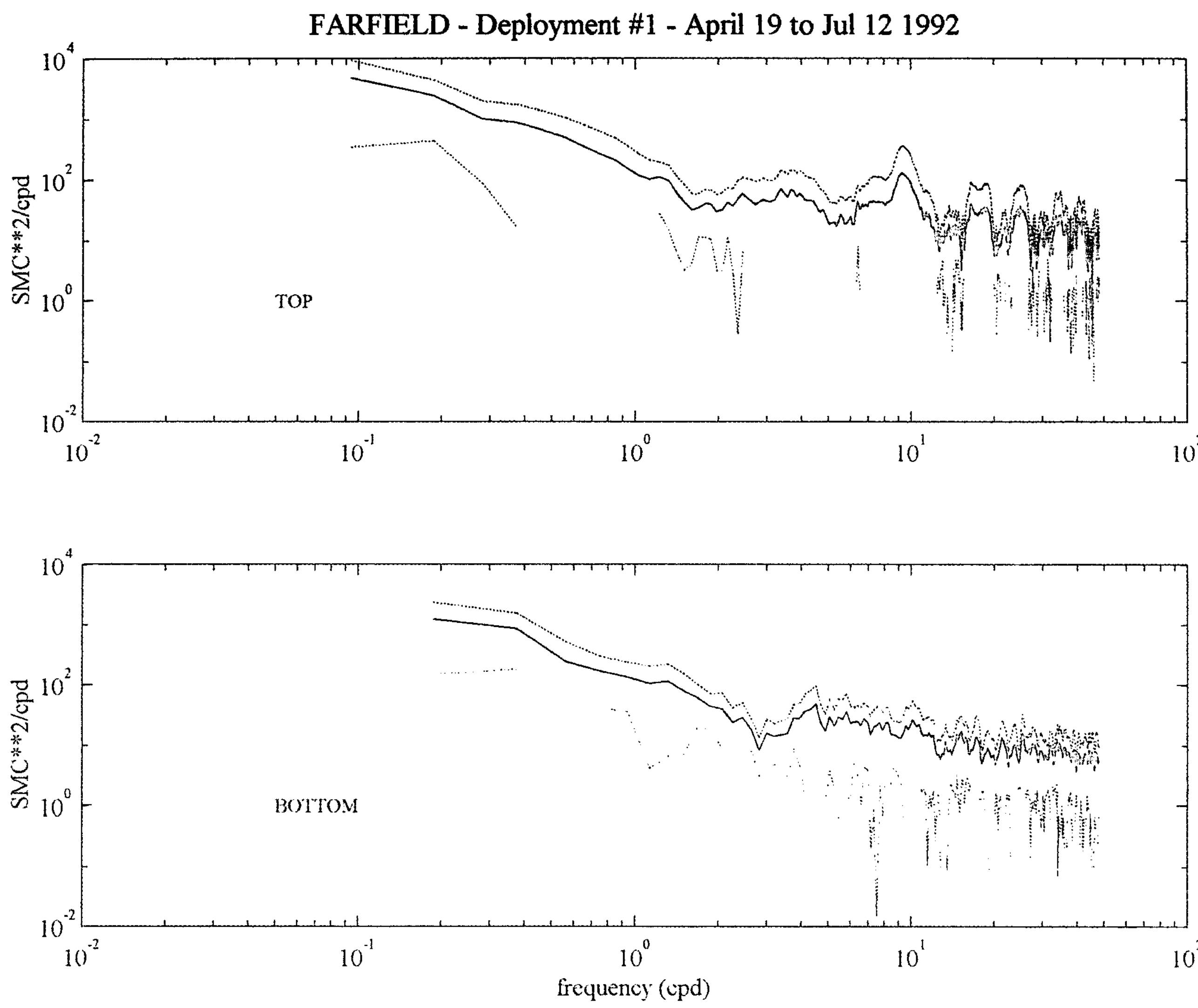


Figure 3.3-23. Spectral analysis of near-bottom suspended material concentrations from Farfield station for Deployment 1. Dashed lines delimit the 95% confidence interval.

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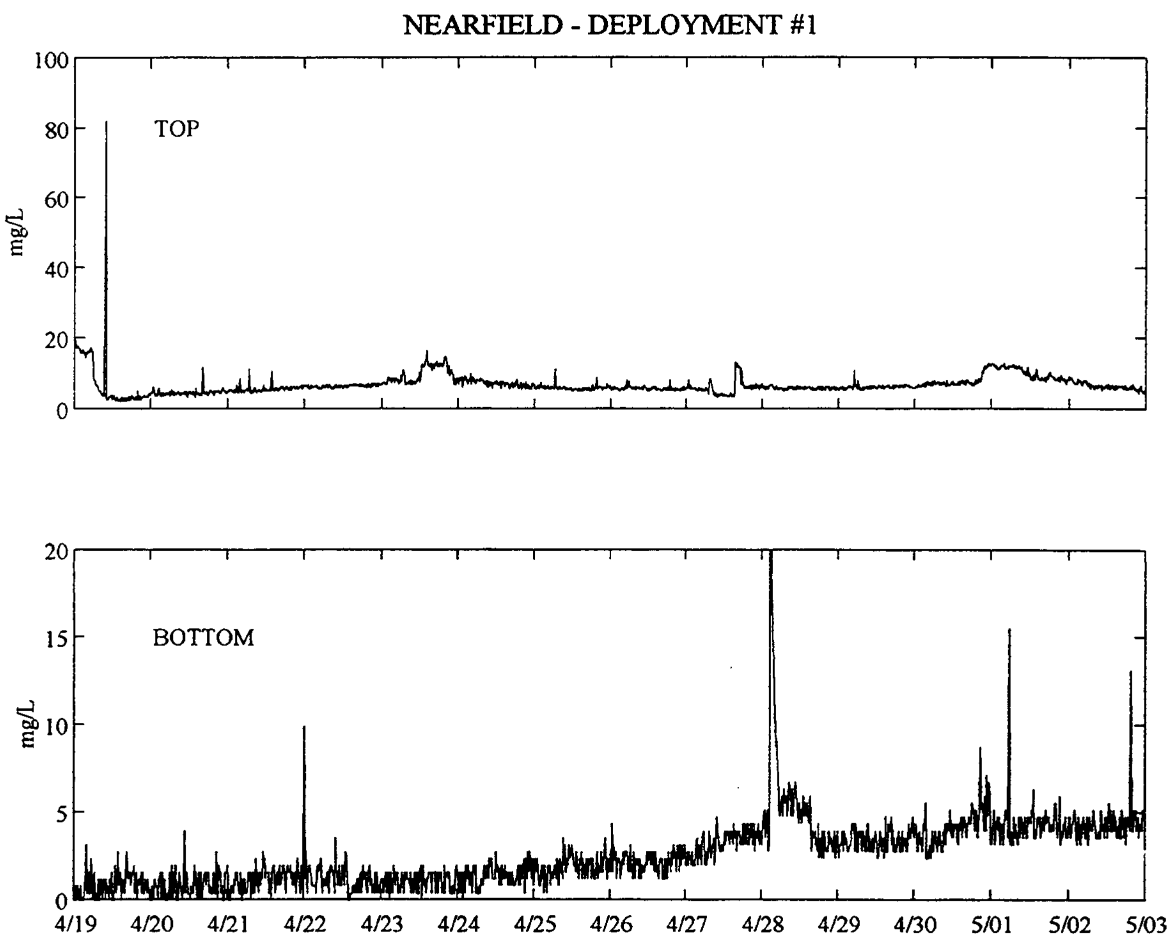


Figure 3.3-24. Time series observations of near-bottom suspended material concentrations from Nearfield station for Weeks 1-2 of Deployment 1.

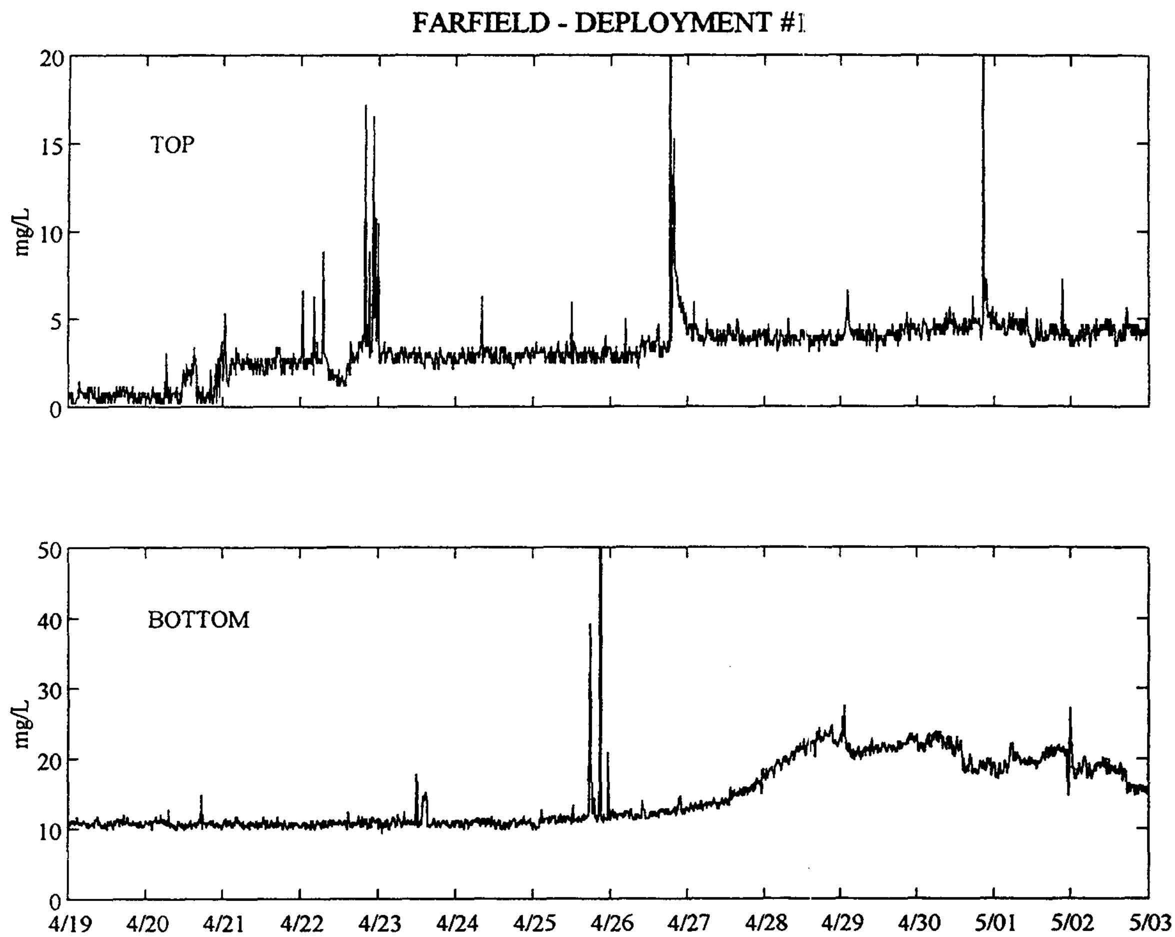


Figure 3.3-25. Time series observations of near-bottom suspended material concentrations from Farfield station for Weeks 1-2 of Deployment 1.

2, May 10, and May 22, 1992 (Figure 3.3-26). The optical data provide no indication that the April 22nd, May 10th or May 22nd events measurably perturbed near-bottom suspended material concentrations at either the Nearfield or Farfield stations. A perturbation coincident with the second event appears only in the near-bottom sensor at the Farfield station (Figure 3.3-23). There is some indication of a delayed response, particularly associated with the April 22nd event, which may be the result of advection of materials from distant, and most probably inshore, sites rather than local resuspension.

### 3.3.3.2 Deployment 2 (18 October 1992 – 7 August 1993)

During Deployment 2 near-bottom suspended material concentrations at the Nearfield station remained low and essentially identical to those observed during Deployment 1. Both the upper and lower sensors indicate concentrations in the vicinity of 2 mg/l at the beginning of the record (Figure 3.3-27). Values slowly increased as bio-fouling accumulated on the sensor windows. Fouling was particularly intense on the upper sensor resulting in a period of operation of approximately one month. The fouling rate was significantly lower on the bottom sensor resulting in nearly three months of useful record (Figure 3.3-27).

Suspended material concentrations at Farfield were higher than those observed during Deployment 1 with the upper level instrument indicating values ranging from 10 to 25 mg/l and the lower sensor values between 5 and 15 mg/l (Figure 3.3-28). At this station the fouling rate was maximum at the lower sensor resulting in a useful record length of approximately one month. The upper level record remained useful for slightly more than two months before abruptly fouling. Once again, neither the Nearfield nor the Farfield record displayed evident spectral signatures coincident with the dominant tidal frequencies or any other primary feature of the local hydrographic system (Figures 3.3-29 and 3.3-30). The absence of simple periodicity is visually evident in the suspended material time series with blowups of the first two weeks of the record from each station over a variety of time scales (Figures 3.3-31 and 3.3-32). The patterns appear representative of a turbulent flow with suspended material concentrations varying in a relatively random manner.

Beyond the persistent high frequency variability, review of the time series records from both the Nearfield and Farfield stations indicates several short-term perturbations during which suspended material concentrations more than doubled resulting in maximum concentrations approaching 50 mg/l (Figures 3.3-27 and 3.3-28). The lack of coincidence between these perturbations and concurrent winds and associated surface wave conditions (Figure 3.3-33) suggests that the perturbations are not caused by local resuspension and are more likely the result of advection of materials resuspended in shallower waters and moving past the monitoring sites. In addition, the absence of similarity in the response observed in the Nearfield record relative to that evident in the Farfield data provides another indication of the differences in the hydrodynamic regimes affecting each site. The near independence of the records from each station suggests that the spatial correlation scales in this segment of the study area are less than 5 km.

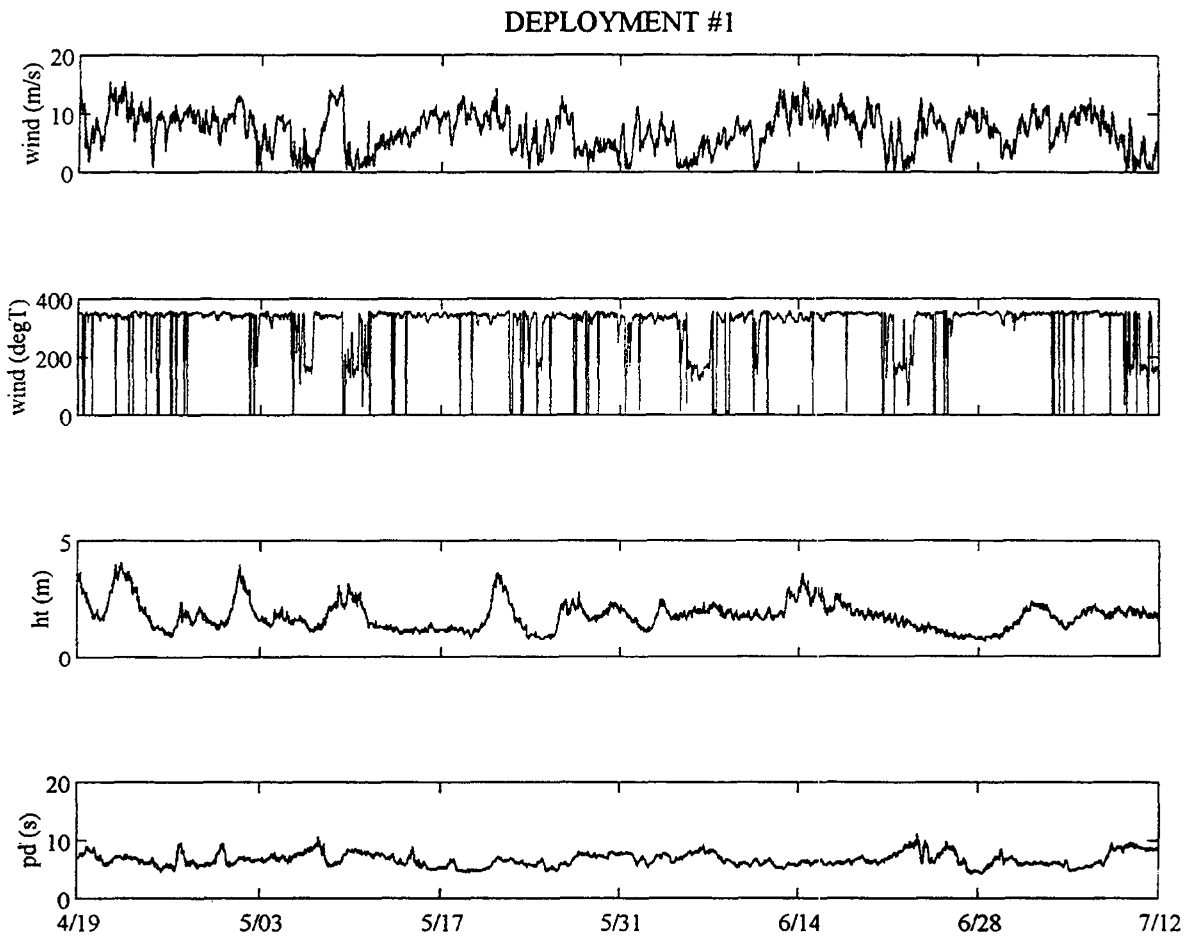


Figure 3.3-26. Meteorological observations from CMAN station PTGC1 and concurrent surface wave conditions for Deployment 1.

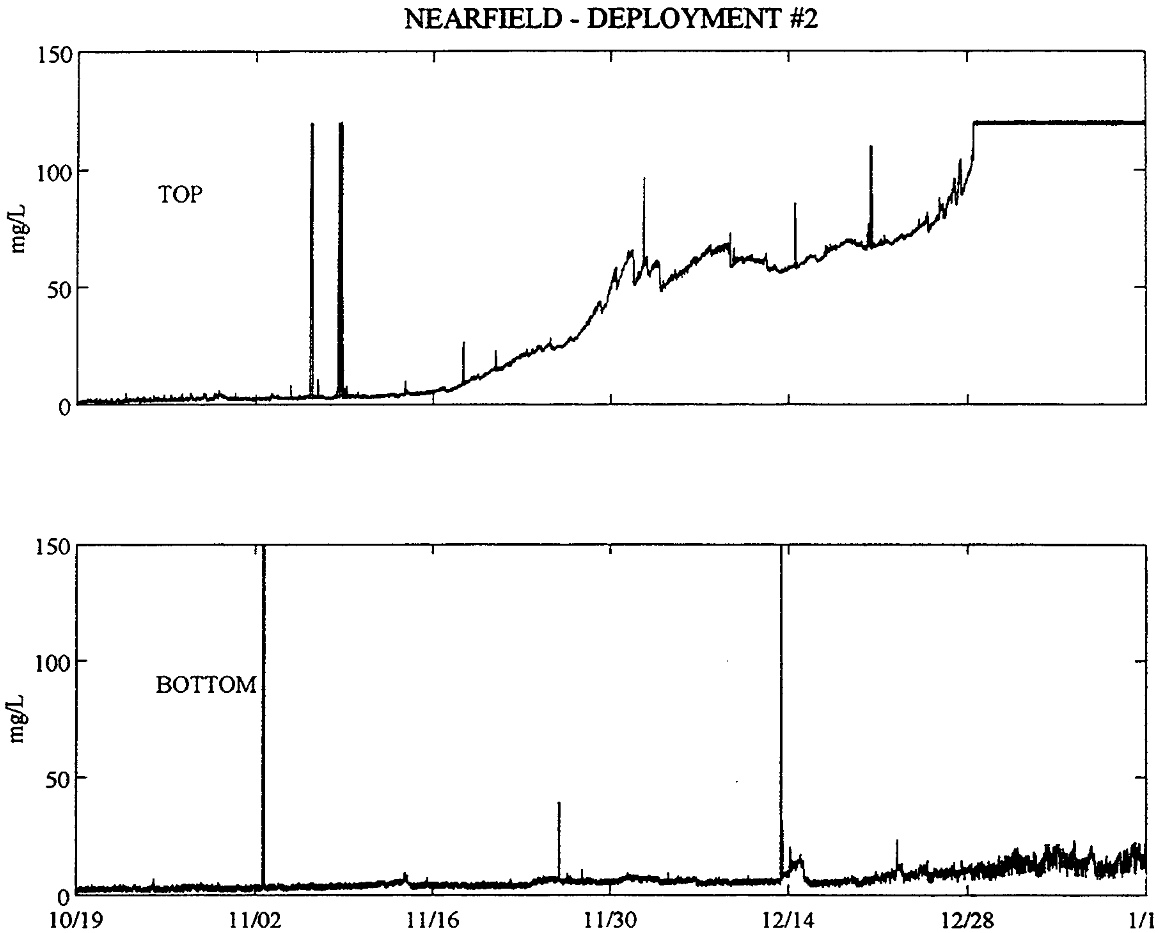


Figure 3.3-27. Near-bottom suspended material concentrations from Nearfield station for Deployment 2.

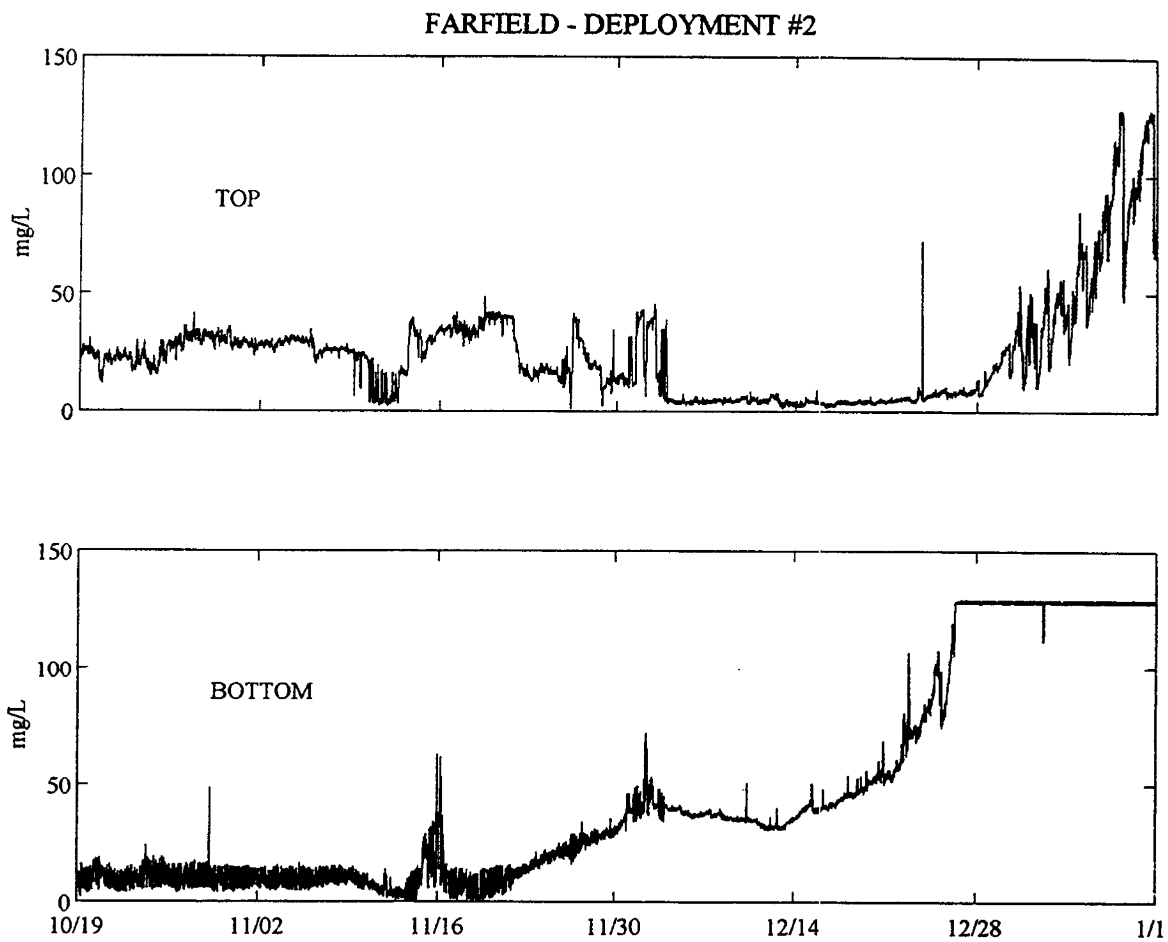


Figure 3.3-28. Near-bottom suspended material concentrations from Farfield station for Deployment 2.

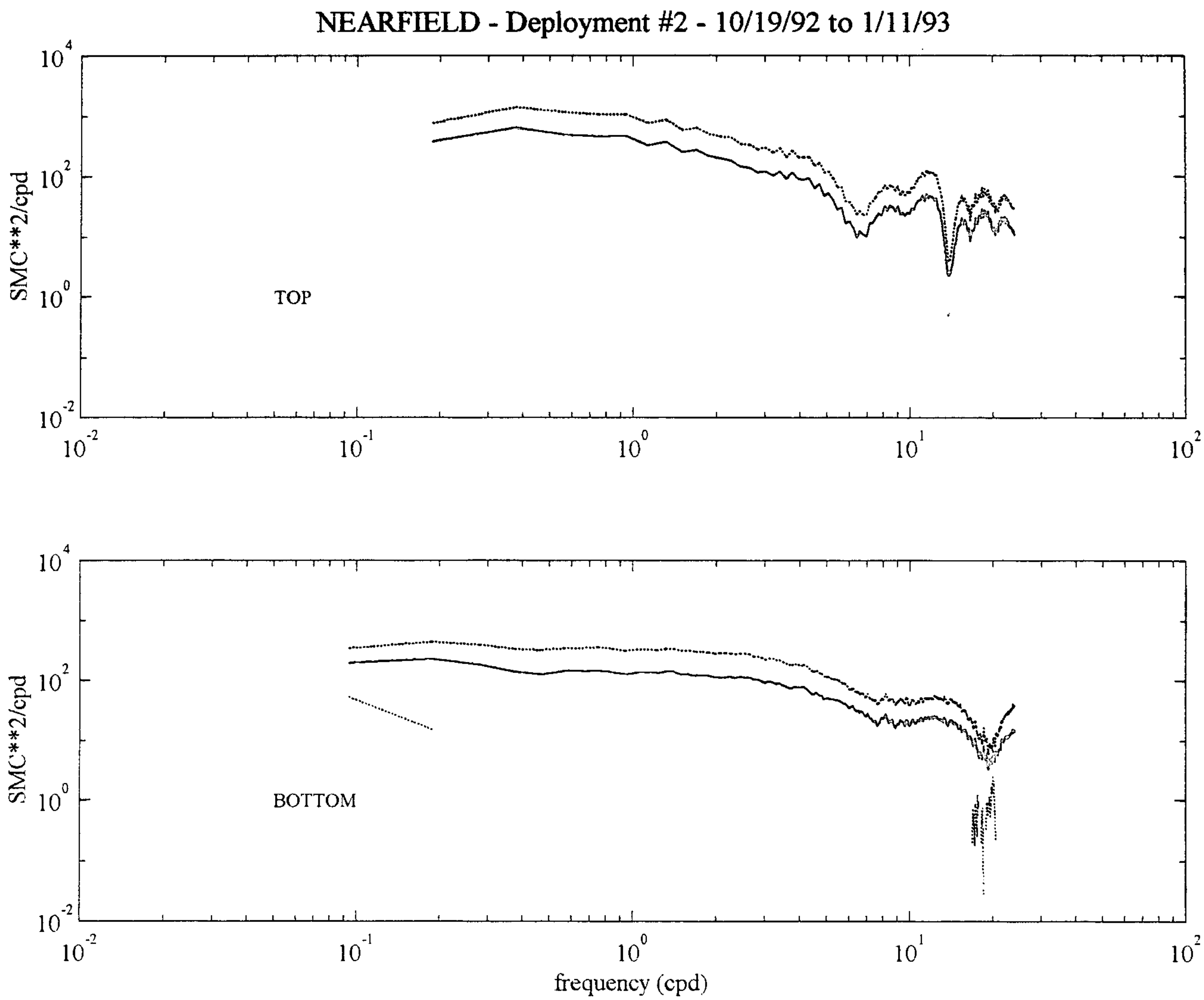


Figure 3.3-29. Spectral analysis of near-bottom suspended material concentrations from Nearfield station for Deployment 2. Dashed lines delimit the 95% confidence interval.

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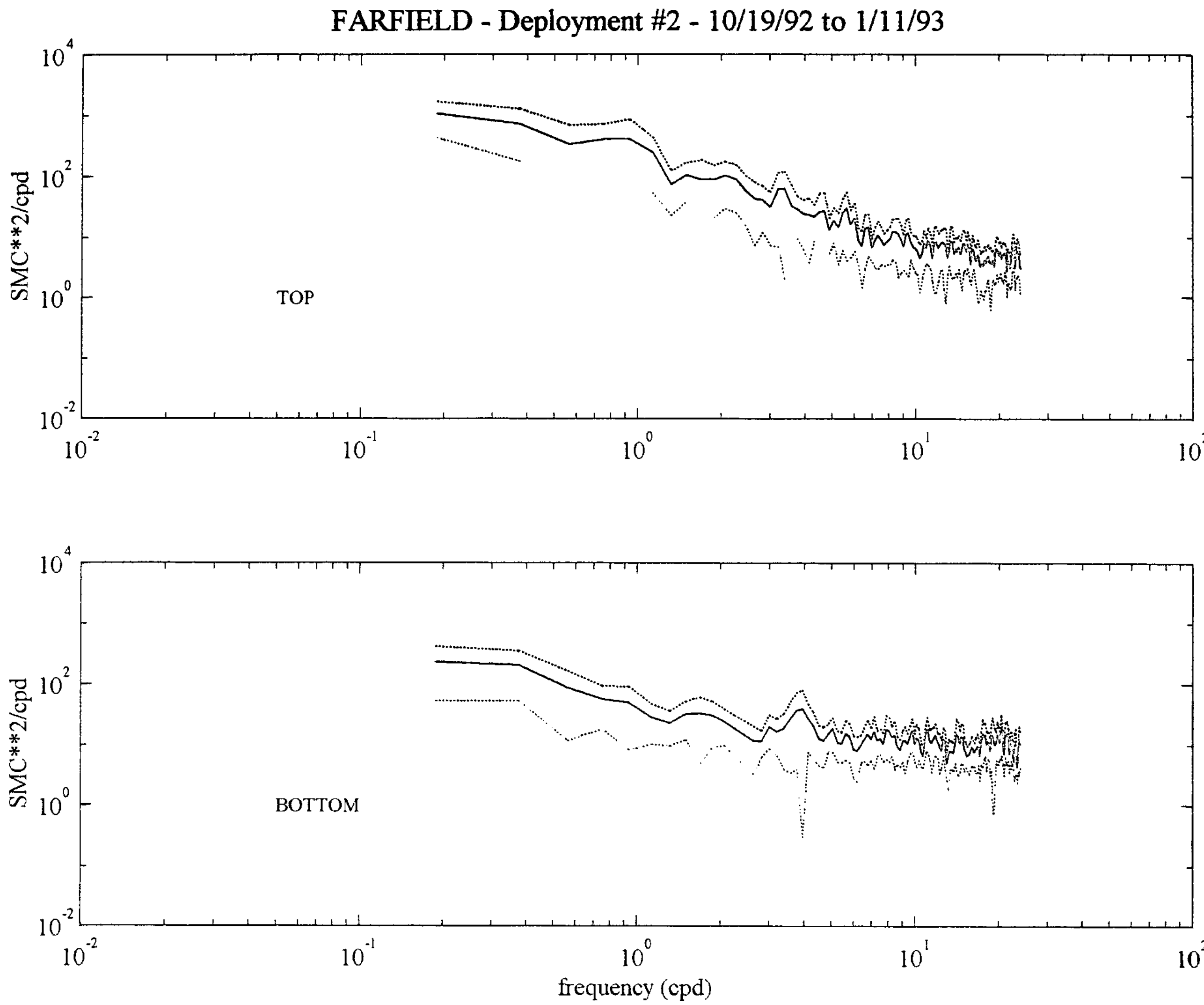


Figure 3.3-30. Spectral analysis of near-bottom suspended material concentrations from Farfield station for Deployment 2. Dashed lines delimit the 95% confidence interval.

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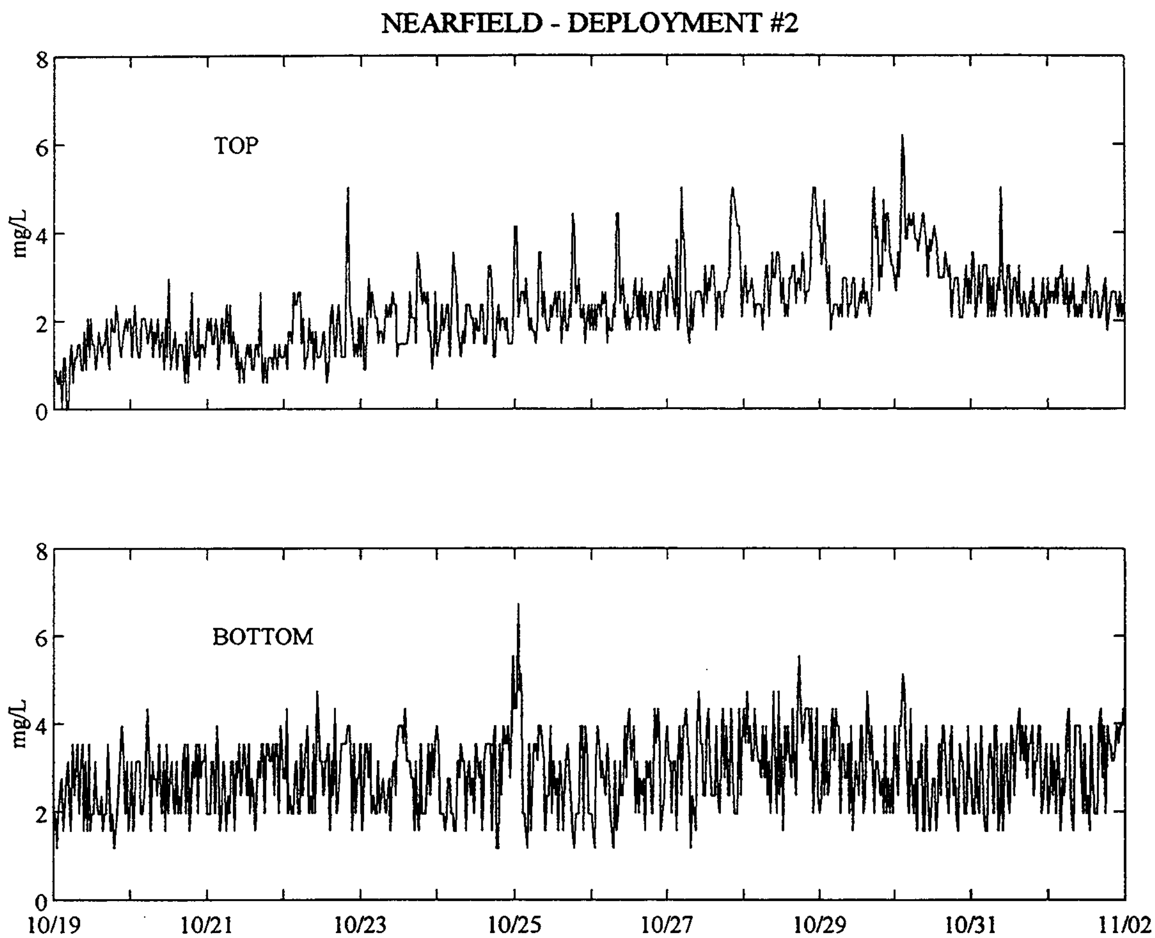


Figure 3.3-31. Time series observations of near-bottom suspended material concentrations from Nearfield station for Weeks 1-2 of Deployment 2.

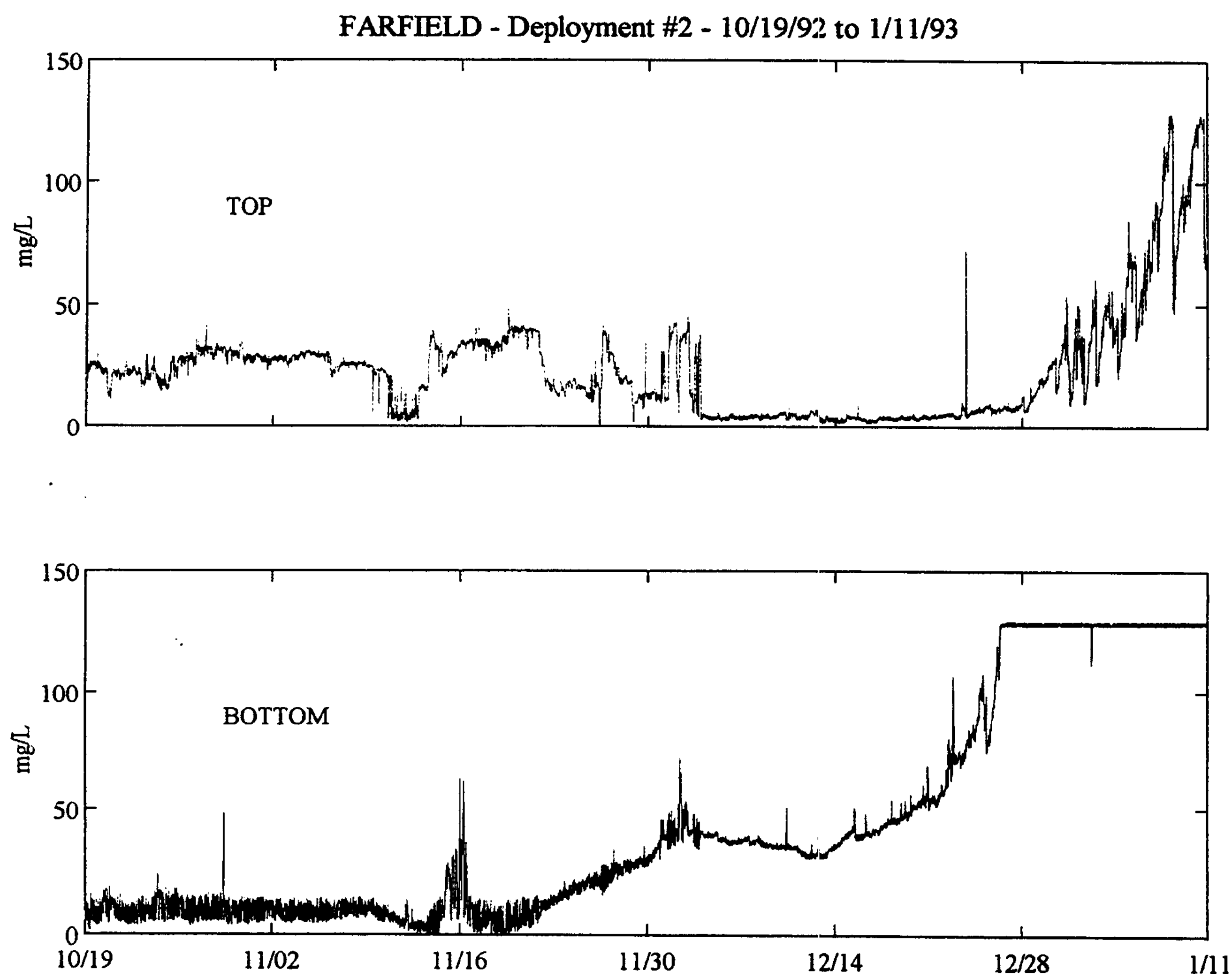


Figure 3.3-32. Time series observations of near-bottom suspended material concentrations from Farfield station for Weeks 1-2 of Deployment 2.

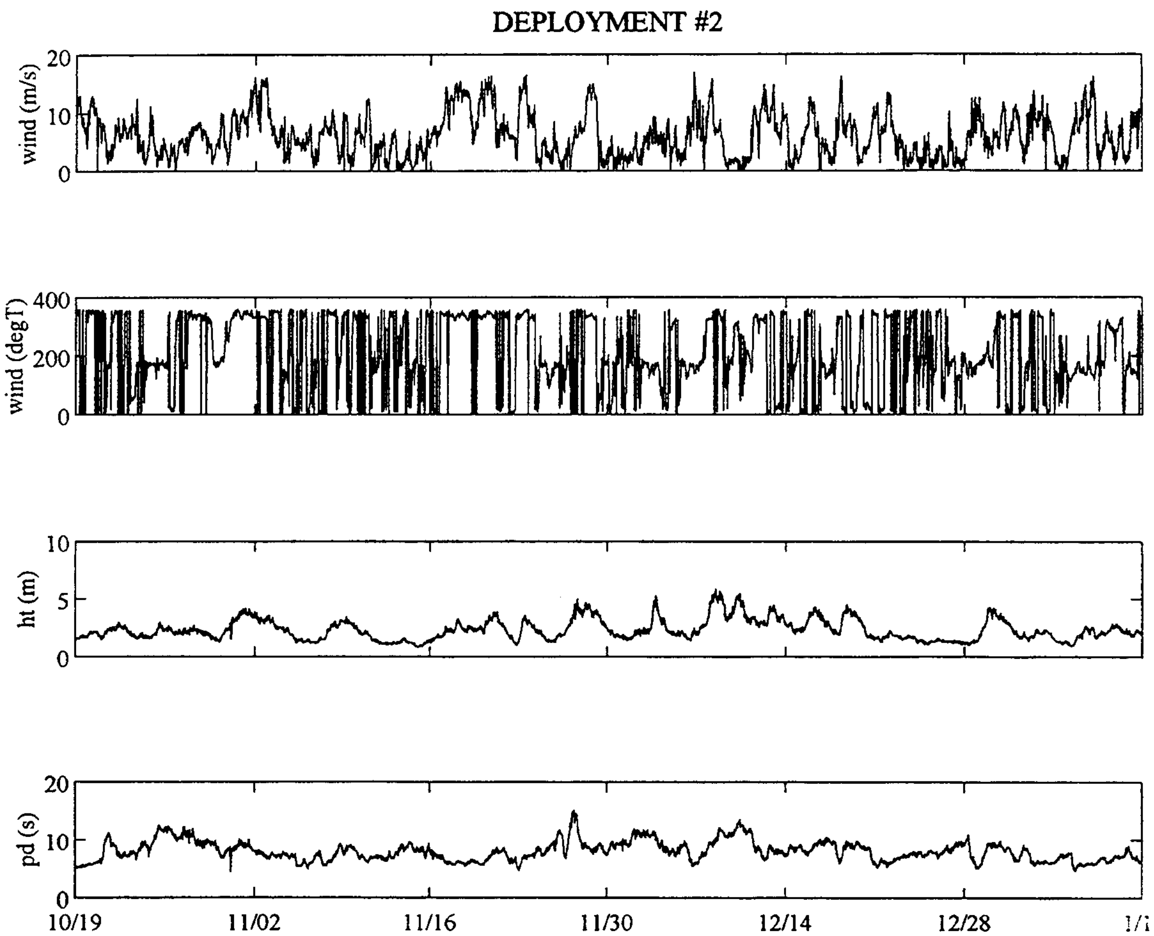


Figure 3.3-33. Meteorological observations from CMAN station PTGC1 and concurrent surface wave conditions for Deployment 2.

### 3.3.3.3 Deployment 3 (9 January 1994 – 7 January 1995)

Platform Hidalgo was operational during much of this deployment, aperiodically discharging spent drilling muds and cuttings into the water column (Figure 3.3-34). Platforms Harvest and Hermosa were not operational during this period. Suspended material concentrations at both Nearfield and Farfield were low with average values remaining below 10 mg/l for the period of observation (Figure 3.3-35). The response observed at each of the stations was similar to that observed at the upper sensors during the previous deployments. Again the records fail to provide any indication of dominant spectral signatures with energies distributed over three orders of magnitude (Figure 3.3-36). Review of the initial weeks of the suspended material record indicates that distributions at both stations were best characterized as a low mean value with small, near-random variations (i.e., aperiodically perturbed by large amplitude, relatively short duration events; Figure 3.3-37).

The optical data from each station again display progressive degradation apparently due to bio-fouling. These effects were most pronounced at Nearfield, thereby limiting the useful period of record to approximately two months (Figure 3.3-35). The Farfield record remained relatively uncontaminated for nearly six months.

In contrast to the relatively unperturbed nature of the record obtained during Deployment 2, time series suspended material concentrations during Deployment 3 displayed a number of marked perturbations with the largest amplitude, longest duration event appearing in the Nearfield record over the period February 10 to February 28, 1994 (Figure 3.3-35). Peak concentrations during this event approached 100 mg/l. Although similar concentrations were observed during previous deployment periods none of the earlier events displayed the persistence of the February 1994 perturbation. No coincident event appeared in the Farfield record although an evident perturbation, albeit smaller in amplitude, began on March 1, 1994 and continued for approximately one week (Figure 3.3-35). Several additional perturbations appear in the Farfield record, one just after the beginning of the deployment and several later in April.

Review of the meteorological data for the deployment period (Figure 3.3-38) fails to provide a clear indication of a correlation between instantaneous wind stress and near-bottom suspended material concentrations. Several wind events occurred during Deployment 3 but none were coincident with the observed perturbations in suspended load. Several wind events precede observed periods of increased concentration, again suggesting that the materials passing the monitoring site could be sediments suspended by the local wave field in shallower waters and subsequently transported offshore. An alternative view is that the observed perturbations are due to material discharges from the operating platform. However, reviews of the platform data indicate that during the period of the maximum concentration perturbation, around the 22nd of February, there was no-discharge of muds or cuttings (Figure 3.3-34). This no-discharge period extended from approximately the 10th of February to the 1st of March.

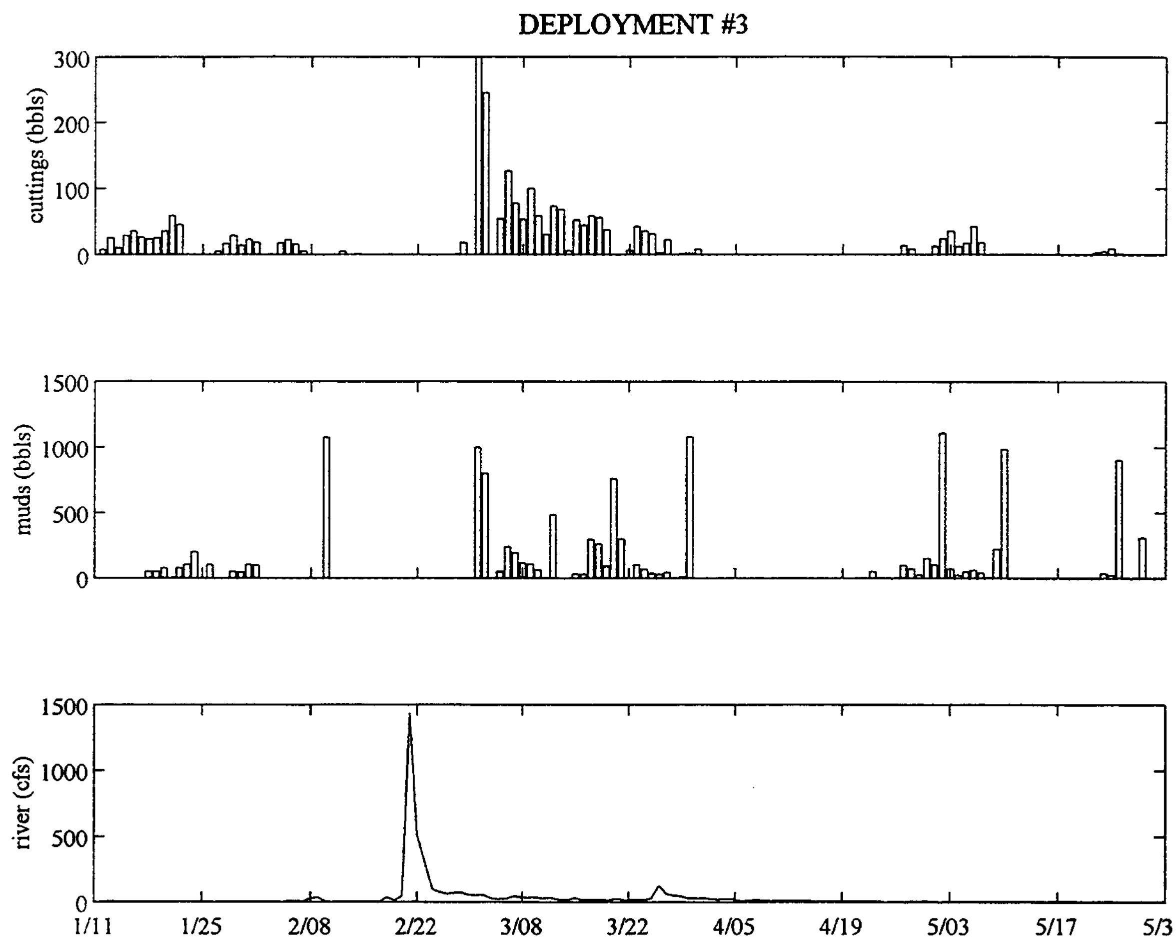


Figure 3.3-34. Platform Hidalgo discharge and concurrent average daily streamflow from the Santa Ynez River for January - May, 1994.

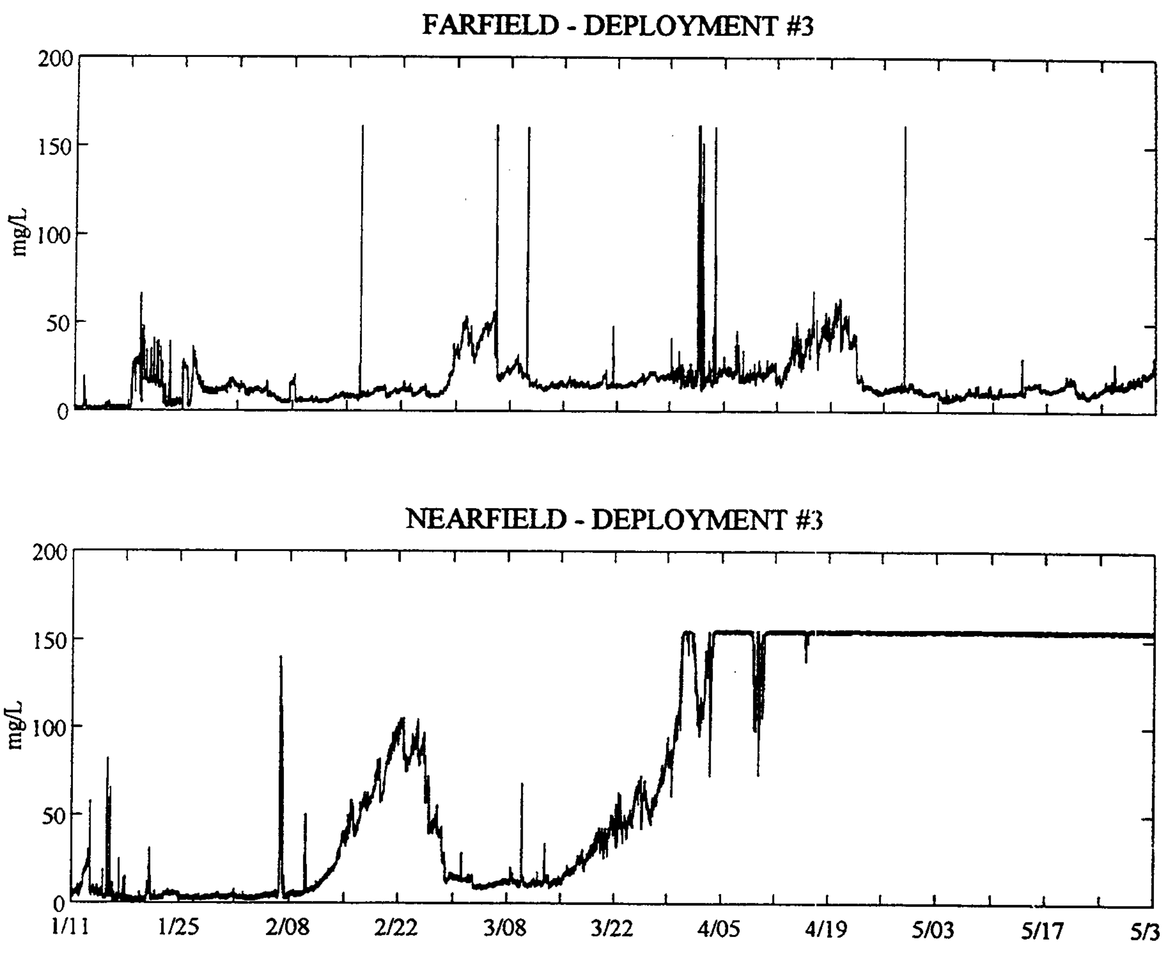


Figure 3.3-35. Time series observations of near-bottom suspended material concentrations from Nearfield and Farfield stations for Deployment 3.

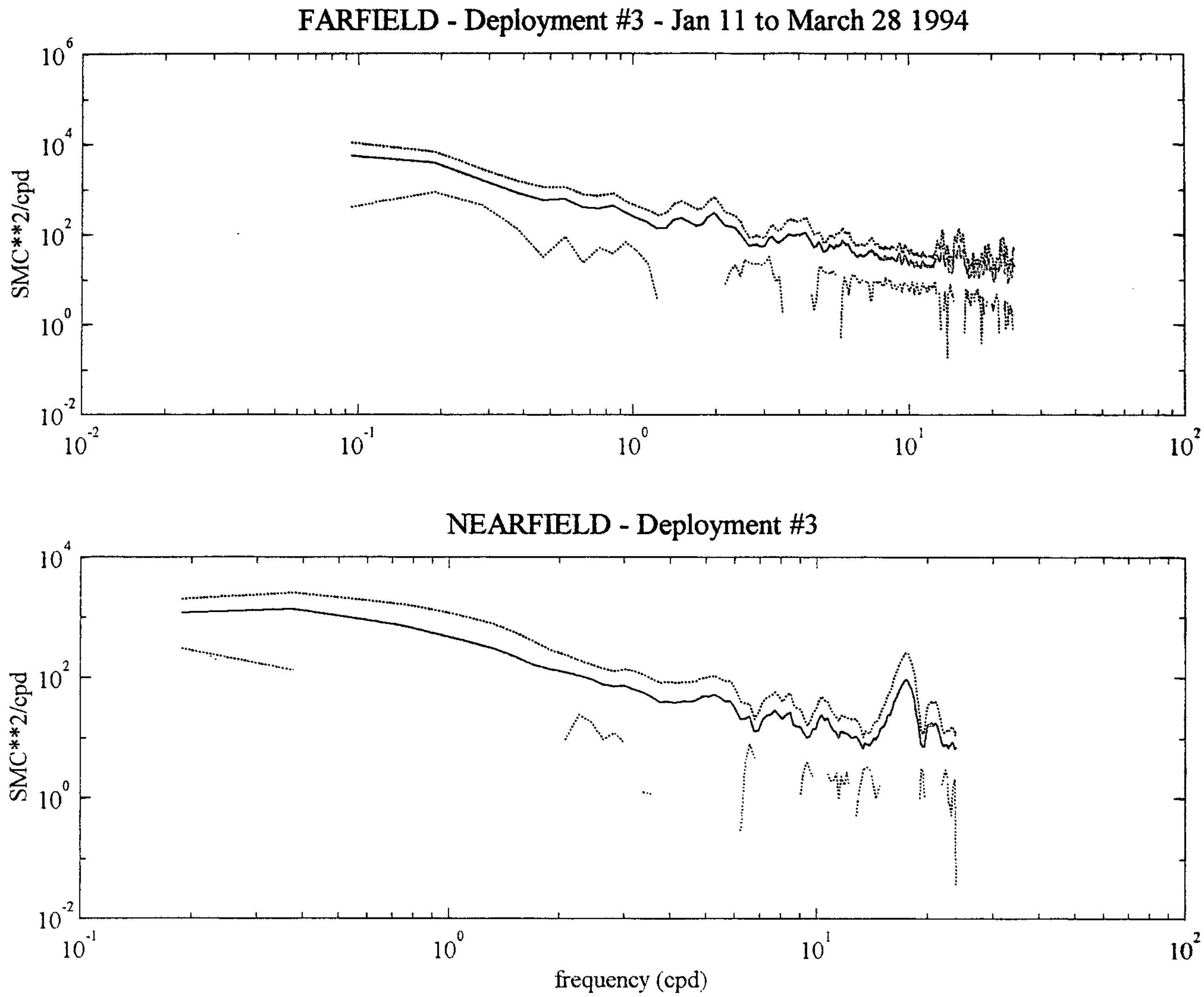


Figure 3.3-36. Spectral analysis of near-bottom suspended material concentrations from Nearfield and Farfield stations for Deployment 3. Dashed lines delimit the 95% confidence interval.

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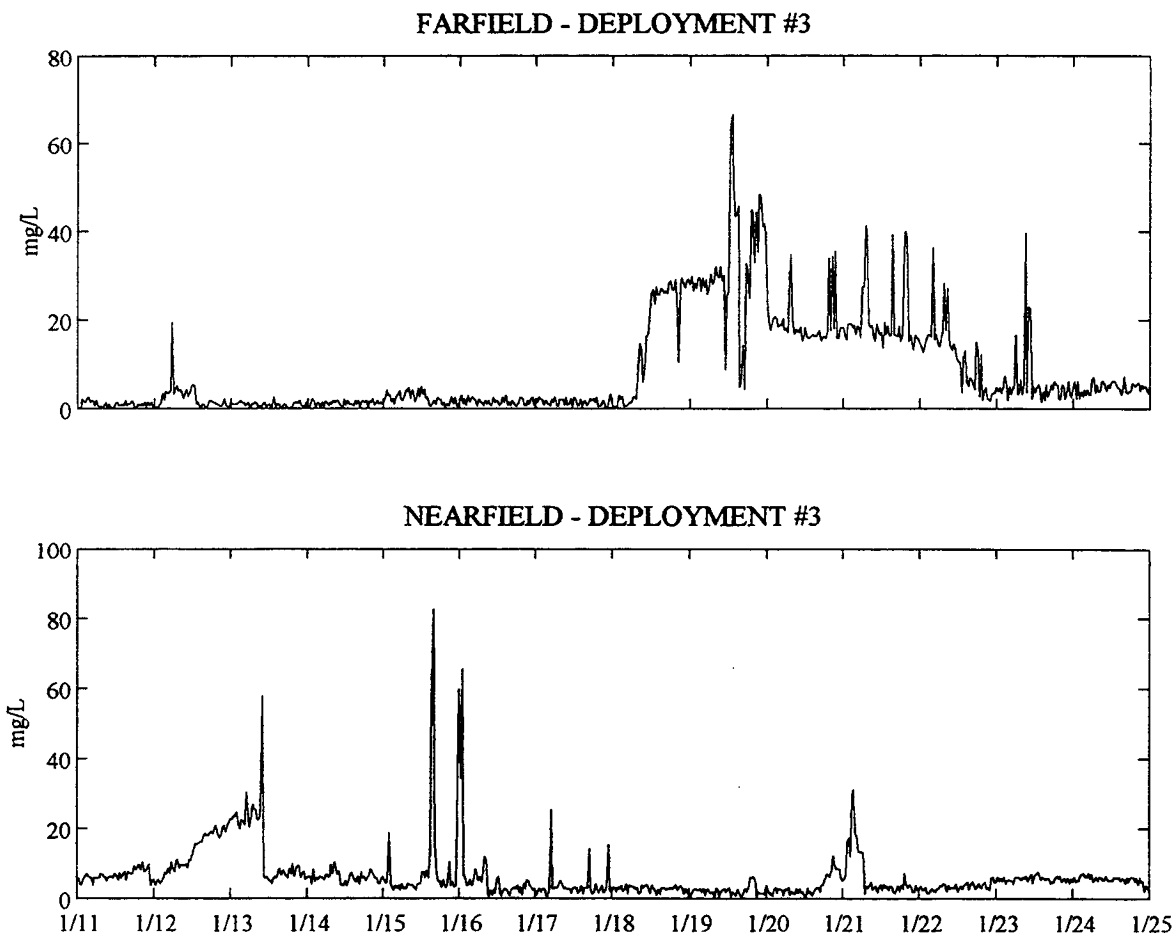



Figure 3.3-37. Time series observations of near-bottom suspended material concentrations from Nearfield and Farfield stations for Weeks 1-2 of Deployment 3.

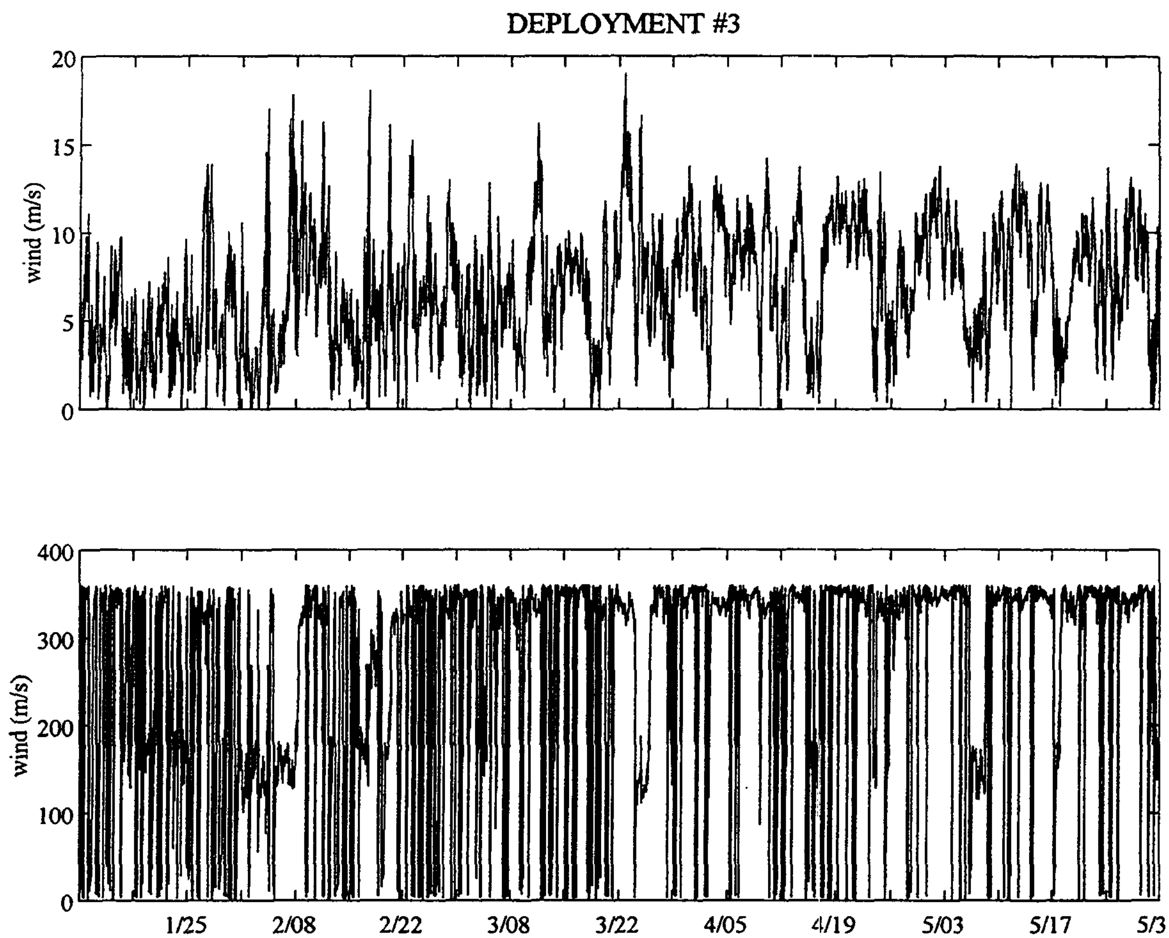



Figure 3.3-38. Meteorological observations from CMAN station PTGC1 for Deployment 3.

In addition to Farfield resuspension and transport or platform discharge, the suspended material perturbation at Nearfield could be the result of high discharge from local freshwater streams. Using the Santa Ynez River as an indicator of local streamflow conditions, late February, 1994 was a period of increased streamflow with a maximum around the 22nd (Figure 3.3-34). However, despite this coincidence the limited response of the salinity field to local streamflow conditions, discussed above, makes it less likely that this is the only source. Rather, the perturbation may be the result of several factors acting in combination. For this event, the combined effects of nearshore, wave dominated resuspension and river discharge, with the resulting suspended load transported offshore past the monitoring station, appear to be the dominant factors. In such a system the perturbation observed at Farfield would be produced by the same range of factors, with the delay representing the result of the variant trajectories affecting the flow field. One factor that was not involved in the observed perturbation is platform-associated discharges of drilling muds and cuttings.

### 3.3.4 Discussion

Data from the bottom mounted arrays provide an indication of significant spatial and temporal variability in the near-bottom sediment transport regime in the region near Platform Hidalgo. This variability, noted in previous investigations addressing local drilling mud discharge effects (Steinhauer and Imamura 1990), complicates data analyses and requires the use of relatively long and comprehensive data sets for process-oriented studies. This complexity makes it difficult to establish cause and effect relationships. The system is clearly perturbed by a variety of factors, acting singly and collectively, that serve to alter both the supply of suspended materials and their transport rates and pathways. These interactions yield a material field characterized by low, long-term average concentrations which are aperiodically perturbed by the passage of high concentration "clouds" of sediment laden waters. Suspended material concentrations in these clouds can exceed the long-term average values by two orders of magnitude over periods of more than seven days. These characteristics determine the sediment exposure affecting the local biological communities. The influence of platform-associated discharges must be scaled against the characteristic variability of the natural processes that affect the regional suspended material field.

The variability evident in the suspended material data and the absence of simple correlations with surface wind and/or wind wave conditions provides clear indication that both the Nearfield and Farfield stations are, under most conditions, beyond the area of direct surface wave influence. This appears consistent with previous observations on the California shelf which indicate that waves become a significant factor affecting sediment transport inshore of the 145m isobath (Cacchione, et al. 1987). Materials moving past these stations appear to be primarily supplied by advection of sediments that are resuspended by waves acting in shallower inshore areas, particulates introduced via river discharge and atmospheric deposition, intruding oceanic waters, and water column productivity. The scales of variability, both spatial and temporal, associated with this system are small, thus establishing some constraints on sampling protocols if accurate identification of the relative contribution of each of these sources is to be determined. For example, the array data indicate that the dynamics of the region in the vicinity of the Farfield station are substantially different than those affecting Nearfield. These differences, appearing in both the near-bottom flow and the suspended material field, suggest that 5 km may be an approximate maximum for the spatial scales of variability in this area. Further, the lack of correlation between events at Nearfield and Farfield may affect the utility of the latter station as a control since local biota would be exposed to a different range of conditions than those experienced at Nearfield. These differences need to be factored into the evaluations of the potential effects of drill platform discharges on the adjoining biological community.

## 3.4 TRANSPORT OF DRILLING MUDS

### 3.4.1 Introduction

Platforms Hermosa and Hidalgo began drilling operations in September and November 1993, respectively. Hermosa discharged 820 $m^3$ of drilling muds over a 30-day period and Hidalgo, 3850 $m^3$ over a six-month period. Drilling muds are primarily composed of fine silt and clay particles with only a small fraction of large particle sizes. As described in Section 3.2, the currents are quite dynamic off Pt. Arguello with a tendency to flow poleward during the summer and winter and equatorwards in spring. Drilling muds are discharged about 34 m below the surface, equating to about 100 to 150 m above the sea-bed. Strong currents, slow particle sinking speeds, and a highly variable discharge rate means that drilling muds are likely to be dispersed over a wide area. The exception will be the heavy fraction of material (sand-sized particles) that will be deposited close to the platform.

In Phase II, three platforms, Hermosa, Harvest, and Hidalgo, discharged a combined total of 41,380 $m^3$ of drilling muds over a two-year period (February 1987 to January 1989). These deposition and sediment fluxes were modeled using a plume and particle tracking model with a single sinking rate (Coats 1994). The large volume discharge means that there was a substantial flux of the principal tracer of drilling muds, barium, to the sea floor, and reasonable agreement was achieved between modeled and measured barium fluxes over three deployments of sediment trap arrays (Coats 1994). An independent modeling approach for determining the region of the sea floor that receives settling drilling muds has been used for the Phase III discharges. The present model is similar to that used by Coats (1994) in that a simple particle tracking algorithm is used. However, differences are that more than one size class of particles is considered, more than one current meter mooring is used to estimate the horizontal advection of the particles, and higher resolution bathymetry is used. The model is described in Hamilton and Ota (1993) as used to investigate the deposition of dredged material from proposed deep water disposal sites off San Francisco.

### 3.4.2 Model Inputs

The particle deposition model (Section 2.2.4) requires detailed bathymetry, current velocity time series data, and discharge data in the form of drilling mud composition, and discharge rate. The bathymetry is constructed from the NOAA/NOS 15 second gridded depth data for the 1° x 1° latitude x longitude square surrounding Pt. Arguello. The grid is not complete but is very dense in coastal regions with depths less than 200 m. These data were interpolated to a 250 m UTM grid which is the basic grid of the model. The interpolation can produce some artificial hills and holes, but these are restricted to deep water areas where the original data are sparse.

Current records are from the P, S5, S6, and I moorings (Figure 2.1-1). S5 was just north of Platform Hermosa during its September 1993 discharge period, and P was adjacent to Platform Hidalgo. S6 and I provide some Farfield data for the more slowly sinking particles that disperse offshore or to the southeast, respectively. The mid-depth, 40-HLP currents from these moorings during the discharge period are shown in Figure 3.4-1. The Hermosa discharges took place during the poleward flowing summer-winter regime. The Hidalgo discharges were mostly in the spring regime with weak fluctuating currents at P and strong southward flows at S6. These records are discussed in more detail in Section 3.2.

The daily volume discharge (bbls) of drilling muds from Platforms Hermosa and Hidalgo are also shown in Figure 3.4-1. It can be seen that discharges are highly variable (e.g., 0–1300 bbls) with 100–200 bbls being typical. The composition of Hermosa and Hidalgo muds (Table 3.4-1) was estimated as the average of a number of different samples taken from different well depths during the drilling periods. Size classes represented are 1, 5, and 6, with silts and clays predominating. The total number of particles used for each size class are 5,160 and 16,390 for the Hermosa and Hidalgo discharges, respectively. Table 3.4-1 also gives the voids ratio for the particle size classes (Section 2.2.4) and the time required to sink 100 m. For example, at 30 cm/s, a common velocity in Figure 3.4-1, class 6 particles will travel a horizontal distance of 60 km in the time taken to descend 100 m. Thus, many class 6 particles are lost out of the grid, particularly during the poleward flowing summer-winter regime.

### 3.4.3 Results

Deposition patterns were calculated for the Hermosa and Hidalgo drilling periods in 1993 and 1994. Hermosa only drilled for 30 days and the relative concentrations in $\mu g/m^2/kg$ of particle size class dumped are given for size class 1 (large heavy particles) and class 5 (coarse silts) in Figures 3.4-2 and 3.4-3, respectively. As expected, the heavy particles are clustered around the platform and cover an area of only 2.75 $km^2$. In contrast, the silt-sized material is widely and thinly dispersed by the strong poleward currents in September 1993, and none of the material is deposited near the drilling platform. Note that some material is deposited to the south and onshore of the platform. This probably is caused by the southward flows at S5 after about

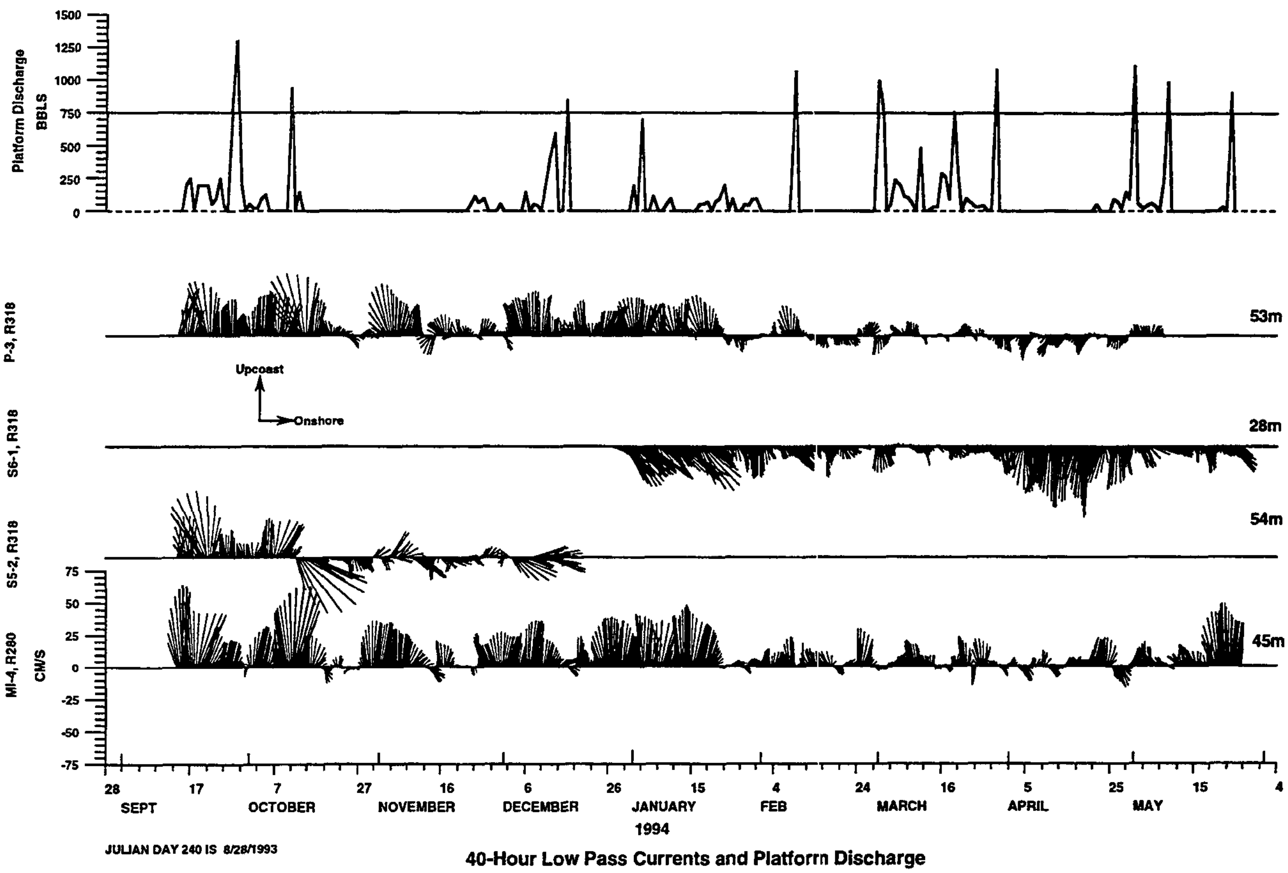



Figure 3.4-1. Mid-depth 40-HLP currents and Hermosa and Hidalgo drilling mud discharges for the drilling periods.

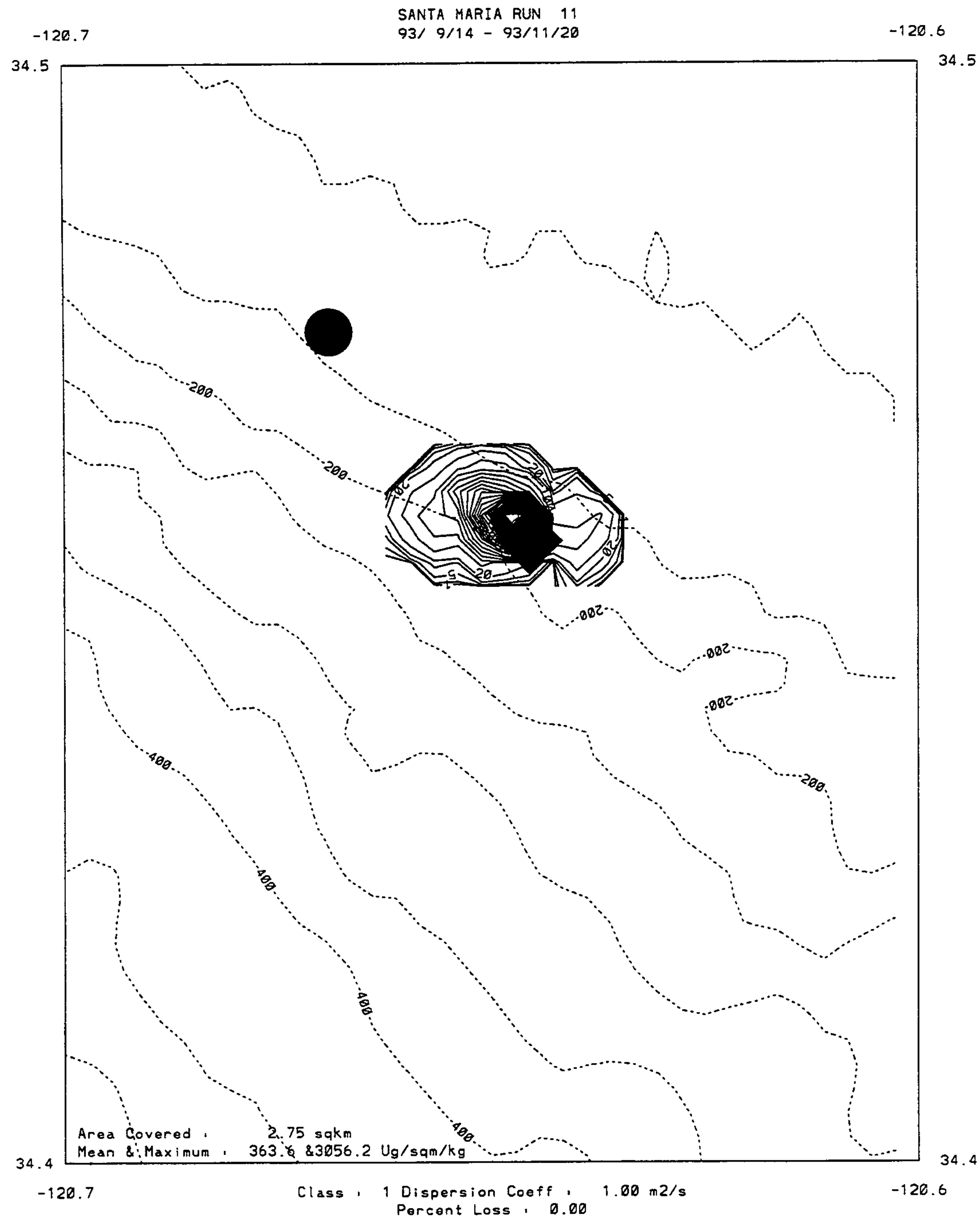



Figure 3.4-2. Class 1 particle concentrations from Hermosa discharges. Contour levels are 1, 2, 5, 10, 20, 50, 100, 200, etc. Moorings and platforms are marked with a circle and diamond, respectively, 500 m in width.

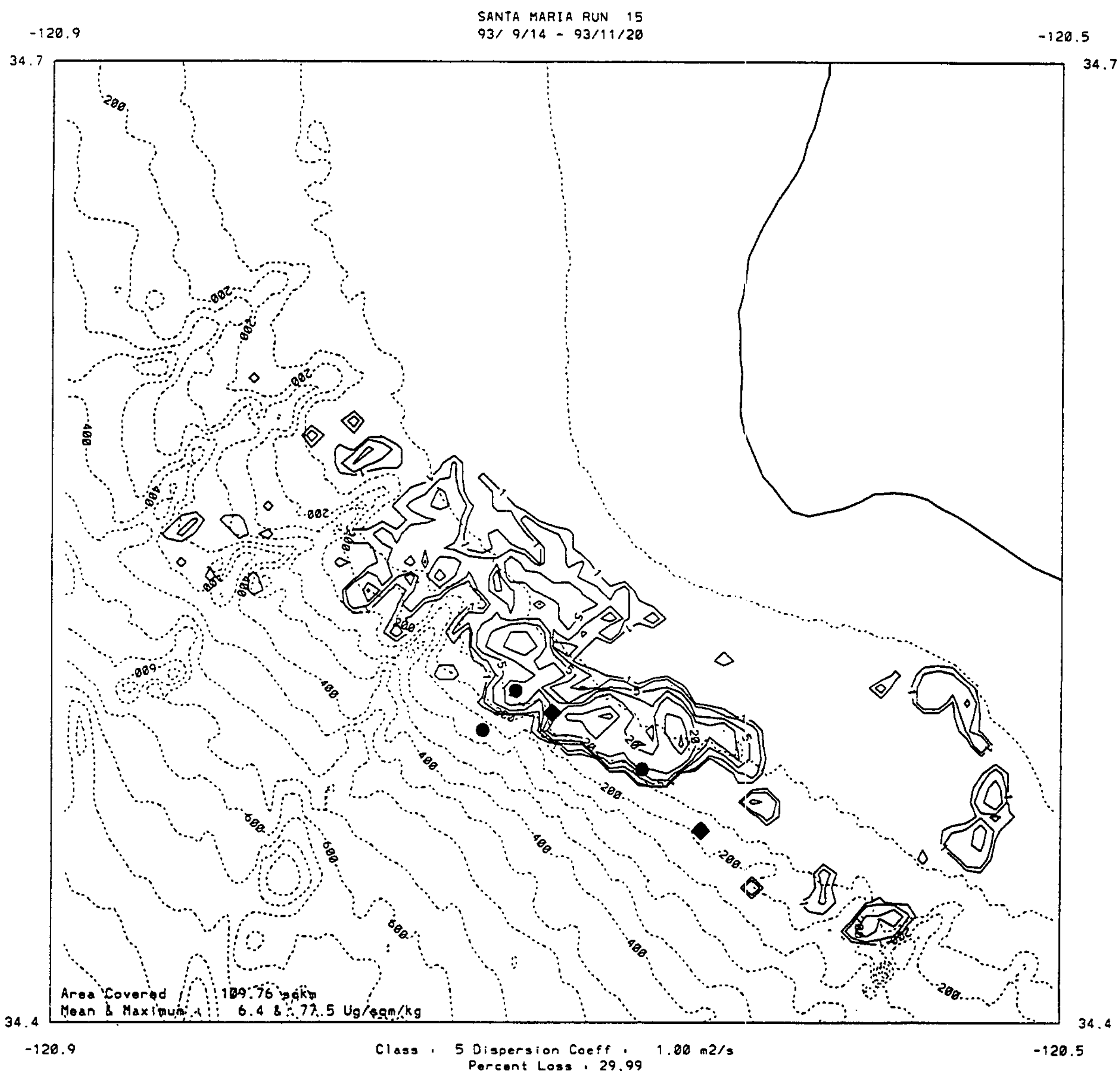



Figure 3.4-3. Class 5 particle concentrations from Hermosa discharges. Contour levels are 1, 2, 5, 10, 20, 50, 100, 200, etc. Moorings and platforms are marked with a circle and diamond, respectively, 500 m in width.

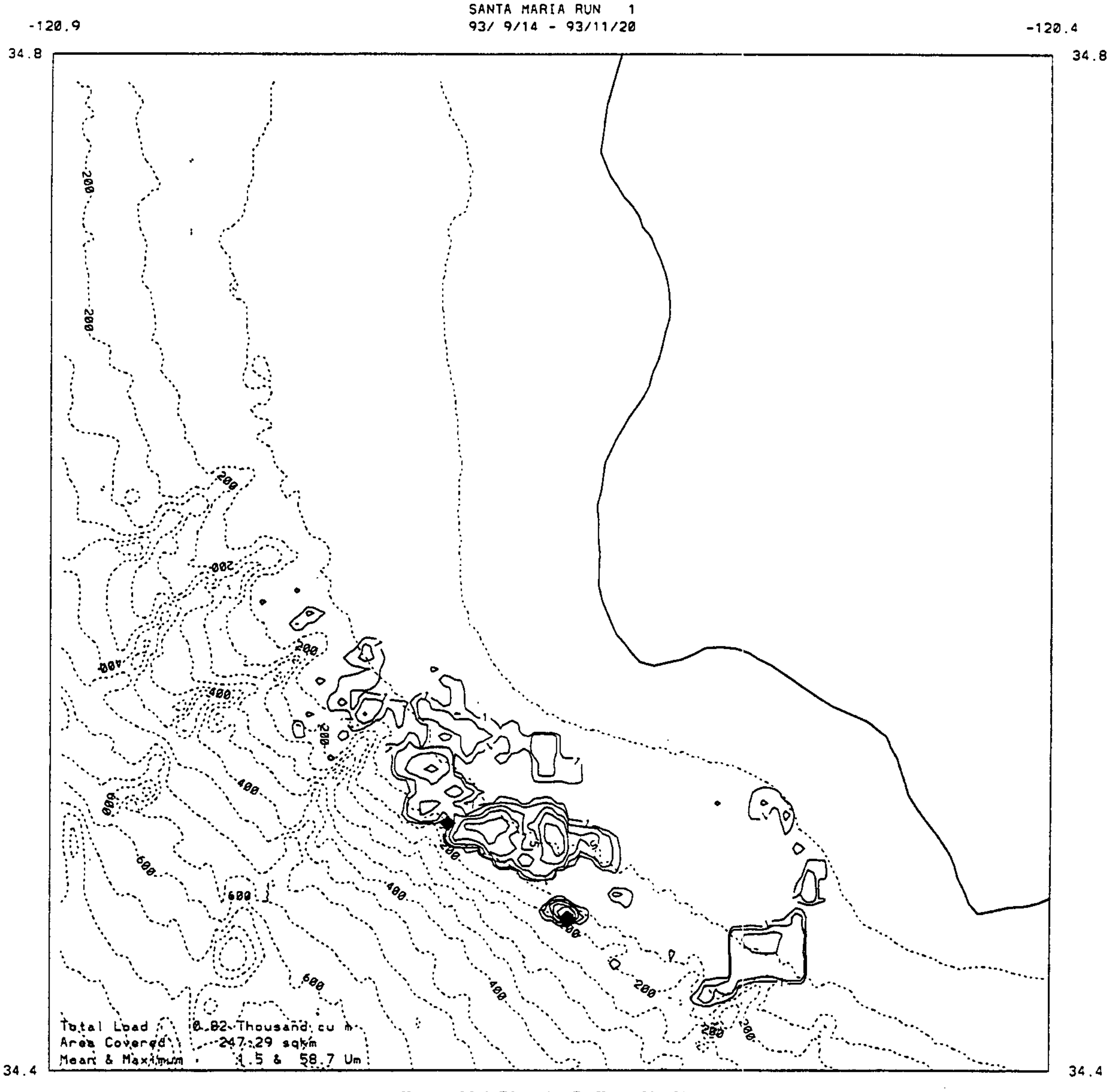
October 10. Thirty percent of class 5 material is advected out of the system and over 80% of class 6 (not shown). Deposition is calculated for the volume fractions in Table 3.4-1 and are shown in Figure 3.4-4. Nearly 50% of the material does not settle in the region of the map and the patterns of deposition resemble a combination of class 1 and class 5 (Figures 3.4-2 and 3.4-3). The results imply that between 1 and 60 microns of material is deposited by the short period of Hermosa drilling operations. This is far too small a volume to detect using chemical tracers (barium).

Table 3.4-1. Phase III platform discharges of drilling muds.

| Sinking Class | Particle Type | Velocity (m/s) | Voids Ratio | Time to Sink 100m (hours) | Fractional Volumes Hermosa (%) | Fractional Volumes Hidalgo (%) |
|---|---|---|---|---|---|---|
| 1 | Coarse Sand | 0.086 | 0.67 | 0.32 | 1.55 | 0.77 |
| 5 | Coarse Silt | 0.0014 | 0.67 | 20 | 9.91 | 12.28 |
| 6 | Clay-Silt | 0.0005 | 4.00 | 56 | 7.27 | 17.87 |
| Fluid | -- | -- | -- | -- | 81.27 | 69.08 |
| Volume Discharged ($m^3$) | -- | -- | -- | -- | 820 | 3850 |

Platform Hidalgo drilled for nearly six months beginning in November 1994. The relative concentrations of class 1 and 5 materials are shown in Figures 3.4-5 and 3.4-6, respectively. Again, the heavy material is clustered around the platform and covers an even smaller area (1.2 $km^2$) than for Hermosa because of a less vigorous current regime and more shallow water depths (130 m versus 180 m) at the Platform Hidalgo site. The class 5 material is about equally dispersed northwest and southeast of the platform. This is a consequence of the more variable current regime in the spring, which also means that less of class 6, the silt-clays, is lost (~40%; not shown) to the system than for Hermosa. However, the region of deposition with a thickness greater than one micron is extensive, over 566 $km^2$, because of the strong dispersion of the particles (Figure 3.4-7). The average deposition thickness is only five times that of Hermosa (7.3 μm versus 1.5 μm) and thus is still minuscule. Such low sediment fluxes are unlikely to be detected directly by the sediment traps. This is consistent with the lack of elevated barium or gradients of barium concentrations in the sediment trap records near the platforms for the drilling periods (Appendix B).

SANTA MARIA RUN 1
93/ 9/14 - 93/11/20




Hermosa Muds Dispersion Coeff : 1.00 m2/s
Percent Loss : 47.04

Figure 3.4-4. Deposition in μm from Hermosa discharges. Contour levels are 1, 2, 5, 10, 20, 50, 100, 200, etc. Moorings and platforms are marked with a circle and diamond, respectively, 500 m in width.

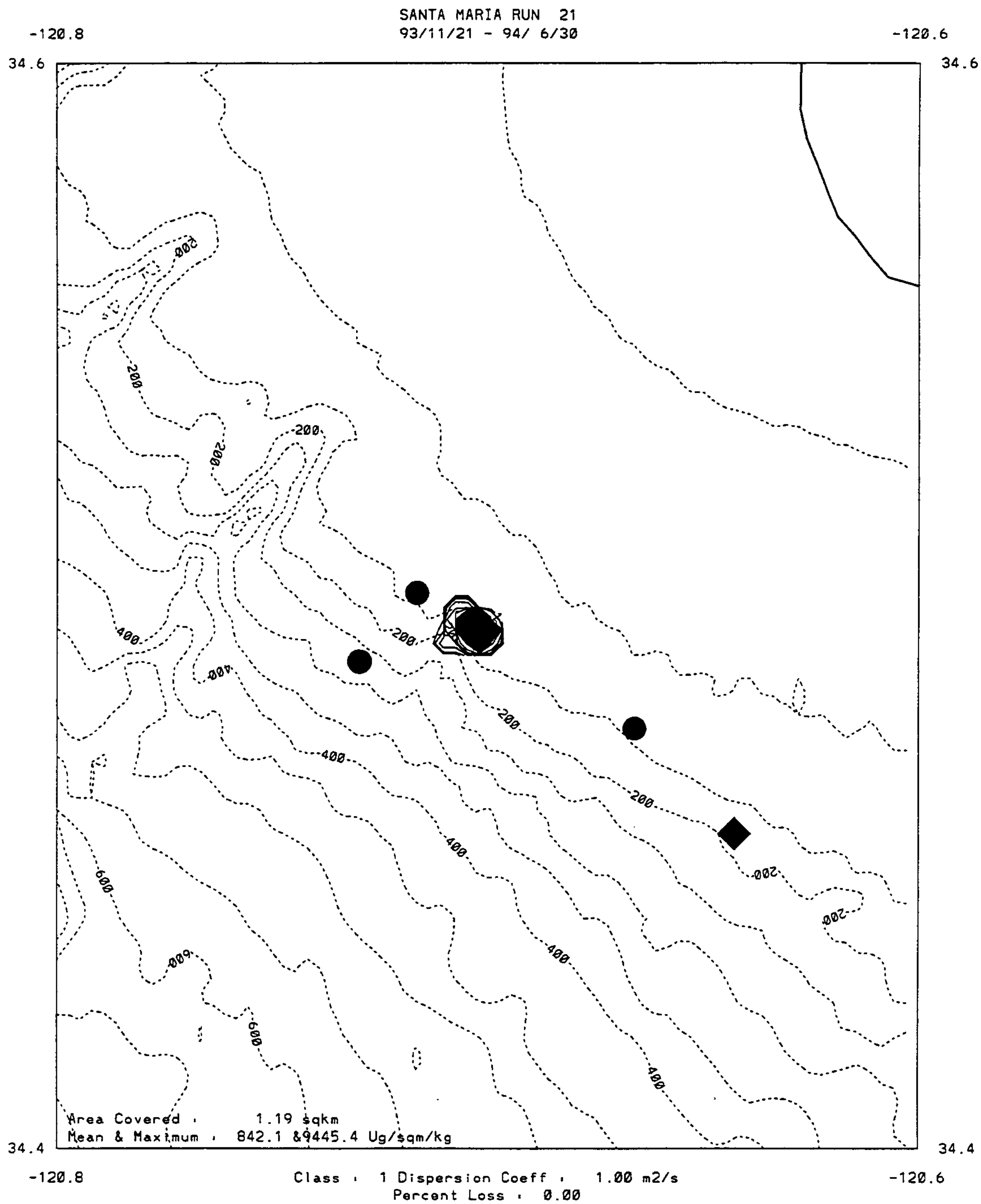



Figure 3.4-5. Class 1 particle concentrations from Hidalgo discharges. Contour levels are 1, 2, 5, 10, 20, 50, 100, 200, etc. Moorings and platforms are marked with a circle and diamond, respectively, 500 m in width.

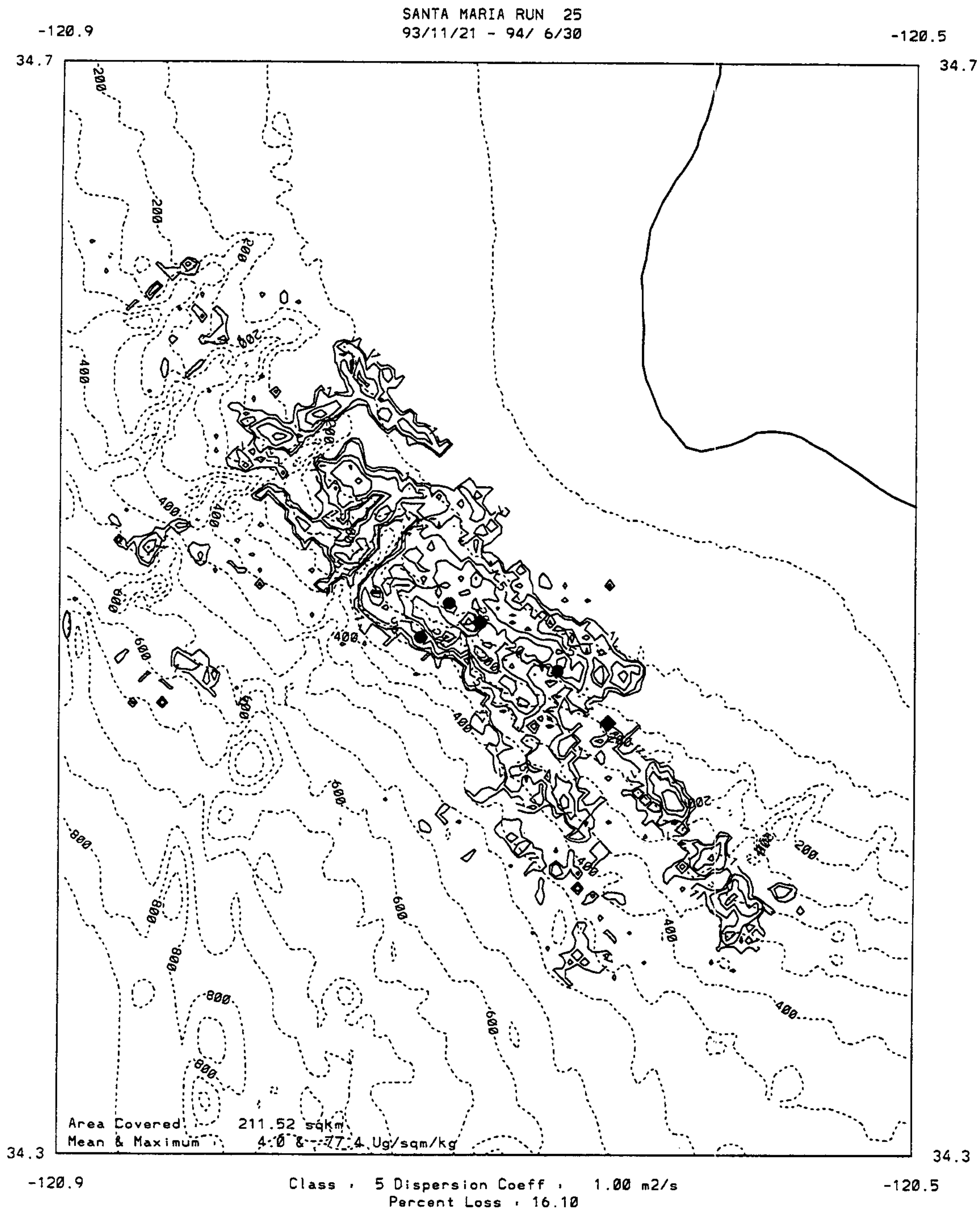



Figure 3.4-6. Class 5 particle concentrations from Hidalgo discharges. Contour levels are 1, 2, 5, 10, 20, 50, 100, 200, etc. Moorings and platforms are marked with a circle and diamond, respectively, 500 m in width.

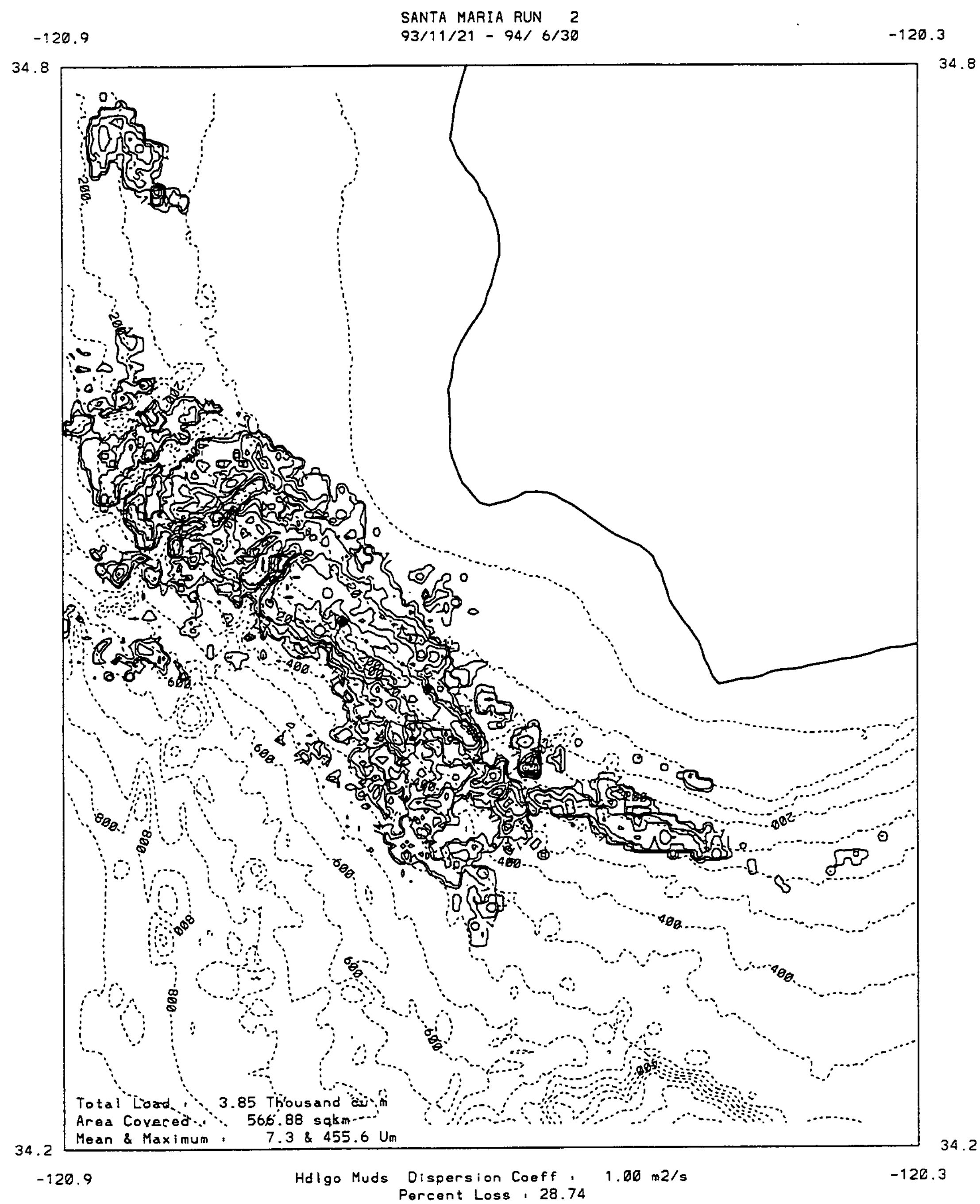



Figure 3.4-7. Deposition in µm from Hidalgo discharges. Contour levels are 1, 2, 5, 10, 20, 50, 100, 200, etc. Moorings and platforms are marked with a circle and diamond, respectively, 500 m in width.

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# 4.0 SUMMARY AND RECOMMENDATIONS

## 4.1 INTRODUCTION

Current velocity, temperature, and bottom pressure were measured for approximately two and a half years on moorings placed at one fixed position (the primary mooring near Platform Hidalgo) and a variable position (the secondary mooring) alongshore and cross-shore from the primary mooring. Resulting data have been used in conjunction with satellite SST imagery to describe elements of the circulation patterns which might be expected to affect transport and subsequent deposition of drilling muds and cuttings discharged from local oil and gas platforms. These current velocities were supplemented with current/temperature observations made by SIO at the western end of the Santa Barbara Channel. Taken as a group, nearly continuous data were available to support synthesis of oceanographic processes and numerical particle transport modeling.

Additionally, for three extended deployments over a three-year measurement effort, near bottom observations of current velocity, salinity, temperature, and suspended and deposited sediment load were made at two sites. One site was close to Platform Hidalgo (Nearfield) and one (Farfield) was placed sufficiently far north that it was expected to be outside the sphere of direct deposition of muds and cuttings. Due to instrument problems, bottom current data measured during the first two deployments are of less use than during the third deployment.

A numerical particle tracking model was used to simulate transport, deposition, and accumulation of muds and cuttings discharged from Platforms Hermosa and Hidalgo. This methodology allowed estimation of the magnitude and areal distribution of material from these releases.

The study area is in an oceanographic transition zone between warmer poleward flowing water associated with the Southern California Countercurrent (coming to the area through the adjacent Santa Barbara Channel) and cooler, often slightly fresher water of the southward flowing Coastal California Current. The broader transition zone between these two controlling patterns can move up- and downcoast as well as on- and offshore so that the study area is under the influence of different regimes having variable magnitudes. Because of the complex nature of currents in the vicinity of Point Arguello and the Santa Barbara Channel, specific patterns in measured currents can vary over comparatively short distances. This is shown in the differing currents that occurred at the primary and secondary mooring when the latter was offshore of the primary mooring, and between the primary mooring and those moorings nearer the entrance to the Channel.

Winds in the study area were usually directed downcoast and approximately parallel to the coast between Pt. Arguello and Pt. Conception. During winter, migrating storms can bring significant wind, rain, and wave events to the area. Increased rainfall and associated larger than usual discharges from local streams may contribute to the variations in sediment load measured by some of the near bottom sensors. Given the considerable water depth near Platform Hidalgo, it is unlikely that direct wave action was a cause of locally measured turbidity events. It is more likely that wave events caused material to be resuspended in shallower water and then transported to these deeper sites.

## 4.2 REGIONAL CIRCULATION PATTERNS

Data indicate that local tides are mixed with semidiurnal and diurnal components. Semi-diurnal ($M_2$) tidal currents at the primary mooring had amplitudes of approximately 3 cm $s^{-1}$, were relatively invariant with depth, and were rectilinear with a slight cross isobath orientation. In contrast, the semidiurnal tidal currents at the secondary mooring locations showed depth variations in current magnitude with greater currents speeds ($\approx$7 cm $s^{-1}$) at some of the secondary mooring sites. The diurnal ($K_1$) tidal currents at the primary mooring were generally weaker, more aligned with local isobaths and more depth variable than the $M_2$ tides. At the secondary mooring, $K_1$ tides varied depending on location and water depth. Tidal currents are a regular and periodic contributor to local currents, but are relatively weak compared to the potentially vigorous background and low frequency currents.

Mean currents over the entire measurement interval were dominated by a seasonally more vigorous and longer lasting summer/winter season and associated poleward directed transport of warmer water from the south. Low frequency currents were different in the summer/winter season and spring season: flow was generally upcoast (poleward) in summer/winter and equatorward in spring. The duration and characteristics of these seasonal patterns varied between years.

The spring season was characterized by equatorward currents in the upper portions of the water column. With increasing depth, mean currents varied in direction and decreased in magnitude. Strongest downcoast currents were near the surface with a weaker and sometimes reversing current nearer the bottom. These equatorward events were interrupted at times by weak poleward currents that were often associated with relaxation of the normally downcoast directed winds. In spring, water temperatures decreased as the equatorward flow moved cooler water into the area from north of Point Arguello.

A rather abrupt transition can occur from the equatorward flows of spring to the poleward flows of summer/winter. This transition did not appear to be linked directly to local winds. Poleward currents were often at a maximum at mid-depth (e.g., Figures 3.2-14 and 3.2-21), which may be associated with some slowing of surface currents by the downcoast winds. This general flow pattern brought warmer water to the Point Arguello area from the south through the Santa Barbara Channel. The resulting water column was stratified until the onset of winter storms and associated vertical mixing. Because of variations in the path, timing, and local intensity of these winter storms, the timing of the creation of the mixed surface layer varied significantly from year to year. It is possible that embedded in the generally poleward directed currents were eddies and meanders that produced clockwise rotation seen in the current vectors. The transition from summer/winter to the following spring season was generally more gradual than the fairly abrupt transition into this season.

## 4.3 NEAR-BOTTOM CONDITIONS

The usable temperature and current velocity data are generally consistent with an extension to near the bottom of some patterns described in the discussion of regional oceanographic conditions. As might be expected the amplitude of the temperature response of the bottom water was less than seen higher in the water column

Data from the bottom mounted arrays showed that the near bottom sediment transport regime has significant variability in time and space. It was common that correspondence did not occur in the time varying suspended material concentration between the Nearfield and Farfield sites even though they were relatively close to one another. It may be significant that the water depth at Nearfield was about 140 m and approximately 200 m at Farfield.

Substantial sediment concentration events were recorded at both sites; however, it was generally not possible to identify a local forcing mechanism that might produce the observed clouds of suspended material. This fairly consistent lack of correspondence in timing between aperiodic wind/wave events and increased concentrations strongly suggests that locally observed suspended material resulted from non-local processes. One possible scenario is that material passing the sensors originated in shallower water, possibly being resuspended due to wave action, and was then transported by regional circulation patterns to the measurement site. During Deployment 3, some of the observed suspended material may have resulted in part from substantially larger local stream discharge caused by increased rainfall amounts. Although probably of remote origin, near bottom clouds of material increased the local suspended material concentrations several orders of magnitude over the average, undisturbed or background concentration. The influence of the relatively limited discharge from Platform Hidalgo during this program should be scaled against this characteristic and naturally occurring variability in the regional suspended material field. Time series from the OBS provided no indication of material that could be identified as being discharged from Platform Hidalgo.

## 4.4 PARTICLE TRANSPORT MODELING

Phase III drilling at Platforms Hermosa and Hidalgo resulted in discharges of relatively small quantities of muds and cuttings. This material was discharged 34 m below the water surface, subsequently transported by regional circulation patterns and, for some size classes, deposited in the general study area. A numerical particle tracking model was used to simulate and quantify this expected sequence of transport and deposition.

To establish a frame-of-reference for the following discussion, it is helpful to scale the magnitude of the discharge being modeled in the present study. During a prior program (CAMP II), approximately 42,380 $m^3$ of drilling muds were discharged over a two-year measurement interval which was 10 times larger than the volume of muds and cuttings released during the present study.

The present model allows the volume by size class (and hence settling velocity) to be incorporated in the model input and subsequent particle tracking. Modeled transport of material used all available current profile data such that the closest available current data (i.e. primary, secondary, or supplemental, SIO, mooring data) controlled movement of a settling particle. In this scheme, the controlling time-dependent current profile used to transport a particle shifted depending on the location of the particle relative to a mooring. Bottom deposition was accumulated by size class over real bathymetry.

The differential distribution between material released at Platform Hermosa and Platform Hidalgo reflects the currents occurring during the different discharge intervals. During the summer/winter season when Platform Hermosa was releasing muds and cuttings, currents were larger with consequently wider dispersion and an associated larger sediment footprint. These conditions also allowed a larger percentage (as compared to Platform Hidalgo) of material to be advected out of the study area prior to being deposited on the bottom. Because of the amount of material leaving the area and the larger sediment footprint in combination with relatively small platform discharge, the depth of deposition of material from Platform Hermosa was between 1 and 60 microns – a very thin layer – with an average depth of 1.5 microns.

More material was released from Platform Hidalgo and the smaller more variable currents during the spring season resulted in less dispersion. However, these conditions combined to produce an average bottom accumulation of only about five times that at Platform Hermosa, or about 7.5 microns. The volume of material from either platform was insufficient to produce an identifiable volume or chemical (barium) signal in the sediment traps placed in the depositional footprint during the discharge periods.

## 4.5 RECOMMENDATIONS

The primary purpose of the physical oceanographic component of Phase III was to provide a description of the current regime to which biological, chemical, and sediment monitoring could be related, and to provide current fields for input into a numerical particle tracking model for predicting drilling discharges transport and deposition. The present project has been successful in making continuous times series of current velocity and temperature at three depths for over two and a half years. Such long-term, continuous records are relatively rare in oceanography and, if sufficiently long, can be used to resolve trends and periodic interannual variability. This is particularly relevant but fairly complex in a transition zone such as the present study area. For these and several other reasons, it would be beneficial if at least the primary mooring was redeployed to maintain and continue these data records. Any other recommendations on deployment of additional moorings should be coordinated with measurements available to NBS from other major studies, such as the SIO/MMS Santa Barbara Channel and Santa Maria Basin field experiments. Because of the locally short cross isobath coherence scale of currents in the vicinity of Pt. Arguello seen in data from this study, it would be appropriate and productive to investigate and better understand this variability, particularly offshore of the primary mooring. In a regional context, an improved understanding of this often abrupt transition between current regimes may have application to other regions in the Southern California Bight, such as the Santa Monica Basin.

The oceanographic regimes that influence the seasonal and other low frequency currents in the vicinity of Pt. Arguello and Pt. Conception often have an expression in the sea surface temperature field. As shown during the present project, satellite thermal images are one of the few data sources that provide a synoptic, regional view of a key oceanographic variable, SST. Consequently, SST imagery in conjunction with subsurface observations of currents and temperature can help provide regional scale, three-dimensional descriptions of the oceanographic regimes governing local transport patterns.

Because of potential impacts on local hard-bottom communities, partitioning sediment deposition between sources such as local oil and gas activities and from ambient or background suspended sediments is a concern in the present series of ecological studies. Ambient deposition is assumed to come from either resuspended sediments or from suspended material discharged primarily from rivers and creeks. Observations to date indicate that suspended sediment events in the vicinity of the hard bottom study sites generally were not from natural, local sources. Rather, these sediments likely were either resuspended at remote onshore locations and then transported towards the measurement sites, or they were transported by the regional circulation from the mouth of a local river or creek.

To understand better the local sediment budget, it is necessary to know where resuspension occurs and what causes it. Based on our present knowledge of local conditions, it is recommended that future studies measure near bottom currents and suspended sediments concentrations at a cross shelf sequence of stations. This design, in combination with regional wave observations made by NDBC, should provide information concerning the linkage between resuspension events at various depths and both waves and near bottom currents.

Resolving transport of locally discharged suspended sediments requires detailed information on the three-dimensional structure of current and sediment concentration fields. Transport patterns can be obtained from either hydrodynamic models or observations. Given the complex and dynamic nature of circulation in this region, a numerical model(s) should be used to reproduce current patterns. This type of model may not be presently available. Consequently, current and suspended sediment concentrations would need to be measured over at least a boundary grid at a resolution determined from time and spatial scales seen in existing and recommended current measurements. In conjunction with the material presented in this report, the above scenarios provide a brief framework for specific recommendations to enhance the understanding of regional and local circulation patterns:

(1) Maintain and continue the primary mooring in its present configuration and location.

(2) Deploy a small scale array of current meter moorings (in addition to the primary mooring) to investigate the cross isobath scales of variability. A possible design would be two secondary moorings: one at the S6 mooring site and another on the 500 m isobath seaward of S6. This could be linked to the coastal currents by another mooring placed on approximately the 50 m isobath, just seaward of the three-mile limit.

(3) Design and deploy near bottom instrument arrays, such as PMAs, containing instruments to measure local instantaneous velocities due to waves and background currents, temperature, and suspended load. The arrays should be placed at several (2-3) inshore locations in 25-50 m of water depth with an objective of better understanding the role of remote sediment resuspension on deeper hard bottom sites. At least one of these could be placed on a shoreward extension of the small mooring array described in (2).

(4) Quantify the potential contribution of naturally occurring sources of sediment which can provide background sediment deposition.

(5) Develop information sufficient to characterize modifications to the regional/local circulation patterns and sediment transport due to the presence of bathymetric features such as canyons.

(6) As part of continued modeling of sediment transport, incorporate a sediment resuspension module based on contemporary formulations of the combined effects of currents and waves.

(7) Continue collection of satellite thermal imagery to be used in conjunction with data from moored and bottom mounted instrumentation. These data provide a valuable synoptic view of surface temperature patterns which are closely linked to circulation.

The above recommendations provide a realistic basis for substantial improvement in understanding circulation patterns and processes, and the movement and deposition of suspended sediments in the study area. This, in turn, provides a expanded basis for resolving and partitioning the impacts on local hard bottom communities of sediments originating from ambient sources or local oil and gas activities.

# 5.0 REFERENCES


Abbott, M. and D. Chelton. 1991. Advances in remote sensing of the ocean. Review of Geophysics Supplement, U.S. National Report to the IUGG 1987-1990, 571-589.

Batchelor, G.K. 1952. Diffusion in a field of homogeneous turbulence. II. The relative motion of particles. Proceedings of the Cambridge Philosophical Society 48:345-362.

Barton, I.J. 1995. Satellite-derived sea surface temperatures: Current status. Journal of Geophysical Research 100:8777-8790.

Brink, K.H. and R.D. Muench. 1986. Circulation in the Point Conception-Santa Barbara region. Journal of Geophysical Research 91(C1):877-895.

Cacchione, D.A., W.D. Grant, D.E. Drake, and S.M. Glenn. 1987. Storm dominated bottom boundary dynamics on the northern California continental shelf: Measurements and predictions. Journal of Geophysical Research 92(C2):1817-1827.

Chelton, D.B., A. Bratkovich, R.L. Bernstein, and P.M. Kosro. 1988. Poleward flow off central California during the spring and summer of 1981 and 1984. Journal of Geophysical Research 93(C9):10604-10620.

Coats, D.A. 1994. Deposition of drilling particulates off Point Conception, California. Marine Environmental Research 37(2):95-127.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger, and N.H. Brooks. 1979. Mixing in Inland and Coastal Waters. Academic Press, New York, New York. 483 pp.

Fry, V.A. and B. Butman. 1991. Estimates of the seafloor area impacted by sewage sludge dumped at the 106-Mile Site in the Mid-Atlantic Bight. Marine Environmental Research 31: 41-160.

Hamilton, P. and A. Ota. 1993. Assessing effects for disposal sites off San Francisco. Pages 14-28, In: M. L. Spaulding, K. Bedford, A. Blumberg, R. Cheng, and C. Swanson (eds.). Estuarine and Coastal Modeling III, Proceedings of the 3rd International Conference, sponsored by the Waterway, Port, Coastal and Ocean Division of the American Society of Civil Engineers, Oak Brook, Illinois, September 8-10, 1993. ASCE, New York, New York. 682 pp.

Hickey, B.M. 1979. The California Current System - Hypotheses and facts. Progress in Oceanography 8:191-279.

Hickey, B.M. 1991. Variability in two deep coastal basins (Santa Monica and San Pedro) off Southern California. Journal of Geophysical Research 96:16689-16708.

Kidwell, K.D. (ed.). 1991. NOAA Polar Orbiter Data Users Guide. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Washington, D.C. 281 pp.

Lynn, R.J. and J.J. Simpson. 1987. The California Current System: The seasonal variability of its physical characteristics. Journal of Geophysical Research 92:12947-12966.

Maier-Reimer, E. and J. Sundermann. 1982. On tracer methods in computational hydrodynamics. Pages 198-217, In: M.B. Abbott, and J.A. Cunge (eds.). Engineering Applications of Computational Hydraulics, Volume 1. Pitman, Boston, Massachussetts.

McClain, E.P., W.G. Pichel, C.C. Walton, Z. Ahmed, and J. Sutton. 1983. Multichannel improvements to satellite derived global sea surface temperatures. Proceedings of the XXIV COSPAR, Advances in Space Research 2:43-47.

Sleath, J.F.A. 1984. Sea Bed Mechanics. John Wiley & Sons, New York, New York. 335 pp.

Steinhauer, M. and E. Imamura (eds.). 1990. Sedimentology. Chapter 4, In: California OCS Phase II Monitoring Program. Year Three Annual Report. Volume 1. Report No. MMS 90-0055 prepared for the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA.

Taylor, G. I. 1954. The dispersion of matter in turbulent flow through a pipe. Proceedings of the Royal Society of London, Series A 223:446-468.

Walton, C.C. 1988. Nonlinear multichannel algorithms for estimating sea surface temperature with AVHRR satellite data. Journal of Applied Meteorology 27:115-124.

# Appendix B

# APPENDIX B

## CHEMICAL MANUSCRIPT
## (Platform Discharges, Sediment and Suspended Particles Chemistry, and Particle Fluxes)

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# TEMPORAL TRENDS IN SEDIMENT CONTAMINANT CONCENTRATIONS ASSOCIATED WITH DRILLING-RELATED DISCHARGES IN THE SANTA MARIA BASIN, CA

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## ABSTRACT

Nine year (1986–1995) records of metal and hydrocarbon concentrations in surficial, subsurface, and suspended sediments near offshore oil and gas development and production platforms in the Santa Maria Basin, California, were analyzed to evaluate the long-term effects of discharges, drilling muds, cuttings, and produced water. Changes in metal and hydrocarbon concentrations in surficial and suspended sediments were minimal during and after periods of active drilling despite elevated levels in the muds and cuttings. Drilling during an initial (Phase II) monitoring period from 1986–1989 resulted in significant changes in barium (Ba) concentrations in suspended particles and surficial sediments, whereas the relatively shorter, 1993–1994 (Phase III) drilling operations resulted in only minor increases in Ba concentrations in suspended particles. No effects from platform discharges or drilling operations on hydrocarbon concentrations were apparent, although significant increases in PAH concentrations in surficial and suspended sediments were observed during November 1991, possibly due to a petroleum product spill approximately 50 km upcoast from the study area. Depositional fluxes of particles were not affected by discharges of drilling muds and cuttings. Residual excess Ba was present in sediments within 500 m of the platforms at concentrations up to an order of magnitude above background concentrations. These elevated levels probably are associated with cuttings particles deposited near the base of the platforms.

## INTRODUCTION

The Department of the Interior (DOI), Minerals Management Service/National Biological Service sponsored a multiphase program to evaluate the long-term effects of development/production drilling and platform discharges on deep water (100–200 m), hard-bottom, epifaunal communities in the Santa Maria Basin region off central California. The conceptual design of the program is described by Brewer et al. (1), Hyland et al. (2,3), and SAIC and MEC (4). An integral part of this study was measurements of metals and hydrocarbons in platform waste sources and in bottom sediment and suspended particles in near-bottom layers. The purpose of these measurements was to determine whether drilling wastes altered the geochemical environment and represented a significant source of contaminants and toxicity to epifaunal organisms.

Phase I of this monitoring program (5) included baseline studies and recommendations of long-term study sites for hard-bottom communities in the Pt. Conception to Pt. Arguello region (Figure 1). The Phase II program initiated monitoring studies at nine hard-bottom sites near Platform Hidalgo, focusing on potential impacts to epifaunal communities from platform discharges of drilling muds (6). The Phase II study included predrilling, during-drilling, and postdrilling periods, with the last drilling activity occurring in January 1989 (Table 1). Drilling from Platform Irene occurred from 1986 through October 1989; however, its location over 10 km to the north of the study area suggested that these discharges had minimal, if any, additional effects near Platform Hidalgo (6). The Phase III field program, initiated in October 1991, represented the continuation of monitoring near Platforms Harvest, Hermosa, and Hidalgo (Figure 1). The Phase III studies focused additionally on natural and anthropogenic (drilling-related) factors and processes that may influence spatial and temporal variability in hard-bottom communities near Platform Hidalgo.

Overall Phase III goals were twofold:

(1) To increase understanding of the environmental fate and effects of chronic, low-level inputs of drilling wastes and their potential for sublethal, long-term, and/or cumulative impacts to hard-bottom communities; and

(2) To improve knowledge of the fundamental processes controlling natural variability in the communities. This knowledge is critical because it distinguishes biotic changes associated with natural variability from changes associated with drilling discharges.

The Phase III study design included assessments of continued (since Phase II) "post"-drilling and "during"-drilling impacts. Phase III provided an opportunity to evaluate further the persistence of chemical residues (i.e., Ba) from discharges during Phase II, as well as the effects from a discharge phase of substantially shorter duration and lower mass emissions.

The Phases II and III drilling operations are summarized in Table 1. Phase III drilling occurred at two platforms (Hermosa and Hidalgo) over an eight-month period, resulted in drilling/redrilling of 5 wells, and generated a total of 4700 $m^3$ of muds and 875 $m^3$ of cuttings. The drilling operations were sequential; therefore, concurrent discharges from the two platforms did not occur during Phase III. Produced water discharges (0.8-1.6 x $10^6$ L/day) also were initiated during Phase III. In contrast, Phase II drilling occurred over a period of 26 months, generated 39 wells, and resulted in discharges of 40,700 $m^3$ of drilling muds and 5400 $m^3$ of cuttings; no produced waters were discharged during Phase II. Concurrent discharges from two or more of the platforms occurred during a significant portion of the Phase II drilling period. This potentially results in important differences between the two drilling phases in the magnitude of drilling waste depositional fluxes.

The purpose of this paper is to describe temporal changes in contaminant concentrations in relation to drilling operations and natural processes, primarily during Phase III. Results from measurements of metals and hydrocarbons, and modeling of drilling mud discharges during Phase II are described by Hyland et al. (3), Steinhauer et al. (7), and Coats (8). This paper focuses on residual effects from the Phase II drilling and effects from the Phase III drilling operations.

**Study Area**

The physical, chemical, and biological characteristics of the study area are described by SAIC (5) and Hyland et al. (2). The general region consists of the continental shelf, extending from shore to approximately 110 m depth, and the continental slope off southern California, between Pt. Conception and Pt. Arguello (Figure 1). The coastal axis and bathymetric contours in the region are oriented approximately southeast-to-northwest. Bottom study depths range from approximately 90 to 215 m.

Oceanographic and geochemical characteristics of the study area are influenced strongly by interannual variations associated with drought conditions, such as those that persisted in California from approximately 1985 through at least early 1991, and El Niño events that occurred in 1992 through 1994. River flow data (9) indicate an approximate four- to tenfold increase in volumes during Phase III, corresponding to water years 1991 through 1994 and up to December (1994) of water year 1995 compared to Phase II, corresponding to water years 1987 through 1990. (A water year is defined as extending from October of one year through September of the following year.)

The distribution of nearshore and offshore sediments is influenced strongly by discharges of silts, clays, and sandy materials from rivers and streams, primarily to the north of Pt. Arguello, and littoral transport of sands from north and south of the study area (5). Sediment types in the study area range from approximately 35–85% fines and 15–65% sand (6).

Natural chemical sources in the study region include hydrocarbon seeps (10, 11). Evidence of submarine oil seeps in the Santa Maria Basin includes macroscopic tar particles observed in bottom sediment samples from Phase II (6) and observations of bacterial mats (*Beggiatoa* spp.) associated with seeps and gas bubbles at some hard-bottom sites (12). Other anthropogenic sources can include atmospheric deposition, tanker/shipping discharges, and wastewater discharges from platforms and vessels. Further, releases to the ocean of several million liters of a petroleum product (diluent) occurred over a period of several years from the Guadalupe oil field, north of Pt. Sal and approximately 50 km from the study site. Otherwise, anthropogenic influences to the coastal area in this region are relatively minor.

## METHODS AND MATERIALS

This section summarizes methods used for collections and analyses of sediment and suspended particle samples for chemical analyses during Phase III. Detailed descriptions of methods are provided in SAIC and MEC (4). Sample collection and analytical procedures were in most cases identical to those employed for Phase II (6, 7) to ensure data comparability between phases.

Surface sediments were collected at nine sites near the hard-bottom study locations associated with Platform Hidalgo (Figure 1). Three separate samples were collected at each station with a 0.1 $m^2$, Kynar-coated Van Veen grab. The 0–2 cm layer of sediments in each sample was removed from the sampler with a Kynar-coated scoop. The three samples were subsequently combined into a single composite for each station. Composite samples of surficial sediments were analyzed for trace metals, hydrocarbons, total organic carbon (TOC), and grain size. Samples for trace metal and hydrocarbon analyses were placed in precleaned glass jars and stored at approximately -20°C until analysis. Samples for analysis of TOC and grain size were placed in Ziploc bags and stored at 4°C.

During October/November 1991 and January 1995, a 0.015 $m^2$ box corer was used to collect surface and subsurface sediment samples from a radial array of stations at distances of 50, 125, 250, 500, and 1000 m from Platforms Hidalgo, Hermosa, and Harvest. The surface layer (0–2 cm) was collected and placed in a precleaned glass jar. The subsurface layer (10–12 cm) then was extruded through the box, collected with the scoop, and placed in a precleaned jar. All samples were stored at approximately -20°C until analysis.

Suspended particles were collected in sediment traps from nine stations associated with Platform Hidalgo. Sediment trap arrays consisted of a 40-inch diameter cement base with spring supports of stainless steel for four individual traps. Each trap was constructed of butyrate tubing having Hexcel baffles with 1 cm cell spaces in the mouth of the tube to reduce turbulence. The diameter of each trap was 6.6 cm, and the height:diameter ratio of the baffle was approximately 7:1. Replicate traps were seven diameters apart and the openings were 1 m above the sea bed. Sodium azide was added to each trap as a preservative.

Samples from the sediment traps were frozen at approximately -20°C onboard the survey vessel, except that samples for TOC and particle size measurements were stored at approximately 4°C. Suspended sediments were analyzed for total dry weight (for particle flux calculations); trace metal, hydrocarbon, and TOC concentrations; and grain size distributions.

Field blanks and equipment rinses were collected at an overall frequency of approximately 5% of the total number of field samples. In all cases, field QA samples were free from contamination.

Drilling mud and cuttings samples were collected by the operators, based on established sampling instructions, at Platforms Hidalgo and Hermosa. Samples from multiple wells at each of the two platforms subsequently were composited by well depth into surface, mid-depth, near-bottom (muds only), and bottom samples. Produced water and formation oil samples also were collected from Platforms Hidalgo and Hermosa. Muds and cuttings were analyzed for metals, hydrocarbons, TOC, and grain size; produced waters were analyzed for metals and hydrocarbons; and formation oils were analyzed for hydrocarbons only. A sample of the diluent from Guadalupe oil field also was analyzed for hydrocarbons (alkanes, aromatics, and saturated biomarkers).

Sediment and suspended particle samples for hydrocarbon analyses were Soxhlet-extracted in methylene chloride (DCM). Extracts were combined and dried by passing through anhydrous sodium sulfate, concentrated, and then solvent-exchanged from DCM into hexane. Final extract volumes were reduced and extracts were subjected to liquid-column chromatography for separation using silica gel into saturated and aromatic fractions. Saturated hydrocarbons were initially eluted with hexane; aromatic hydrocarbons were subsequently eluted with a mixture of DCM and acetone (1:1, v:v). Final extracts for saturated and aromatic hydrocarbons were concentrated and analyzed by flame ionization detector-gas chromatography (FID-GC) and gas chromatography/mass spectroscopy-selected ion monitoring mode (GC/MS-SIM), respectively. Polycyclic aromatic hydrocarbons (PAHs) were identified and quantified using primary quantitation ions and accompanying secondary confirmation ions. Final confirmation of target analytes was based on specific retention-time data for selected compounds. Selected surface and suspended sediment samples also were analyzed for suites of triterpane and sterane compounds (m/z 191 and 217, respectively) using GC/MS-SIM.

Laboratory control and matrix spike samples and standard reference materials were analyzed with every 20 samples or with every sample set, whichever was more frequent. Duplicate analyses by FID-GC or GC/MS-SIM were performed with a frequency of one for every 20 samples or sample set, whichever was more frequent. Compound quantitation limits for most target saturated and aromatic analytes were approximately 1–5 ppb and were comparable to or lower than those achieved during the Phase II program.

Samples of sediments and suspended particles for metals analyses were initially freeze-dried and digested in concentrated $HNO_3$ and HF at 130°C. Following digestion, the samples were diluted to final volume with $H_3BO_3$. Sediment, suspended particle, and drilling muds and cuttings samples for Ba analyses were dried, placed in heat-sealed polyvials, and irradiated (thermal neutron flux of $1x10^{13}$ n/cm$^2$/sec) with a Triga Reactor. Digested samples were analyzed by FAAS (Al and Cr), GFAAS (As, Ag, Cd, Cu, Pb, Ni, and Zn), CVAAS (Hg), and INAA (Ba). Analyses of procedural blanks, duplicates and matrix spikes, and certified reference materials were performed at the same frequencies as for hydrocarbon analyses.

TOC analyses were performed using a combustion method and infrared spectroscopy. QA/QC analyses were performed in conjunction with field samples and consisted of duplicate analyses, surrogate spikes, and external reference standards that were analyzed with every sample set at a frequency of 10%.

Monthly platform discharge data were obtained from Discharge Monitoring Reports submitted by the operators to the U.S. Environmental Protection Agency (EPA), Region IX. Additional daily discharge reports and drilling mud inventories were obtained from the operators.

Statistical analyses, including linear regression, t-tests, and analysis of variance (ANOVA), were used to evaluate spatial and temporal trends and relationships between different physical and chemical variables. Principal component analysis (PCA) was performed on PAH and biomarker data for selected formation and seep oils, the Guadalupe diluent, and suspended particle samples to evaluate potential hydrocarbon sources to the suspended materials. Excess Ba in sediments near each of the three platforms was calculated from measurements in surface and subsurface sediments at the radial array of stations using the procedure developed by Boothe and Presley (13). The excess Ba was calculated by subtracting the background Ba concentration from the measured concentration. The background concentration was interpolated over the nearfield region of the platform from subsurface sediment concentrations at sites 500 m and 1,000 m from the platform. This approach was used to account for the depth-related gradient in sediment Ba concentrations. The volume of sediment containing "excess Ba" was calculated by multiplying the area described by a linear decrease with depth to a presumed background in Ba concentrations by a unit surface area. Based on the Phase III data, the linear decrease with depth represents a reasonable approximation of sediment Ba profiles reported by Crecelius (14) from the Phase II program. Unit volumes were multiplied by the sediment density (assumed to be 2.6 g/cm$^3$) and the excess Ba concentration. Excess Ba (in kg) was summed for all unit areas within 500 m of Platform Hidalgo. In two cases, highly elevated Ba concentrations were not included because they were considered unrepresentative of spatial trends and artificially skewed the calculation.

## RESULTS

### Chemical Compositions and Mass Emissions of the Platform Wastes

The drilling mud formulations used during the Phase III drilling activities contained approximately 40% by weight of barite, 24% bentonite, and <10% each of potassium chloride and carbonate; other additives comprised approximately 25% of the total dry weight. These formulations were similar to those used during Phase II drilling operations. Metal and hydrocarbon concentrations in muds and cuttings, composited over specific well depth ranges for Platform Hidalgo are listed Tables 2 and 3, along with the corresponding concentrations for samples analyzed during Phase II. Contaminant levels typically increased with well depth. Specific metal and total hydrocarbon concentrations (THC: sum of resolved and unresolved components) in the Phase III muds and cuttings generally were comparable to those in platform waste materials discharged during Phase II (3, 7). Differences in concentrations of some constituents between drilling phases of up to an order of magnitude occurred for various well depths (e.g, Ba and THC in muds from the bottom well depths), presumably due to differences in downhole conditions and changes in the specific drilling mud formulations. Hydrocarbon compositions, particularly the patterns and relative concentrations of alkanes and parent and alkylated PAHs, of muds and cuttings resembled those of the formation oil, indicating that hydrocarbons in waste material probably were primarily from the formation instead of mud additives (Figure 2).

Barium was the only metal in muds and cuttings that was consistently elevated relative to crustal abundances (Table 5). Barium concentrations in muds were up to two orders of magnitude higher than background concentrations in surficial sediments; concentrations of other metals generally were within 2–3 times the background sediment concentrations. Elevated Pb and Zn concentrations occurred in selected cuttings samples, probably due to contamination from mud additives.

Concentrations of individual metals in produced waters from Platforms Hermosa and Hidalgo typically were below 1 mg/L, with the exception of Ba which ranged from 5.2–16 mg/L. Total hydrocarbon concentrations ranged from 2.2–33 mg/L. Other than the more soluble naphthalenes, PAHs in the produced waters generally were at or below the detection limits; total PAH ($\Sigma$PAH) concentrations ranged from 0.3–0.4 mg/L.

Mass emissions of individual metal and hydrocarbon components from Phase III muds and cuttings discharges at Platform Hidalgo ranged from 0.3–120,000 kg (Table 4). Produced water discharges from Platform Hidalgo represented additional emissions of 5720 kg Ba/yr, 779 kg THC/yr, and 112 kg PAH/yr. Deck drainage, cooling waters, and sanitary wastes also were discharged at the platforms, although the mass emissions associated with these waste sources are expected to be relatively small. Phase III mass emissions were typically lower, but within an order of magnitude, of those from Phase II. Assuming proportional mass emissions from Platforms Harvest and Hermosa, discharges of muds and cuttings during the Phase II and III drilling operations combined represented contaminant emissions ranging from approximately 3.6 kg (Hg) up to $1.8 \times 10^6$ kg (Ba), as well as 30,000 kg THC and 830 kg PAH. With the exceptions of Ba and Zn, mass emissions associated with platform discharges were up to several orders of magnitude lower than mass inputs associated with natural riverine flow and oil seeps (Table 4; ref 6).

**Sediment Fluxes**

During Phase III, particle fluxes (mass dry weight per unit area and time) in sediment traps at the nine monitoring stations ranged from 18–91 g dw/m$^2$/day (Figure 3). Shallower sites typically exhibited relatively greater fluxes, as well as smaller median grain size and higher percentages of fines (<62 um diameter particles), than deeper stations. Depth-related trends are expected due to the generally finer grain size and predicted higher rate of sediment resuspension at the shallower compared to deeper sites. Particle fluxes measured by sediment traps on physical measurements arrays deployed at nearfield and farfield sites (15) were similar to those collected at the monitoring sites. Specifically, fluxes in the upper traps (1.5 m above the bottom) at the nearfield and farfield sites ranged from 18–25 $g/m^2/day$ and 23–33 $g/m^2/day$, respectively, during the three deployment periods. Bottom traps (1.0 m above the bottom) at the nearfield and farfield sites collected 30–38 $g/m^2/day$ and 34–44 $g/m^2/day$, respectively. For comparison, the range in particle fluxes measured during Phase II, 1986–1990, (20–90 $g/m^2/day$; ref 6) was consistent with those measured during Phase III.

Fluxes at individual monitoring stations were reasonably constant over time with a few exceptions, presumably related to natural sediment resuspension and transport events. Temporal and spatial variability appeared to be unrelated to drilling operations. The highest fluxes at the 110–120 m stations occurred between October 1989 and May 1990, coinciding with a post-drilling phase and relatively low river flow. Relatively higher fluxes occurred at Stations PH-K and PH-N during August 1993–January 1994, overlapping with drilling operations at Platform Hidalgo (from November 1993 to May 1994). However, due to the short period of overlap, and limited emissions, this relationship to drilling is probably coincidental. Similarly, SAIC and MEC (15) observed that trends in concentrations of suspended particles in near-bottom waters during Phase III were unrelated temporally with periods of drilling operations.

**Metals in Surficial and Suspended Sediments**

With the exception of Ba, surficial and suspended sediment metal concentrations generally reflected average crustal abundances and, therefore, were equivalent to the respective background concentrations (Table 5) as reported from other studies in the Santa Maria Basin (5,7), western Santa Barbara Channel (5,16–18), and Southern California Bight (19–21). Over the nine-year monitoring period, changes in Ba concentrations in suspended particles were the most prominent geochemical effect attributable to the drilling discharges (Figure 4). However, during Phase III, trends in Ba concentrations in suspended and surficial sediments at the nine monitoring stations were relatively constant. For example, during the post-Phase II drilling period (October 1989–August 1993), Ba concentrations in suspended sediment samples ranged from 582–815 ppm, consistent with expected background levels (e.g, refs 5, 7). Barium concentrations in sediment trap samples ranged from 404–913 ppm during surveys coinciding with the subsequent (Phase III) drilling period (September 1993–May 1994). Barium concentrations in suspended particles collected during January 1994–January 1995 at near-platform Stations PH-I, -K, and -N were relatively higher (867–913 ppm) than those at the other monitoring stations (653–757 ppm). However, differences between surveys that coincided with Phase III drilling for five pooled nearfield stations (PH-I, -J, -K, -N, and -R) were not statistically significant (ANOVA, $p>0.05$). These results indicate minimal effects from drilling mud fluxes during Phase III.

Using the approach of Hyland et al. (3), drilling mud depositional fluxes over the nine-year monitoring program were calculated from the excess Ba concentrations in sediment trap materials (Table 6). The Phase II depositional fluxes from Hyland et al. (3) were recomputed based on the lowest Ba concentration measured during the combined Phase II/Phase III periods. Mean and maximum depositional fluxes for moderate and high flux (i.e., near-platform) stations during the

Phase III drilling period were substantially lower than those estimated for the Phase II drilling period. Phase III drilling depositional fluxes at the high flux stations were only a factor of two times greater than post-drilling fluxes, and depositional fluxes at the low and moderate flux (i.e., up to several kilometers from the platform) stations during the Phase III drilling period were essentially unaffected by the platform discharges.

During October 1991 through January 1995, sediment Ba concentrations at the five nearfield stations ranged from 724–1090 ppm. The highest concentrations, averaged over the three Phase III monitoring surveys, occurred at Stations PH-I and PH-J (950–990 ppm). Compared to pre-drilling levels defined by Steinhauer et al. (7) and SAIC (5) (i.e., approximately 700–800 ppm), mean concentrations were consistently higher at most stations during drilling and post-drilling surveys (Figure 4). However, differences between surveys for the Phase III period were not statistically significant (one-way ANOVA on ranks; $p>0.05$).

Some statistically significant differences between surveys were apparent for concentrations of other metals such as Pb (ANOVA; $p<0.05$). However, based on the results of multiple comparison tests (SNK or Dunns method) there were no significant temporal relationships to drilling periods. Despite elevated concentrations of Pb and Zn in selected cuttings samples, there was no corresponding evidence of altered concentrations for these metals in surficial or suspended sediments. Based on similarities between concentrations of other metals in muds and cuttings to background sediment concentrations (Table 5), little or no detectable effects from platform discharges would be expected (7).

Measurements of Ba concentrations in surface and subsurface sediments at near-platform locations were performed to evaluate residual inventories and residence times of excess Ba. During November 1991, Ba in surface and subsurface sediments near Platform Hidalgo ranged from 770–1700 ppm and from 570–1170 ppm, respectively. The highest Ba concentrations occurred within 50 m of the platform. The magnitude of the Ba concentrations, as well as the Ba/Al ratios, indicated the presence of residual Ba within 1 km of the platform. Elevated Ba/Al values (approximately 200–300 x $10^4$) were apparent in surface sediments at distances up to 125 m from the platform in alongshore and offshore directions. In contrast, Ba/Al values from subsurface sediments were consistently <200 x $10^4$ and essentially equal to the baseline ("pollution-free") Ba/Al range of 125–175 x $10^4$ defined by Finney and Huh (20, 21) for San Pedro and Santa Monica Basins.

In January 1995, Ba in surface and subsurface sediments near Platform Hidalgo ranged from 853–9699 ppm and from 667–964 ppm, respectively. With the exception of two surface sediment samples from the 125 m radius of stations, Ba/Al values in all other core samples were <200 x $10^4$.

Concentrations of Ba >1600 ppm also occurred during October 1991 and January 1995 in surface and subsurface sediments within 125 m of Platforms Hermosa and Harvest. Several of the samples with the highest Ba concentrations, including a subsurface sediment sample with 30,510 ppm Ba collected 125 m from Platform Harvest, likely contained cuttings particles coated with drilling muds.

Differences between the 1991 and 1995 samples in Ba concentrations in surface and subsurface sediments within 1000 m of the three platforms are shown in Figure 5. Negative differences, indicating decreases in mean Ba concentrations between 1991 and 1995 occurred at most platform, depth, and distance combinations except in surface sediments $\geq$250 m from Platform Hidalgo. The greatest change in surface Ba concentrations occurred at sites within 50 m of the platforms. Also, the relative change in Ba concentrations at the 50 m sites near Platforms Hidalgo and Hermosa, where drilling occurred, was comparable to that of Platform Harvest where no Phase III drilling occurred.

**Hydrocarbons in Surficial and Suspended Sediments**

Sediment and suspended particle hydrocarbons measured during Phase III reflected a complex mixture of petrogenic, biogenic, and pyrogenic (i.e., combustion-derived) sources. These various input sources were characterized by a large chromatographic hump, corresponding to an unresolved complex mixture (UCM) of weathered branched and cyclic hydrocarbons, dominant terrestrial plant wax n-alkanes ($nC_{27}$, $C_{29}$, $C_{31}$), the diagenetic PAH perylene, and other 4- and 5-ring PAHs from combustion and runoff sources. Similar features have been described in sediments and suspended particles from the Santa Maria Basin (5, 7, 22, 23), western Santa Barbara Channel (5, 11, 24–26), and Southern California Bight (27, 28). Characteristics and concentrations of hydrocarbons in bottom and suspended sediments during the Phase III period generally were comparable to those described by Steinhauer et al. (7) for the Phase II period.

There were no trends in key hydrocarbon parameters obviously related to periods of active drilling (Figure 6). During Phase III, mean concentrations of THC in suspended and surficial sediments at the nine nearfield stations ranged from 32–207 ppm and from 36–250 ppm, respectively. Corresponding concentrations measured during Phase II were 48–524 ppm and 24–217 ppm, respectively. The highest THC concentrations in suspended sediments occurred during May 1988–May 1989, during Phase II drilling at Platforms Hermosa and Hidalgo. This was after Ba concentrations had started to decline from maximum levels in May–October 1987. ANOVA of THC normalized to organic carbon in surficial and suspended sediments from the five nearfield stations indicated significant differences between surveys. However, multiple comparison tests did not reveal any significant temporal patterns related to the Phase II or Phase III drilling periods. Further, as noted by Steinhauer et al. (7), there was no evidence from compositional features of the hydrocarbon samples that increases of THC in suspended sediments during Phase II drilling were related to platform discharges.

Based on results of ANOVA, sediment $\Sigma$PAH concentrations during the November 1991 survey were significantly higher ($p<0.05$) than those during all other surveys. The mean $\Sigma$PAH concentration in bottom sediments was 3.0 ppm, with a maximum concentration of 7.0 ppm. Mean $\Sigma$PAH concentrations in bottom sediments decreased to presumed background levels (i.e., 0.1 ppm) by October 1992. The mean $\Sigma$PAH concentration in suspended sediments collected in

November 1991 was 0.7 ppm, and the highest concentration was 1.1 ppm. Concentrations of ΣPAH in suspended particles also declined during subsequent surveys but remained at or above 0.2 ppm through January 1995 (Figure 6). By comparison, between May 1988 and October 1990, and throughout the period of Phase II drilling, mean ΣPAH concentrations in surficial and suspended sediments from the nine sites were $\leq$0.1 ppm. Prior to the start of drilling (during the May 1987 survey), higher ΣPAH concentrations occurred in sediment traps at nearfield Station PH-I and farfield Station PH-U (0.9 ppm and 1.1 ppm, respectively). Relatively higher ΣPAH concentrations (up to 1.5 ppm) also occurred in surficial sediments at several sites during the October 1986 survey--also prior to initiation of drilling. Statistically significant differences between surveys inΣPAH concentrations in suspended sediments also were evident (ANOVA, $p<0.05$), although patterns related to drilling periods or other events could not be discerned from multiple comparison tests. In contrast, concentrations of the higher molecular weight PAHs (i.e., 4- and 5-ring compounds) and perylene in suspended and surficial sediments remained relatively constant over the nine-year monitoring period (Figure 5), suggesting that combustion/runoff emissions of PAHs and natural (diagenetic) sources remained uniform.

Temporal trends in the lower molecular weight PAHs and chrysenes during Phase III are further exemplified by patterns at Stations PH-N and PH-R (Figure 7). Alkylated naphthalenes and fluorenes were primary components of the ΣPAH during November 1991. However, the abundances of these PAHs declined substantially during subsequent surveys. Abundances and ratios of PAHs observed in the November 1991 samples were appreciably different from those reported for Phase II (7).

During the Phase III November 1991 survey, several of the surficial and suspended sediment samples exhibited features characteristic of a fresh (i.e., unweathered) hydrocarbon product. Specifically, elevated concentrations (up to several hundred ng/g per compound) of naphthalenes, fluorenes, and phenanthrenes, especially the $C_1$ through $C_4$- alkylated homologues, occurred sporadically in both surficial and suspended sediments. Because no drilling occurred during this time, the presence of fresh petroleum was attributed to sources other than platform discharges. Further, the presence of the triterpane 17α,22β,28,30-bisnorhopane, which is a unique biomarker for Monterey formation crude oils (25), suggested a locally sourced oil. During Phase II, Steinhauer et al. (7) noted sporadic evidence for petroleum hydrocarbons in suspended sediments, and attributed these occurrences to the presence of seep oils and/or tar balls. However, elevated naphthalenes and enriched n-alkanes within the $C_{13}$ to $C_{23}$ range in the November 1991 samples were inconsistent with expected characteristics of seep oil (11, 26, 29). Notably higher levels of tricyclic terpanes and short-chain ($C_{20}$ and $C_{21}$) steranes also were present in suspended sediments from selected stations. These patterns are suggestive of a petroleum product, such as a diesel fuel, from a Monterey formation oil and consistent with the composition of the Guadalupe diluent (30).

Results from PCA of selected source and suspended sediment samples indicated contributions from multiple hydrocarbon sources, including Guadalupe diluent, seep oils, and combustion materials, to suspended particles collected at Stations PH-N and PH-R during November 1991 (designated n1 and r1, respectively, in Figure 8). Bivariate plots of PCA axes 1 and 2, which explained 58% and 14% of the variance, respectively, show distinct differences between samples n1 and r1 relative to samples collected at Stations PH-N and PH-R during subsequent surveys and to all suspended sediment samples collected at Station PH-K. Differences along PCA axis 1 are related primarily to enrichment in 4- and 5-ring PAHs (positive values) and enrichment in alkylated naphthalenes, alkylated dibenzothiophenes, and lower molecular weight tricyclic terpanes and steranes (negative values). The Guadalupe diluent contained elevated concentrations of alkylated naphthalenes and lower molecular weight terpanes and steranes. Samples n1 and r1 also exhibited greater similarities to the diluent, and separation from the seep and formation oils, in bivariate plots of PCA axes 2 and 4. Groupings of samples n1 and r1 along with the diluent corresponded to enrichment with alkylated fluorenes and $C_{19}$–$C_{21}$ terpanes. Thus, the separation of samples n1 and r1 from other suspended sediment samples reflected differences in the relative contributions of lower and higher molecular weight PAHs from petroleum and combustion sources, respectively (e.g., ref 31). Although the suspended sediments exhibited contributions from multiple hydrocarbon sources, the PCA results clearly demonstrate similarities between samples n1 and r1 and the diluent.

## DISCUSSION

### Effects on Geochemical Characteristics

Discharges of muds, cuttings, and produced waters from the Phase III drilling and production operations had minimal effects on contaminant concentrations in bottom and suspended sediments. During 1991–1995, no residual effects from the Phase II drilling or from the limited Phase III drilling were evident in the metal concentrations. The exception was slightly elevated Ba concentrations in sediments, presumably from previous Phase II discharges of cuttings, in the immediate vicinity of the platforms. Further, no residual effects from drilling or discharge operations on sediment and suspended particle hydrocarbon concentrations were evident during Phase III. Hydrocarbon concentrations in suspended and surficial sediments reflected changes in natural background sources (natural seeps and biogenic materials) and, during October 1990–November 1991, the possible effects of a petroleum product (diluent) spill approximately 50 km from the study site (30).

During the Phase II drilling period, platform discharges resulted in increased Ba concentrations of 10–40% in surface sediments and 200–300% in suspended particles (7). Elevated Ba concentrations in suspended sediments persisted throughout the drilling period, and then decreased within a period of 1–1.5 years to background concentrations. In contrast, Ba concentrations in surface sediments did not return to pre-drilling levels, but remained approximately 10% higher than background. The Phase II drilling operations did not significantly alter concentrations of other metals or hydrocarbon constituents in surficial sediments or suspended particles (3, 7).

The absence of altered metal and hydrocarbon concentrations--other than Ba--is attributable to several factors. Concentrations of metals in the drilling muds and cuttings, except for enriched

Ba and occasionally elevated Zn and Pb in contaminated cuttings, generally were comparable to background concentrations for bottom sediments. Consequently, platform wastes were not expected to substantially alter the concentrations of metals other than Ba (7). Hydrocarbons in the study area are characterized by a large and temporally variable background signal. The petroleum hydrocarbons most highly enriched in the platform wastes, particularly the lower molecular weight PAHs (e.g., unsubstituted and alkylated naphthalenes), are relatively soluble and, therefore, are expected to be released readily from the particulate to the dissolved phases of discharged drilling mud (32). Although concentrations of these hydrocarbons were present in muds and cuttings at concentrations up to several orders of magnitude above background sediment concentrations, the absence of corresponding increases in concentrations in suspended and surficial sediments was attributed to losses from selective solubilization and/or microbial degradation of these less refractory compounds. Consequently, the ratios of hydrocarbons to Ba in dispersed muds and cuttings were expected to change with time, and depositional fluxes of PAHs would not be proportional to those of Ba. Finally, since the mass emissions of contaminants from the Phase III drilling operations were substantially lower than those during Phase II, and the three platforms did not discharge wastes concurrently, significant alterations in the geochemical conditions--other than increases in Ba concentrations--were not expected.

Because average Ba concentrations in waste materials were up to 150 times higher than background levels, and Ba is relatively insoluble, subsequent deposition of barite or Ba adsorbed to natural or cuttings particles likely would be evident from measurements of the Ba signature in bottom or suspended sediments (33). In contrast, the saturated and PAH compounds traditionally used as diagnostic of relatively non-weathered petrogenic hydrocarbons, and which might be affected by platform discharges, were rarely observed in surface sediments or suspended particles during or after drilling. Any contributions from platform discharges to concentrations of petroleum hydrocarbons either were masked by the dominant background signal of hydrocarbons from natural sources (e.g, local oil seeps) or reduced due to solubilization and/or weathering.

**Drilling Mud Inventories**

Modeling of drilling mud discharges, based on the actual discharge rates and particle sizes of muds used during Phase III, predicted that approximately 50% of the total mass of muds discharged would be advected out of the study area and, therefore, would not contribute substantially to the drilling mud deposition flux (15). These estimates appear to be reasonable given the generally high water content and predominant fine grain sizes of the drilling muds and the vigorous currents off Point Arguello that disperse and transport suspended particles (15). Of the total mass of drilling muds predicted by the model to be deposited within the study area, only the coarse fraction would be deposited near the platforms. Silt and clay-sized particles were predicted to be widely dispersed. Coats (8) also assumed that 20% of the muds discharged from Platform Hidalgo would be deposited near the base of the platform. Further, based on actual Phase III discharges at Platforms Hermosa and Hidalgo, and corresponding current patterns, mean depositional thicknesses of drilling mud were predicted to range from 1.5–7.3 microns over relatively large areas of ocean bottom. Estimated maximum depositional thicknesses of 59 and

456 microns were associated with discharges at Platforms Hermosa and Hidalgo, respectively. The mean drilling mud deposition thickness would result in upper limit increases in sediment Ba concentrations of approximately 1%, based on assumed drilling mud and sediment densities of 4.5 g/cm$^3$ and 2.6 g/cm$^3$, drilling mud and background sediment Ba concentrations of 50,000 ppm and 800 ppm, respectively, and a sediment mixed layer of 10 cm thickness (ref. 14). Increases in Ba concentrations up to 1.5 times above background (i.e., 1200 ppm) would be associated with the predicted maximum depositional thicknesses. Based on measured Ba concentrations in drilling muds, suspended sediments, and surface sediments, Hyland et al. (3) estimated that discharged drilling muds comprised 2.0% of the suspended particle flux and 0.32% of the surface sediments at Station PH-J during Phase II. Relative to the Phase III estimates, the higher Phase II contributions probably were due to concurrent discharges from multiple platforms. Boothe and Presley (13) noted that effects from multiple well discharges on the mass of excess Ba in near-platform sediments were directly additive; whereas, CSA (34) concluded from studies in the Gulf of Mexico that discharges from multiple wells affected the thickness of deposited particles but not the magnitude of Ba enrichment in surficial sediments.

The calculated total excess Ba in sediments within 500 m of Platform Hidalgo in November 1991 and in January 1995 was 52,200 kg and 53,100 kg, respectively (Table 7). The total mass of Ba discharged during the Phase II and Phase III drilling operations at Platform Hidalgo was 520,000 kg. Thus, the calculated excess Ba in sediments within 500 m of the platform during October 1991 and January 1995 represents 13% and 10% of the original discharges associated with Phase II and with Phases II and III combined, respectively. These values probably overestimate the residual Ba because contributions of Ba associated with drilling mud particles advected from Platforms Harvest and Hermosa are significant (7). Boothe and Presley (13, 35) reported inventories of excess Ba within 500 m of platforms in the Gulf of Mexico ranging from 1.5–12% of the total Ba used in drilling operations. They concluded that depth-related differences in the magnitude of sediment resuspension and transport were the primary variables controlling the magnitude of excess Ba contained in bottom sediments; a relatively greater mass of excess Ba was retained in the vicinity of deeper than shallower platforms. The length of time since drilling operations ended had little effect, over the duration of the study, on the magnitude of the excess sediment Ba.

Differences between the November 1991 and January 1995 excess Ba inventories near Platform Hidalgo were negligible, suggesting that the net loss in Ba due to sediment mixing or resuspension and transport was essentially equal to the Ba accumulation associated with Phase III discharges. The total excess Ba, and percentages of the total Ba mass emissions, in sediments near Platform Hermosa were comparable to those at Platform Hidalgo (Table 7). The absolute change between 1991 and 1995 in excess Ba (-15%; Table 7) was appreciably greater than that at Platform Hidalgo, reflecting the relatively lower Ba emissions during Phase III. Because no Phase III drilling occurred at Platform Harvest, the difference between the 1991 and 1995 excess Ba inventories was relatively higher (-25%), and represented an apparent loss of 20,000 kg of Ba from sediments within 500 m of the platform.

The residual Ba near Platform Hidalgo likely was associated with the heavier cuttings particles and coarser grained particles in the muds that were deposited near the base of the platform. In fact, the residual Ba in near-platform sediments during January 1995 (53,100 kg) was within 15% of the total Ba mass emissions associated with cuttings discharges (i.e., 60,000 kg; Table 4). This difference is probably within the error range of the estimate. Similarly, Boothe and Presley (13) concluded that much of the Ba within 500 m of platforms in the Gulf of Mexico probably was associated with cuttings, instead of muds, because discharged drilling muds were likely to be transported distances >500 m (in water depths greater than 40–50 m) before the particulate fractions settled. Similar predictions were made for dispersion of cuttings discharged from platforms in 15–72 m of water off Nova Scotia (37).

The slightly elevated (by approximately 10%) Ba concentrations in surficial sediments at the nine monitoring stations suggest that some residual excess Ba also was present outside of the 500 m radius of the platforms. The total excess Ba (or drilling mud residue) remaining within the study area can not be extrapolated from the present station array.

Data collected during Phase III from the physical measurements array (15), as well as GEOPROBE measurements at a site approximately 50 km upcoast (38), indicate that currents with sufficient energy to resuspend and transport bottom sediments are uncommon at the depths of the platforms. Therefore, decreases in the present residual excess sediment Ba presumably will be related more to mixing and dilution by newly deposited sediments. Based on $^{210}Pb$ measurements, Crecelius (14) estimated conservative sedimentation rates for the region of 0.2–0.3 cm/yr. At these rates, predicted decreases in excess Ba concentrations would be small--approximately 5–10% per 10 years. Similarly, recent studies in the Gulf of Mexico (ref. 36) concluded that little change in Ba enrichment is expected in deeper water ($\geq$50-70 m) depositional environments after periods of 5–10 years following cessation of discharges. Additional monitoring will be required to determine whether these predictions also pertain to the Santa Maria Basin region.

## CONCLUSIONS

Only minor alterations of the geochemical environment were attributable to Phase III platform drilling operations off Point Arguello. The Ba signal in suspended particles--which was the most sensitive chemical signature of platform waste discharges during Phase II--was minimal during Phase III. The absence of significant changes in the chemical compositions of suspended and surficial sediments likely was due to several factors including minimal enrichment of most metals in waste materials, solubility of lower molecular weight PAHs contained in drilling muds, large natural variability in background hydrocarbon concentrations, relatively low discharge volumes, high dispersion of drilling muds, and the absence of simultaneous discharges from multiple platforms associated with Phase III drilling. Based on these observations, deposition of particulate contaminants from platform discharges should have negligible impacts to the deep-water, epifaunal communities in the Point Arguello region. Other, short-term increases noted for lower molecular weight PAHs during November 1991 appeared to be related to a spill of petroleum product tens of kilometers from the study site and not due to drilling or platform discharges.

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## LITERATURE CITED


(1) Brewer, G.; F. Piltz; Hyland, J. Proceedings, 1989 Oceans Conference. MTS Washington, D.C., 1989.

(2) Hyland, J., D. Hardin, E. Crecelius, D. Drake, P. Montagna, M. Steinhauer. *Oil and Chem. Poll.* **1990**, 6, 195–240.

(3) Hyland, J.; Hardin, D.; Steinhauer, M.; Coats, D.; Green, R.; Neff, J. *Mar. Environ. Res.* **1994**, 37, 195–229.

(4) SAIC and MEC (Science Applications International Corporation and MEC Analytical Systems, Inc.). Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III. Final Year One Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, California, under Contract No. 14-35-0001-30584. 1993.

(5) SAIC. Assessment of Long-Term Changes in Biological Communities of the Santa Maria Basin and Western Santa Barbara Channel-Phase I. Final Report (Volumes MMS 86-9911 and MMS-9912) to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, California, under Contract No. 14-12-0001-30032. 1986.

(6) Steinhauer, M.; Imamura, E. (eds.). California OCS Phase II Monitoring Program, Year Three Annual Report. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, under Contract No. 14-12-0001-31262. 1990.

(7) Steinhauer, M.; Crecelius, E.; Steinhauer, W. *Mar. Environ. Res.* **1994**, 37, 129–163.

(8) Coats, D. *Mar. Environ. Res.* **1994**, 37, 95–127.

(9) USGS (United States Geological Survey). *Water Resources Data Guide, California Water Years 1988–1994.* 1988–1993, 1994.

(10) Allen, A.; Schlueter, R.; Mikolaj, P. *Science.* **1970**, 170, 974–977.

(11) Reed, W.; Kaplan, I. *J. Geochem. Explor.* **1977**, 7, 255–293.

(12) Lissner, A. et al., pers. obs., October 1992.

(13) Boothe, P. and B.J. Presley. Distribution and Fate of Drilling Fluids and Cuttings Around Gulf of Mexico Sites. Final Report to the American Petroleum Institute, Washington, D.C., 1985.

(14) Crecelius, E. Chemical analysis of trace metals in sediments, pore waters, and animal tissues. In: California OCS Phase II Monitoring Program, Year Three Annual Report. Steinhauer, M. and E. Imamura (eds.) Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, under Contract No. 14-12-0001-31262. 1990.

(15) SAIC and MEC. Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III. Final Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, California, under Contract No. 14-35-0001-30584. 1995.

(16) Bruland, K.; Bertine, K.; Koide, M.; Goldberg, E. *Environ. Sci. Technol.* **1974**, 8, 425–432.

(17) Ng, A.; Patterson, C. *Geochim. Cosmochim. Acta.* **1982**, 46, 2307–2321.

(18) Chow, T. and J. Earl. Trace Metal Distribution in Southern California OCS Benthic Sediments. Southern California Baseline Study, Benthic Year 2 Final Report, Volume 2 (SAI-77-917-LJ). Report to the U.S. Department of the Interior, Bureau of Land Management. 1979.

(19) Katz, A.; Kaplan, I. *Mar. Chem.* **1982**, 10, 261–299.

(20) Finney, B.; Huh, C. *Environ. Sci. Technol.* **1989**, 23, 294–303.

(21) Finney, B.; Huh, C. *Mar. Poll. Bull.* **1989**, 20, 181–187.

(22) Curiale, J.; Cameron, D.; Davis, D. *Geochim. Cosmochim. Acta.* **1985**, 49, 271–288.

(23) Kennicutt, M.; Brooks, J. *Appl. Geochem.* **1988**, 3, 573–582.

(24) Crisp, P.; Brenner, S.; Venkatesan, I.; Ruth, E.; Kaplan, I. *Geochim. Cosmochim. Acta.* **1979**, 43, 1791–1801.

(25) Simoneit, B.; Kaplan, I. *Mar. Environ. Res.* **1980**, 3, 113–128.

(26) Stuermer, D.; Spies, R.; Davis, P.; Ny, D.; Morris, L.; Neal, S. *Mar. Chem.* **1982**, 11, 413–426.

(27) Venkatesan, I.; Brenner, S.; Ruth, E.; Bonilla, J.; Kaplan, I. *Geochim. Cosmochim. Acta.* **1980**, 44, 789–802.

(28) Eganhouse, R.; Venkatesan, I. Chemical oceanography and geochemistry. In: *Ecology of the Southern California Bight: A Synthesis and Interpretation*. Daily, M.; Reish, D.; Anderson, J. (eds.), Univ. California Press. Berkeley, CA. 1994.

(29) Kennicutt, M.; Brooks, J.; Denoux, G. *Mar. Chem.* **1988**, 24, 35–59.

(30) Phillips. C.; Clayton, J.; Evans, J.; Hom, W. in prep.

(31) Brooks, J.; Kennicutt, M.; Wade, T.; Hart, A.; Denoux, G.; McDonald, T. *Environ. Sci. Technol.* **1990**, 24, 1079–1085.

(32) Boehm, P.; Brown, J.; Requejo, R. The fate and partitioning of hydrocarbon additives to drilling muds as determined in laboratory studies. In: *Drilling Wastes*. Engelhardt, F.; Ray, J.; Gillam, A. (eds.), Proceedings of the 1988 International Conference on Drilling Waste. Elsevier Applied Sciences. NY. 1989.

(33) Trocine, R.; Trefrey, J. *Environ. Sci. Technol.* **1983**, 17, 507–512.

(34) Continental Shelf Associates, Inc. (CSA). Environmental Monitoring Program for Exploratory Well No. 3, Lease OCS-G 3316, Block A-384, High Island Area, South Extension near the West Flower Garden Bank. Draft Report to Union Oil Company. Tequesta, Florida. 2 Vols. 1983.

(35) Boothe, P.; Presley, B.J. Trends in sediment trace metal concentrations around six petroleum drilling platforms in the northwest Gulf of Mexico. In: *Drilling Wastes*. Engelhardt, F.; Ray, J.; Gillam, A. (eds.). Elsevier Applied Sciences. NY. 1989.

(36) Kennicutt, M. (ed.) Gulf of Mexico Offshore Operations Monitoring Experiment. Phase I: Sublethal Responses to Contaminant Exposure. Final Report to the U.S. Department of the Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, Louisiana, under Contract 14-35-001-30582. 1995.

(37) de Margerie, S. Modeling drill cuttings discharges. In: *Drilling Wastes*, Engelhardt, F.; Ray, J.; Gillam, A. (eds.). Elsevier Applied Sciences. NY. 1989.

(38) Drake, D., Cacchione, D. *Cont. Shelf Res.* **1992**, 12, 1331–1352.

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**Table 1.** Summary of Drilling Activities: Phase II[a] and Phase III[b].

| Platform | Study Phase | Drilling Period | Duration (months) | No. of Wells | Platform Discharges | | |
|---|---|---|---|---|---|---|---|
| | | | | | Muds ($m^3$) | Cuttings ($m^3$) | Produced Water ($L/d \times 10^6$) |
| Harvest | Phase II | 11/86 - 05/88 | 18 | 19 | 16,340 | n/a | 0 |
| | Phase III | n/a | n/a | 0 | 0 | 0 | 0.80[c] |
| Hermosa | Phase II | 01/87 - 09/88 | 20 | 13 | 16,373 | 3,114 | 0 |
| | Phase III | 09/93 - 11/93 | 2 | 1 | 822 | 136 | 1.6[d] |
| Hidalgo | Phase II | 11/87 - 01/89 | 14 | 7 | 7,963 | 2,294 | 0 |
| | Phase III | 11/93 - 05/94 | 6 | 4 | 3,850 | 739 | 0.95[d] |

(a) Phase II data from Steinhauer and Imamura (Ref. 6).
(b) Phase III data from NPDES Discharge Monitoring Reports and MMS (pers. com.).
(c) Starting 7/94.
(d) Starting 9/93.

**Table 2.** Metal and Hydrocarbon Concentrations (ppm dry weight) in Drilling Muds Collected at Platform Hidalgo, Phases II[a] and III.

| Trace Metals | Surface | | Mid-Well | | Near-Bottom | | Bottom | |
|---|---|---|---|---|---|---|---|---|
| | Phase II | Phase III | Phase II | Phase III | Phase II | Phase III | Phase II | Phase III |
| Silver | 0.19 | 0.20 | 0.36 | 0.46 | 0.31 | 0.30 | 0.23 | 0.52 |
| Aluminum | n/a | 64,000 | n/a | 56,800 | n/a | 24,800 | n/a | 20,600 |
| Cadmium | 0.84 | 0.91 | 1.24 | 0.97 | 1.40 | 0.99 | 1.33 | 1.81 |
| Copper | 26 | 18.9 | 38.1 | 25.2 | 28.0 | 17.3 | 27.0 | 33.8 |
| Nickel | 49 | 35.6 | 51 | 47.7 | 40 | 33.4 | 22 | 37.6 |
| Lead | 20 | 21.4 | 3.2 | 31.6 | 2.3 | 12.3 | 51 | 25.5 |
| Arsenic | 8.95 | 8.98 | 4.41 | 8.38 | 5.28 | 8.03 | 6.74 | 15.7 |
| Barium | 24,742 | 17,700 | 49,083 | 30,000 | 178,900 | 148,000 | 178,405 | 19,900 |
| Chromium | 82 | 76 | 126 | 88 | 96 | 83 | 37 | 118 |
| Zinc | 126 | 114 | 138 | 117 | 182 | 142 | 714 | 296 |
| Mercury | 0.085 | 0.067 | 0.102 | 0.067 | 0.154 | 0.222 | 0.182 | 0.061 |
| Vanadium | 78 | 84 | 99 | 78 | 69 | 62 | 38 | 82 |
| Iron | n/a | 29,800 | n/a | 27,700 | n/a | 19,500 | n/a | 17,600 |
| THC | 159 | 427 | 137 | 770 | 268 | 421 | 988 | 3,227 |
| Naphthalene | 0.27 | 2.4 | 5.4 | 11 | 28 | 6.7 | 39 | 10 |
| Fluorene | <DL | 0.22 | 0.38 | 0.26 | 2.0 | 0.69 | 4.1 | 1.1 |
| Phenanthrene | 0.34 | 0.37 | 0.94 | 0.45 | 5.3 | 1.4 | 4.5 | 3.4 |
| Dibenzothiophene | 0.03 | 0.33 | 0.71 | 0.40 | 2.9 | 1.1 | 3.9 | 2.2 |
| ΣPAH | 0.87 | 2.4 | 8.0 | 13 | 39 | 10 | 51 | 16 |

(a) Phase II data from Steinhauer and Imamura (Ref. 6).

**Table 3.** Metal and Hydrocarbon Concentrations (ppm dry weight) in Drill Cuttings Collected at Platform Hidalgo, Phases II[a] and III.

| Trace Metals | Surface | | Mid-Well | | Bottom | |
|---|---|---|---|---|---|---|
| | Phase II | Phase III | Phase II | Phase III | Phase II | Phase III |
| Silver | 0.20 | 0.48 | 0.86 | 0.42 | 0.66 | 0.60 |
| Aluminum | n/a | 53,800 | n/a | 36,500 | n/a | 10,400 |
| Cadmium | 1.37 | 1.21 | 2.56 | 2.57 | 2.95 | 4.90 |
| Copper | 43 | 29 | 60 | 130 | 41 | 50 |
| Nickel | 53 | 47.7 | 83 | 44.2 | 64 | 47.9 |
| Lead | 5,559 | 139 | 25 | 903 | 193 | 28.3 |
| Arsenic | 9.5 | 8.2 | 9.4 | 12 | 11 | 9.8 |
| Barium | 2,547 | 2,040 | 3,355 | 42,400 | 9,697 | 811 |
| Chromium | 106 | 103 | 209 | 112 | 140 | 96 |
| Zinc | 2,871 | 128 | 179 | 1,670 | 988 | 193 |
| Mercury | 0.089 | 0.054 | 0.122 | 0.111 | 0.092 | 0.032 |
| Vanadium | 71 | 87.0 | 122 | 92.0 | 122 | 121 |
| Iron | n/a | 25,300 | n/a | 30,000 | n/a | 14,300 |
| THC | 600 | 539 | 95 | 2,001 | 526 | 1,343 |
| Naphthalene | 1.2 | 1.5 | 8.9 | 20 | 96 | 11 |
| Fluorene | <DL | 0.03 | 0.35 | 0.40 | 8.2 | 1.9 |
| Phenanthrene | 0.79 | 0.63 | 0.64 | 4.7 | 9.3 | 3.9 |
| Dibenzothiophene | <DL | 0.30 | 0.40 | 3.3 | 8.1 | 3.7 |
| ΣPAH | 2.3 | 2.9 | 12 | 29 | 121 | 26 |

(a) Phase II data from Steinhauer and Imamura (Ref. 6).

**Table 4.** Total Contaminant Mass Emissions From Drilling Operations at Platform Hidalgo During Phases II and III and From Natural Sources.

| Mud/Cutting Constituent | Mud Discharge (kg) | | Cutting Discharge (kg) | | Produced Water (kg/y) | Riverine and Petroleum Seep Input[b] (kg/y) |
|---|---|---|---|---|---|---|
| | Phase II[a] | Phase III | Phase II[a] | Phase III | | |
| Silver | 1.0 | 0.7 | 3.6 | 1.0 | <0.35 | 88 |
| Arsenic | 22 | 17 | 6.0 | 19 | <83 | 6,700 |
| Cadmium | 4.2 | 2.0 | 13.7 | 5.6 | <0.35 | 460 |
| Copper | 104 | 41 | 290 | 130 | <3.5 | 12,000 |
| Chromium | 300 | 154 | 910 | 200 | 3.5 | 99,200 |
| Mercury | 0.4 | 0.2 | 0.6 | 0.1 | 29 | 56 |
| Nickel | 140 | 66 | 400 | 90 | <6.9 | 33,600 |
| Lead | 66 | 39 | 11,000 | 684 | <10 | 12,000 |
| Vanadium | 250 | 130 | 630 | 190 | <3.5 | 45,600 |
| Zinc | 1,000 | 280 | 8,000 | 1,300 | 13 | 57,600 |
| Barium | 370,000 | 91,000 | 31,000 | 29,000 | 5,720 | 670,000 |
| THC | 1,300 | 2,030 | 2,900 | 2,500 | 779 | 2,230,000 |
| ΣPAH | 86 | 17 | 230 | 36 | 112 | 18,500 |

(a) Source: Steinhauer et al. (Ref. 7).
(b) Source: Steinhauer and Imamura (Ref. 6).

**Table 5.** Mean Metal and Hydrocarbon Cencentrations in Drilling Muds and Cuttings and Surficial and Suspended Sediments During Phase III. Concentrations are ppm dry weight.

| | Concentration (ppm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Drilling Muds | | Cuttings | | Nearfield Sites | | Farfield Sites | |
| | Platform Hidalgo | Platform Hermosa | Platform Hidalgo | Platform Hermosa | Surficial Sediment | Suspended Sediment | Surficial Sediment | Suspended Sediment |
| Silver | 0.37 | 0.39 | 0.50 | 0.63 | 0.14 | 0.17 | 0.15 | 0.18 |
| Arsenic | 10 | 9.3 | 10 | 13 | 8.7 | 6.5 | 6 | 6.2 |
| Barium | 53,900 | 12,500 | 15,084 | 1,180 | 923 | 736 | 869 | 687 |
| Cadmium | 1.17 | 1.75 | 2.89 | 3.62 | 0.45 | 0.59 | 0.47 | 0.61 |
| Chromium | 91 | 84 | 104 | 94 | 115 | 99 | 120 | 98 |
| Copper | 24 | 24 | 70 | 56 | 10 | 16 | 12 | 16 |
| Mercury | 0.09 | 0.06 | 0.07 | 0.04 | 0.043 | 0.065 | 0.059 | 0.066 |
| Nickel | 39 | 42 | 47 | 17 | 34 | 45 | 38 | 48 |
| Lead | 23 | 40 | 356 | 32 | 14 | 13 | 14 | 14 |
| Vanadium | 76 | 46 | 100 | -- | 72 | 87 | 72 | 90 |
| Zinc | 167 | 235 | 664 | 972 | 78 | 93 | 76 | 93 |
| THC | 1,200 | 745 | 1,300 | 3,756 | 80.2 | 97.5 | 79.1 | 75.6 |
| ΣPAH | 10 | 11.5 | 19 | 24.4 | 1.32 | 0.38 | 1.14 | 0.26 |

**Table 6.** Drilling Mud Depositional Fluxes ($mg/m^2/day$) Computed From Excess Barium Concentrations in Sediment Traps. Phase II Data From Hyland et al. (Ref. 3) Were Recomputed Based On the Lowest Phase II/III Barium Mean Concentration.

| | Phase II Drilling | | | | Phase II Post/Phase III Pre-Drilling | | | | | | | | Phase III Drilling | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | May-88 | Oct-88 | May-89 | Mean | Oct-89 | May-90 | Oct-90 | Oct-91 | Apr-92 | Oct-92 | Aug-93 | Mean | Jan-94 | Jan-95 | Mean |
| **Low Flux** PH-W | 97 | 135 | 93 | 108 | -- | 45 | 20 | 82 | -- | 99 | 0 | 49 | 13 | 20 | 16 |
| PH-U | -- | 213 | 158 | 185 | 63 | 0 | 9 | 58 | -- | 37 | 29 | 33 | 4 | 56 | 30 |
| **Moderate Flux** PH-R | 451 | 211 | 162 | 275 | 62 | 23 | 27 | 46 | 9 | 28 | 0(a) | 28 | 0 | 19 | 10 |
| PH-F | -- | 276 | 245 | 260 | 33 | 37 | 15 | 54 | -- | 27 | 0 | 28 | 60 | 58 | 59 |
| **High Flux** PH-K | 461 | -- | 107 | 284 | 43 | 28 | 5 | 27 | 18 | 0 | 6 | 18 | 60 | 44 | 52 |
| PH-E | -- | 481 | 229 | 355 | -- | 72 | 53 | -- | -- | 55 | 0 | 60 | -- | -- | -- |
| PH-N | 571 | 357 | 101 | 343 | -- | 25 | 25 | 30 | 21 | 14 | 0 | 19 | 61 | 48 | 54 |
| PH-I | 483 | 432 | 310 | 408 | 92 | 104 | 58 | 104 | -- | 130 | 0 | 81 | -- | 153 | 153 |
| PH-J | 572 | 506 | 167 | 415 | 67 | 31 | 12 | 63 | -- | 17 | 0 | 32 | -- | -- | -- |
| | | | | | | | | | | | | | | | |
| Mean | 439 | 326 | 175 | | 60 | 41 | 25 | 58 | 16 | 45 | 4 | | 33 | 57 | |

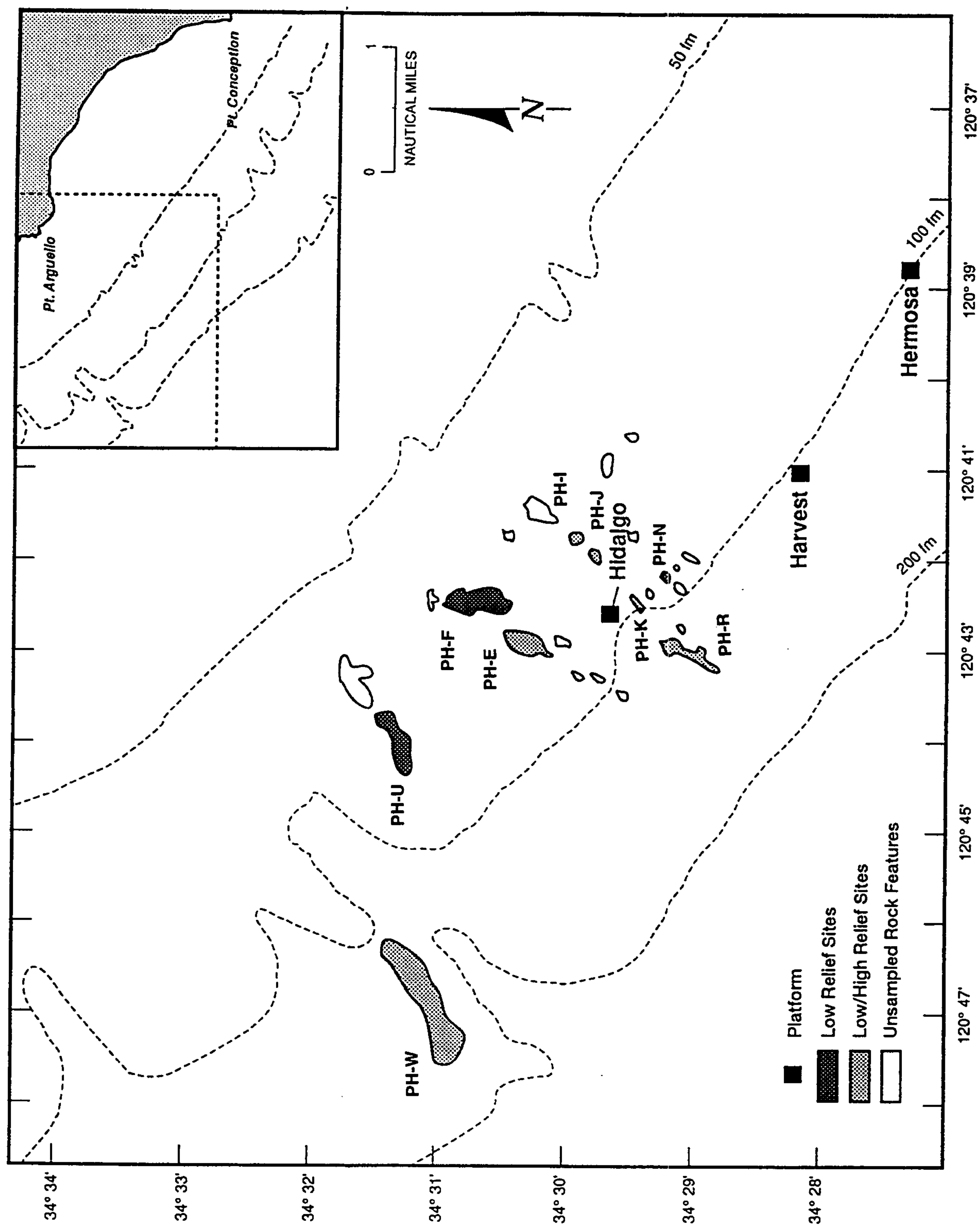
-- No data available.
(a) Anomalously low Ba concentration discarded; depositional flux assumed to be 0.

**Table 7.** Total Excess Barium in Sediments Within 500 m of Platforms Hidalgo, Hermosa, and Harvest.

| | Total Excess Ba (kg) | | | % Total Ba Emissions | |
|---|---|---|---|---|---|
| | Nov. 1991 | Jan. 1995 | % Change | Nov. 1991 | Jan. 1995[a] |
| Hidalgo | 52,200 | 53,100 | +1.7% | 13 | 10 |
| Hermosa | 57,500 | 49,000 | -15% | 17 | 14 |
| Harvest | 74,900 | 54,200 | -25% | — | — |

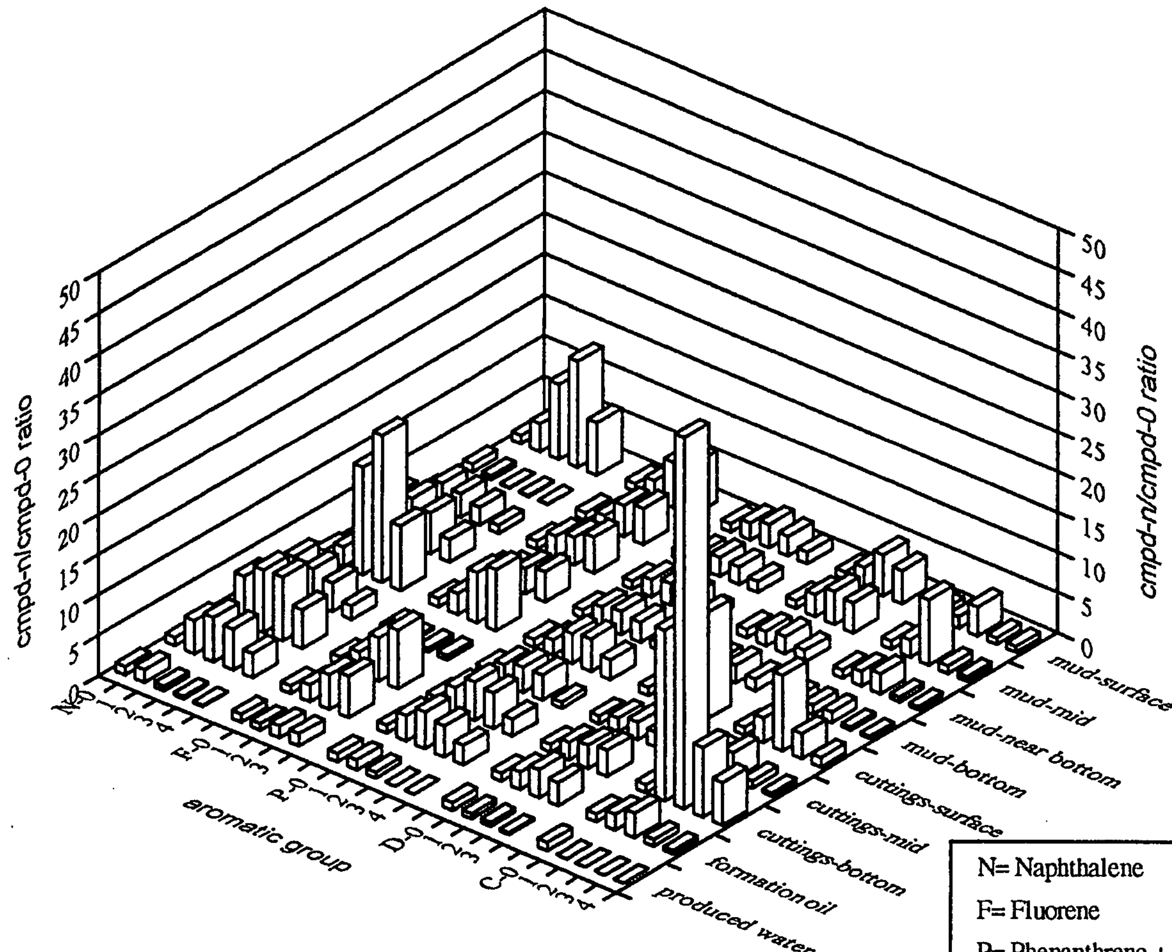
(a) Total of Phase II and Phase III Ba emissions.
— Cannot be determined due to incomplete Phase II data.

**Figure 1**



Pt. Arguello
Pt. Conception
0
1
NAUTICAL MILES
N
50 fm
100 fm
200 fm
Hermosa
Harvest
Hidalgo
PH-I
PH-J
PH-N
PH-K
PH-R
PH-F
PH-E
PH-U
PH-W
Platform
Low Relief Sites
Low/High Relief Sites
Unsampled Rock Features
120° 37'
120° 39'
120° 41'
120° 43'
120° 45'
120° 47'
34° 34'
34° 33'
34° 32'
34° 31'
34° 30'
34° 29'
34° 28'

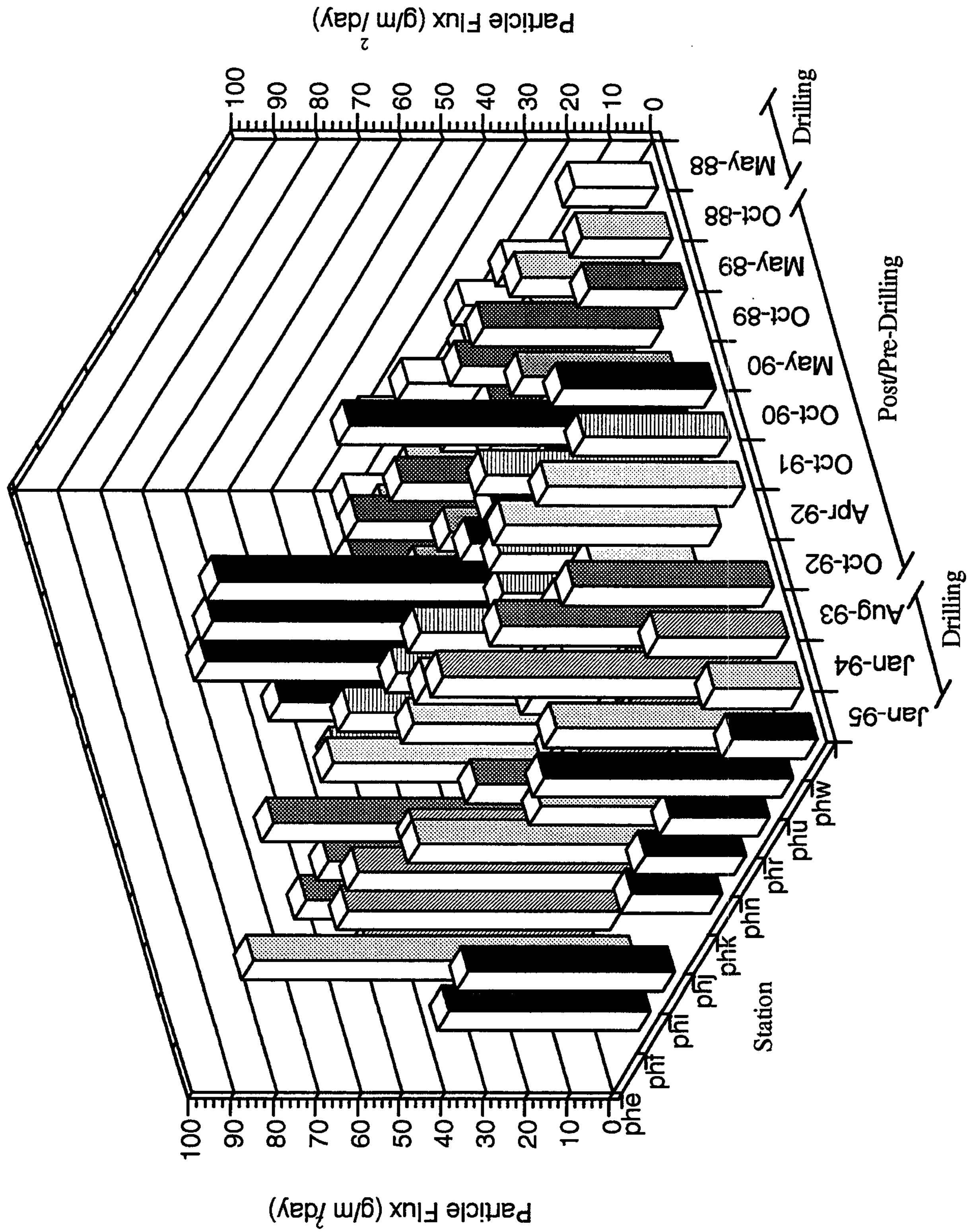
## Platform Hidalgo - Mud, Cuttings, Production Water, and Oil




N= Naphthalene
F= Fluorene
P= Phenanthrene + Anthracene
D= dibenzothiophene
C= chrysene; number (0 to 4)= carbon number of alkyl substitutions

Figure 2

Figure 3



Particle Flux (g/m²/day)
Particle Flux (g/m²/day)
0
10
20
30
40
50
60
70
80
90
100
May-88
Oct-88
May-89
Oct-89
May-90
Oct-90
Oct-91
Apr-92
Oct-92
Aug-93
Jan-94
Jan-95
Drilling
Post/Pre-Drilling
Drilling
Station
phe
phf
phi
phj
phk
phn
phr
phu
phw

Figure 4

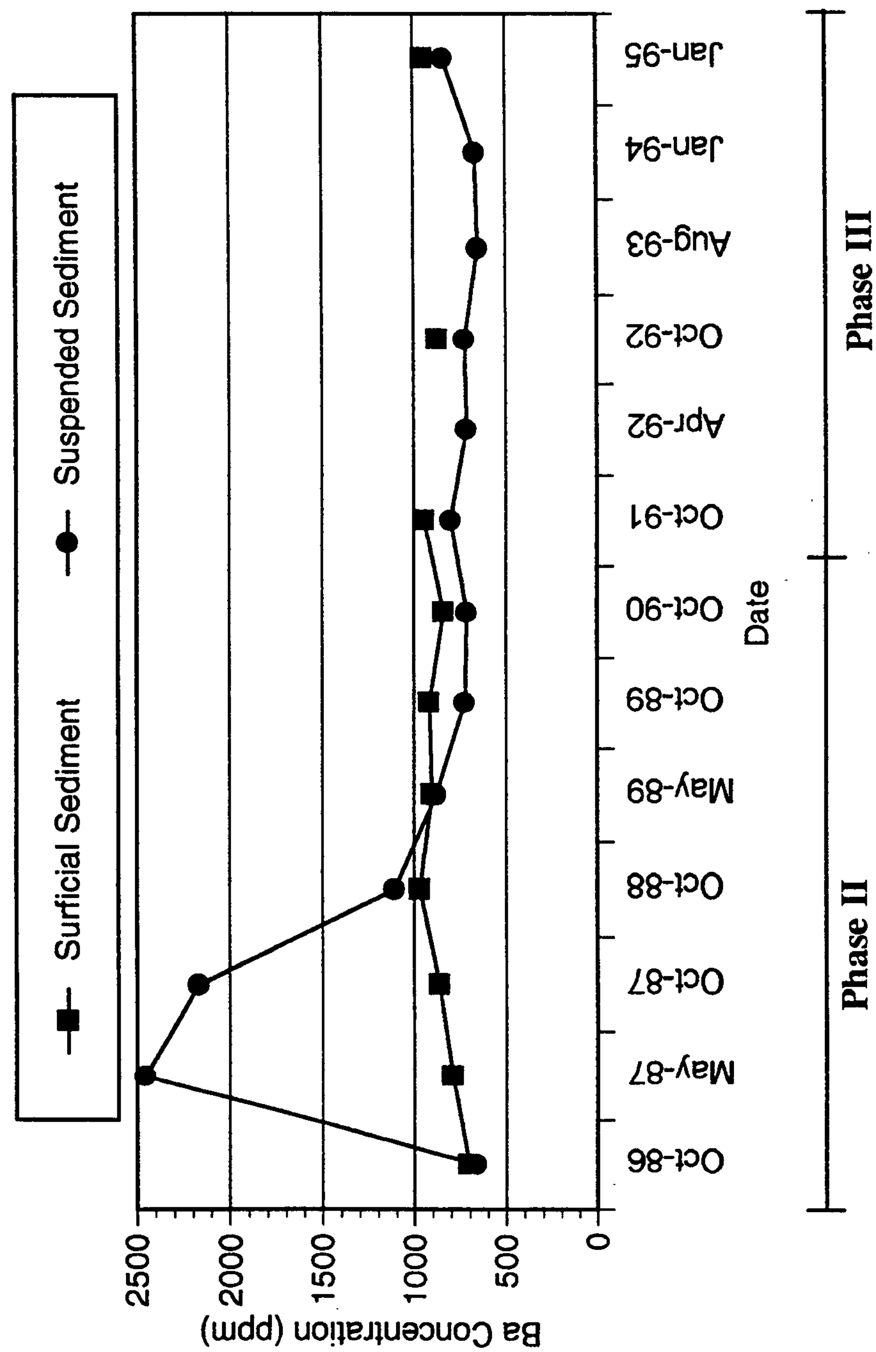
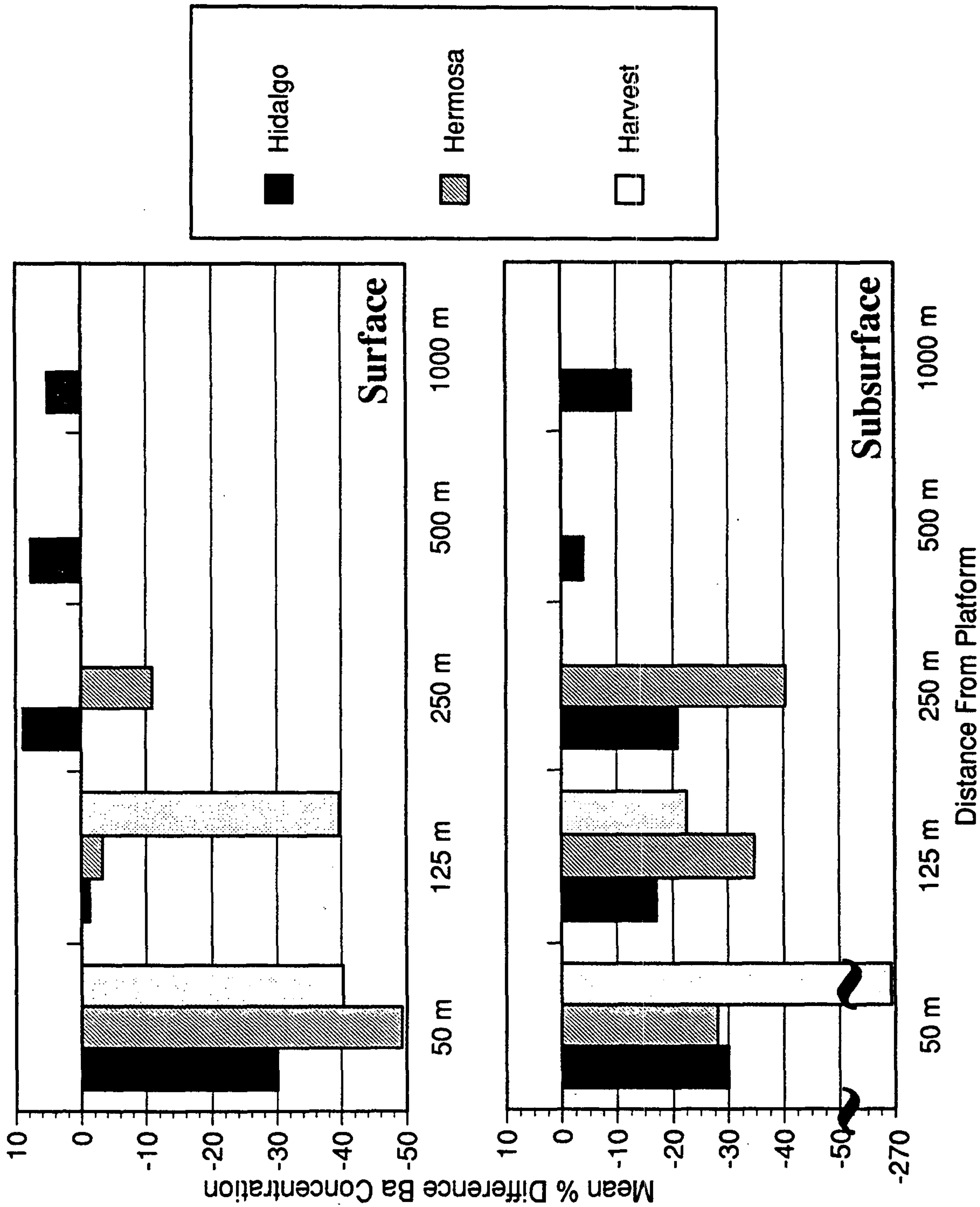

Surficial Sediment
Suspended Sediment
Ba Concentration (ppm)
2500
2000
1500
1000
500
0
Date
Oct-86
May-87
Oct-87
Oct-88
May-89
Oct-89
Oct-90
Oct-91
Apr-92
Oct-92
Aug-93
Jan-94
Jan-95
Phase II
Phase III

Figure 5



Hidalgo
Hermosa
Harvest
Surface
Subsurface
Mean % Difference Ba Concentration
10
0
-10
-20
-30
-40
-50
-270
50 m
125 m
250 m
500 m
1000 m
Distance From Platform

**Figure 6**

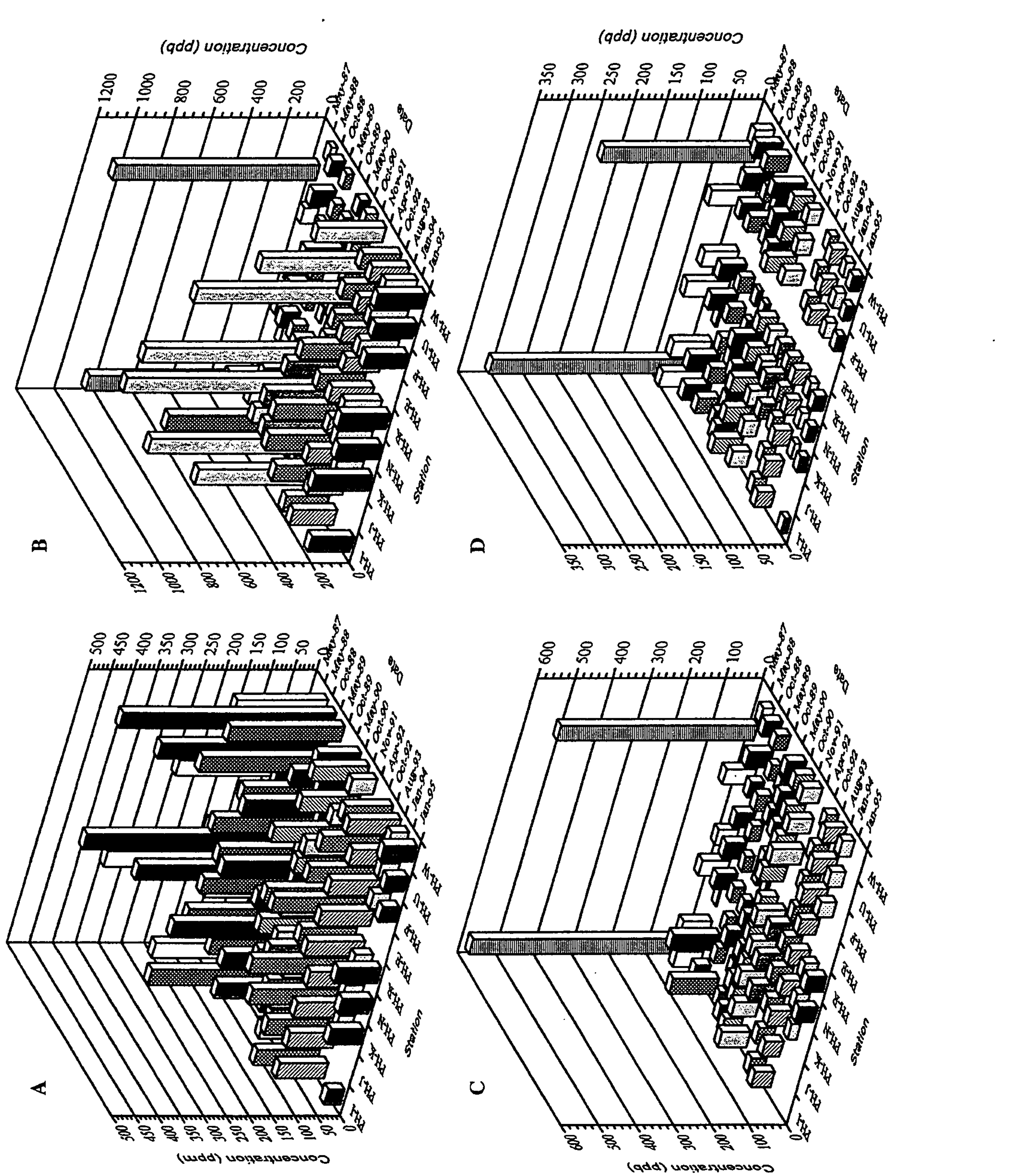
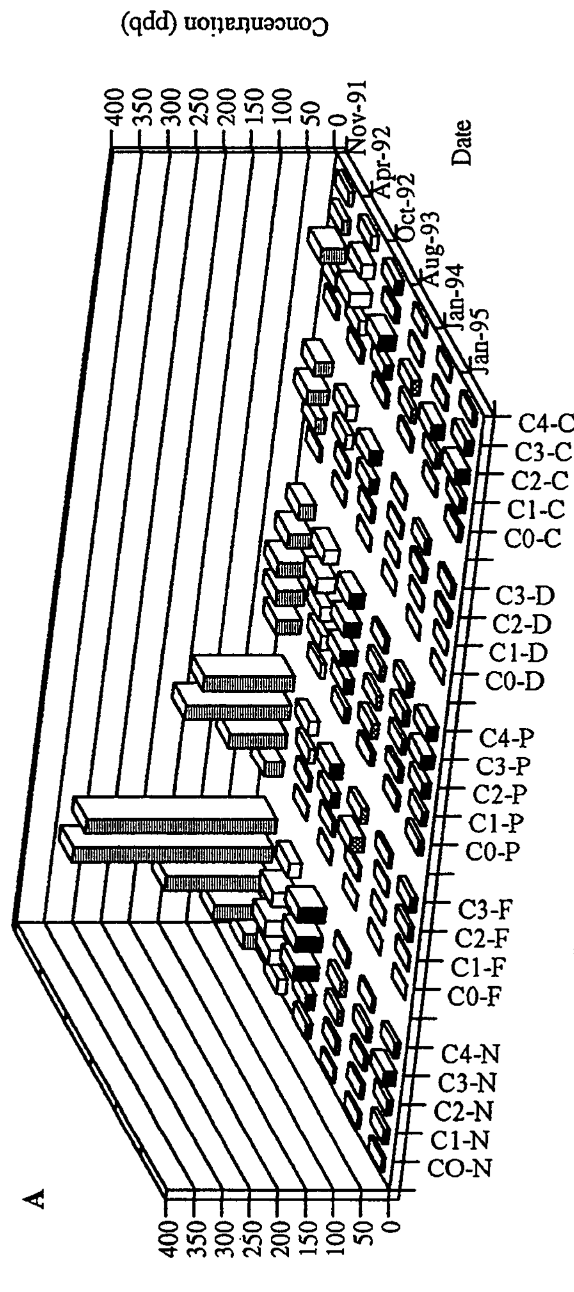
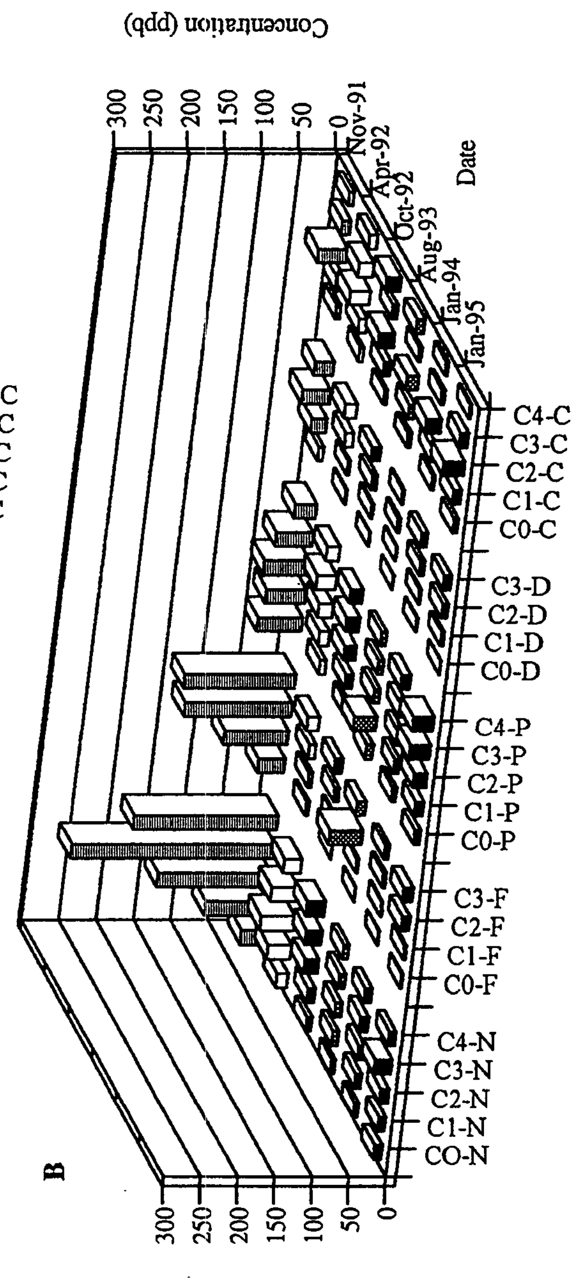


**Figure 7**

A


Concentration (ppb)
400
350
300
250
200
150
100
50
0
Date
Nov-91
Apr-92
Oct-92
Aug-93
Jan-94
Jan-95
C4-C
C3-C
C2-C
C1-C
C0-C
C3-D
C2-D
C1-D
C0-D
C4-P
C3-P
C2-P
C1-P
C0-P
C3-F
C2-F
C1-F
C0-F
C4-N
C3-N
C2-N
C1-N
CO-N

B


Concentration (ppb)
300
250
200
150
100
50
0
Date
Nov-91
Apr-92
Oct-92
Aug-93
Jan-94
Jan-95
C4-C
C3-C
C2-C
C1-C
C0-C
C3-D
C2-D
C1-D
C0-D
C4-P
C3-P
C2-P
C1-P
C0-P
C3-F
C2-F
C1-F
C0-F
C4-N
C3-N
C2-N
C1-N
CO-N

# DOI - PCA Stations

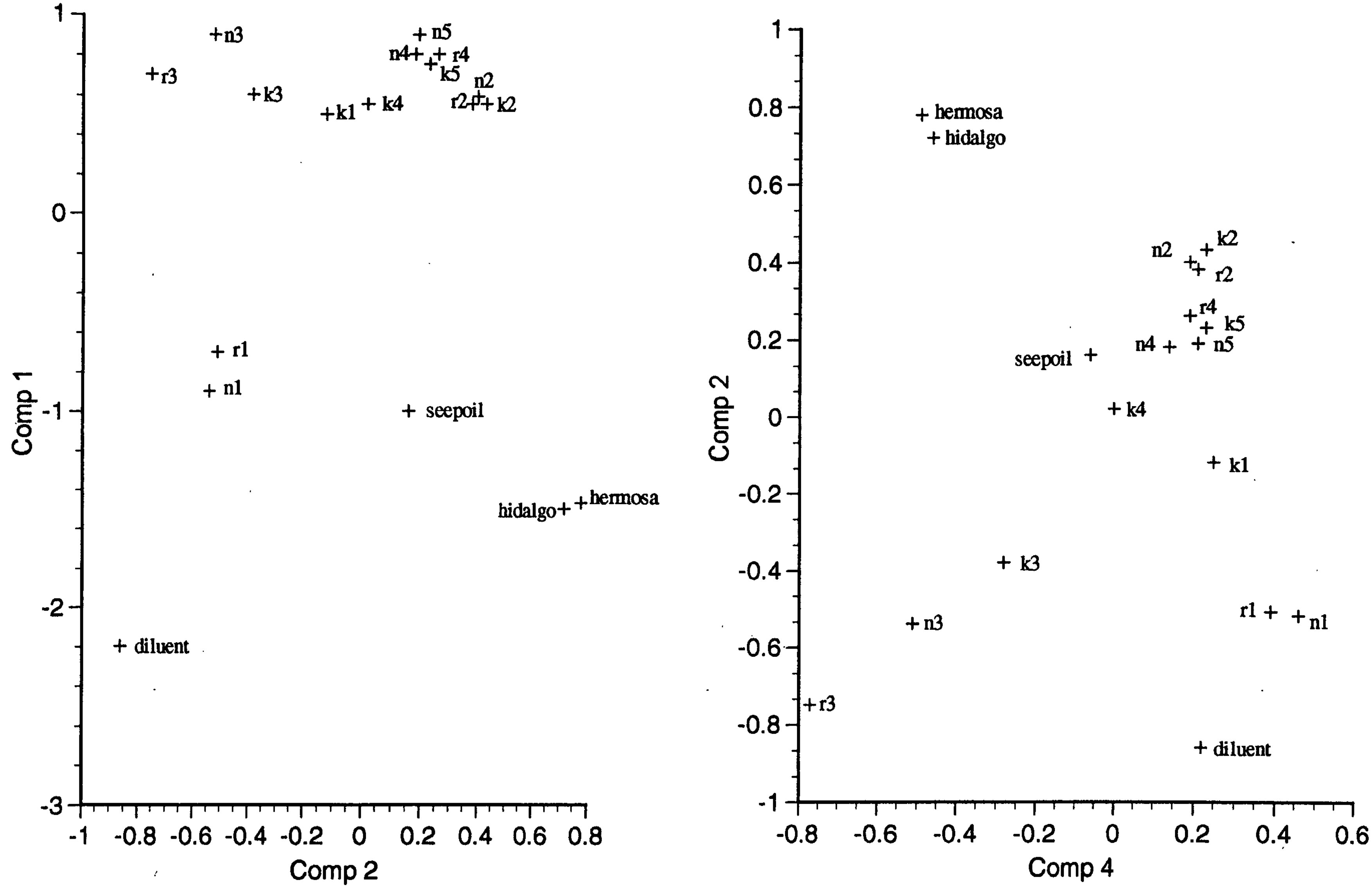



Figure 8

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# Appendix C

# APPENDIX C

## IN SITU LARVAL EXPERIMENTS AND LABORATORY TOXICITY TESTS MANUSCRIPTS

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# APPENDIX C-1

## IN SITU RED ABALONE SETTLEMENT EXPERIMENT MANUSCRIPT

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# EFFECTS OF OFFSHORE OIL AND GAS DEVELOPMENT ON MARINE LARVAL SETTLEMENT: IN SITU MANIPULATED FIELD EXPERIMENTS

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[To be submitted to: *Journal of Marine Biology and Ecology* or *Marine Environmental Research*]

## ABSTRACT

A series of in situ, manipulated field experiments were conducted to determine the effects of oil and gas drilling mud and produced water discharges on the settling ability of larval red abalone (*Haliotis rufescens*). The study area focused on a series of three oil platforms and three reference sites between Pt. Arguello and Pt. Conception in the southern Santa Maria Basin, California. Study depths were approximately 200 m. The experiments involved reciprocal transplants of groups of settling plates that first were "filmed" with bacteria at each site, and then transplanted to all other sites at each of two heights ("high" and "low") from the bottom. Unfilmed plates were used to test the effects of the filming treatments. Plates were placed into specially designed chambers, covered with mesh, and placed onto recoverable larval arrays for deployment to the sea bottom. Approximately 500 laboratory-reared red abalone larvae, competent for settlement, were placed into separate chambers (each containing a settling plate) prior to deployment. One experimental array containing replicate larval chambers was deployed on the sea floor for 3 days at each of the six locations. Upon recovery, settled abalone larvae were counted to test location-related (platform vs. reference sites), waterborne, and height effects on settlement. Experiments were carried out over a three year period that incorporated pre-drilling and drilling phases. Discharges during drilling occurred sequentially from two of the three platforms, with somewhat overlapping particle dispersion patterns between the platform sites. Results showed: (1) red abalone are suitable for deep ocean in situ bioassay work; (2) the presence of a bacterial film significantly affected the number of abalone larvae that settled onto plates; and (3) settlement was lower at all locations in the period during drilling; settlement at drilling platforms relative to reference sites was depressed significantly further.

## INTRODUCTION

Offshore oil and gas drilling activities along the California Outer Continental Shelf (OCS) have prompted concern for ecological effects associated with such activity (Piltz 1986; Brewer et al. 1991). One area that has been extensively studied and which has been the site of several exploratory and development/production platforms is the Santa Maria Basin offshore of Pt. Conception in southern California (SAIC 1986; Steinhauer et al. 1992; Steinhauer and Imamura 1990; Hyland et al. 1994; Steinhauer et al. 1994). The oil fields in this area are among the largest discovered in OCS waters and contain 50 of the 102 active lease tracts in the Pacific OCS region (Steinhauer et al. 1992). Previous and potential drilling activity represent substantial discharges of drilling wastes to the marine environment of this region.

Oil and gas drilling discharges (e.g., muds, cuttings, fluids, and produced waters) to the marine environment may have far reaching effects at several ecological levels; however, much of the recent research in the California OCS region has focused on effects to adult populations (Brewer et al. 1991; Hardin et al. 1994; Hyland et al. 1994). Few studies have addressed other factors such as changes in larval settlement, recruitment of new individuals, or how such changes might influence population dynamics. Larval settlement and recruitment can be affected by interactions with both biotic and abiotic factors (Crisp 1974; Crisp 1984; Rodriguez et al. 1993). Factors affecting larval recruitment may have long lasting effects at the population level leading to community wide effects (Connell 1985; Mullineaux 1988; Raimondi 1990). Thus, studies addressing these factors can provide early evidence of potential effects at higher ecological levels.

Until recently, the use of bioassays to detect impacts to marine systems has been largely restricted to the laboratory. This was chiefly due to the logistical constraints of working with live animals in field situations and because the bioassays often took so long to perform that it was infeasible to maintain them in the field. However, relatively new approaches to assess biological impacts have been developed to overcome these problems (Raimondi and Schmitt 1992; Krause 1995; Raimondi and Reed 1995). These methods utilize early life history stages instead of adults. Early life stages are small, manipulatable, and respond rapidly to perturbations. Moreover, early life stages are generally more susceptible to disturbances, making them ideal test systems for bioassay experiments (Neff et al. 1976; NRC 1983; Krause et al. 1992; Raimondi and Schmitt 1992).

The purpose of the present study was to examine the extent to which oil and gas drilling activity might affect larval settlement. This study was performed in conjunction with several concurrent investigations as part of the Department of the Interior, Minerals Management Service (MMS)/National Biological Service (NBS) Phase III Long-Term Monitoring Program of the Santa Maria Basin. The Phase III program was designed to assess cumulative effects of offshore drilling and production activities on the marine environment of the study region (SAIC and MEC 1993).

For this study, in situ assays of larval settlement were conducted at sites near and far from drilling platforms. The experiments provided a basis for determining factors that affected the settlement of a controlled population, in this case red abalone larvae. Because natural settling rates are relatively low (Mullineaux 1988), manipulations were performed in which known numbers of larvae were exposed to a series of treatments in the field to determine how settlement was affected by: (1) waterborne factors (e.g., suspended solids, food, and dissolved chemicals); (2) surface films on settlement plates (e.g., bacteria and particulates incorporated into the surface film); and (3) reef height (relief height from the bottom). The specific design of these experiments allowed for the determination of causation related to drilling operations.

## METHODS

### Study Site

The study was conducted along a portion of the southern California continental shelf between Pt. Conception (34° 28' N 120° 28' W) and Pt. Arguello (34° 35' N 120° 38' W), at water depths of 160 – 210 m (Figure 1). Three nearfield oil platforms and three farfield reference sites were utilized for the study. Nearfield sites were located near hard-bottom reefs adjacent to Platforms Hidalgo, Harvest, and Hermosa (Figure 1). The farfield sites were also near hard-bottom reefs, upcoast (1 site) and downcoast (2 sites) of the platforms along the same depth contour. The farfield sites were selected to be beyond the major influence of Phase III drilling activities, based on dispersion and deposition information from Phase II studies (Coats 1994). In addition, experiments were conducted at two heights (0.35 and 1.25 m) above the ocean bottom corresponding to low and high relief reefs in the region (Hardin et al. 1994).

Current patterns in the region that may affect dispersion of drilling discharges and larvae are influenced by the California Current. Current meter data show that the physical oceanography of the study site is characterized by along-shelf surface flows that generally run parallel to the shoreline (Chelton et al. 1982; SAIC and MEC 1993). The general coastal orientation of the region is southeast to northwest. Hyland et al. (1990) found that there is a high-frequency tidal influence that produces across-shelf currents. These currents can be particularly strong near the bottom. Influences of along-shelf and across-shelf currents cause patterns of circulation at the study site that are complex and often consist of eddies, swirls, filaments, meanders, and narrow jets (Mooers and Robinson 1984; SAIC and MEC 1993).

Natural and anthropogenic factors can affect the abundance and type of organisms present in a community. Natural factors include oil seeps and variability in physical substrates that can interfere with larval settlement. Natural oil seeps have not been characterized to a great degree in the study area, but are known to be present along the southern California coast (Wilkinson 1972). Previous studies in the area have observed microscopic tar particles in the bottom sediments (Steinhauer et al. 1994), even though hydrocarbon concentrations in sediments are generally low (Steinhauer and Steinhauer 1990). The general topography of the area includes extensive soft-bottom areas of mud and, much less commonly, hard-bottom areas of rocky outcrops of varying relief height (Lissner et al. 1991; SAIC and MEC 1993). The Phase II study classified the hard-bottom substrates of the area into two distinct height groups: low relief

(0.2–0.5 m) and high relief (>1 m) (Hardin et al. 1994). These areas were distinguished by differences in the abundances and types of organisms, including meroplanktonic larvae, throughout the area (SAIC and MEC 1993; Hardin et al. 1994; Diener and Lissner, in preparation).

**Study Organism**

Red abalone larvae (*Haliotis rufescens*) were used for the study. This species and life history stage has a number of desirable characteristics for use in in situ bioassays (Raimondi and Schmitt 1992). The species has a broad depth range from the intertidal to more than 180 m, and its larval life history is well documented (Morris et al. 1980). Further, it is easy to culture and use in in situ bioassays and is sensitive to a suite of potential anthropogenic disturbances, both physical and chemical in nature (Morse et al. 1980; Raimondi and Schmitt 1992). Its life history also is similar to a number of other marine species, potentially making it a good indicator organism. Finally, larval red abalone have been used in a large number of laboratory and some field bioassay programs, so results can be compared to other studies (e.g., Hunt and Anderson 1989; Raimondi and Schmitt 1992).

Preliminary studies indicated that red abalone larvae could survive and grow on settlement plates in exposures up to 23 days in the field at depths of up to 200 m (Raimondi and Barnett, unpublished data). Surviving individuals showed signs of healthy metamorphosis to the juvenile stage, active feeding on microbial films on the plates, and normal growth. These observations demonstrate that red abalone larvae can settle, survive, and grow under conditions typical of the natural field conditions in the study area.

**In situ Experiments**

In situ settlement experiments using red abalone larvae were conducted in October 1992 and January 1994 from the survey vessels M/V RAMBO and M/V INDEPENDENCE, respectively. Each experiment consisted of a filming period and subsequent exposure period, as described below.

Plexiglass settlement plates (10 x 10 cm) were placed into filming canisters and deployed approximately three weeks prior to the start of the scheduled experimental period (Figure 2). The canisters were covered with 100 μm Nitex mesh to preclude natural settlement of larvae during the filming process. Canisters were placed at each of the six experimental sites and at each of two heights (0.35 and 1.25 m) above the bottom. This general protocol to assess affects of microbial filming on settlement has been used successfully by Todd and Keough (1994) and Keough and Raimondi (1995).

Following the filming period, the plates were retrieved from the canisters and sorted to distribute plates from each filming site to each incubation (exposure) site, thereby representing a reciprocal transplant design. Plates were secured into individual chambers, and then attached to deployable larval arrays referred to as igloos (Figure 2). Igloos were three dimensional structures that carried plates on four separate faces to account for the potentially confounding effects of currents. Each chamber held one settling plate and was covered with 100 μm Nitex mesh. Plate chambers were "injected" with 500 (±50) competent (biologically capable of settling) red abalone larvae prior to a three day deployment of the igloos. Plates remained covered with Nitex mesh for the duration of the incubation to prevent spontaneous natural settlement of other invertebrates, predation, and to contain the red abalone larvae within the chambers. Four replicates were conducted of each combination of filming site, incubation site, and relief height. Plates that were returned to their original filming site were replicated by an additional four plates. In addition to the plates from each filming site, sterile plates (no surface filming) also were transplanted to each site (4 replicates per site).

Sorting of plates was done in an onboard laboratory in cool, dark conditions, and plates were continuously immersed in seawater. Completed trays (see Figure 2) were maintained in cool seawater in the dark until just before igloo deployment. When all trays were completed (abalone larvae injected into all chambers), covers were placed over the trays to keep them bathed in cool seawater prior to deployment, and covered trays were attached to the igloos. Igloos were then lowered using the ship's crane to a depth of 8-10 m and scuba divers removed the tray covers to expose the chambers to in situ conditions. Following removal of the covers the igloos were lowered slowly to the sea floor.

After the three-day incubation period, the igloos were retrieved. Settled abalone larvae are resistant to desiccation and were attached firmly to the settling plates, permitting the igloos to be brought directly from the bottom to the ship's deck without underwater attachment of covers on the trays. However, once onboard, covers were immediately placed on each tray and the trays were moved back to the cool seawater baths in the darkened shipboard laboratory until the settlers could be counted. The number of settled red abalone larvae were counted microscopically within two hours of igloo retrieval. Experiments carried out in October 1992, and January 1994 yielded one data set each for the "pre-" and "during-drilling" periods.

**Experimental Design and Analysis**

The experiment as described above was performed twice. The first experiment was performed in October 1992, during a period when no drilling was occurring or had occurred at any of the three platforms since 1989 (Steinhauer and Imamura 1990). This was defined as the pre-drilling period. The second experiment was conducted in January 1994 at which time drilling was occurring at Platform Hidalgo, had just been completed at Platform Hermosa, and had not occurred at Platform Harvest. This was defined as the drilling period.

In summary, the overall experimental design consisted of the following:

(1) Two experimental periods: pre-drilling and drilling;
(2) Two levels of plate surface filming: near platforms and far from platforms (at reference sites);

(3) Two levels of incubation location (locations to which plates were transplanted and at which settlement occurred): near platforms and far from platforms (reference sites); and
(4) Two levels of relief height (plate height): low (0.35 m) and high (1.25 m).

The basic statistical design is a Before-After-Impact-Reference factorial ANOVA design (Green 1979; Stewart-Oaten et al. 1986) with three replicates of the platform sites and three replicates of the reference sites. With true "field" replication such as this, the question of whether impacts were attributable to some aspect of drilling discharges could be addressed; without true replicates, the effect of a platform would be confounded with location-to-location variability. If activities associated with the operations at the platform sites were contributing to changes in settlement then this should be seen as differences (deltas) in settlement between the before and after periods. This statistical design has been advocated by several authors as the most powerful technique to demonstrate environmental impacts using field studies (Green 1979; Hurlburt 1984; Stewart-Oaten et al. 1986; Underwood 1994).

Settling plate replication within this factorial design was achieved as follows:

(1) At all incubation sites there were plates that were filmed at all filming sites;
(2) The mean number of settlers for all plates filmed at a site and transplanted to an incubation site was considered one replicate. (As an example, at Reference Site 1 four of the plates filmed at one relief height were transplanted to Reference Site 2 for incubation at the same relief height); and
(3) The mean number of settlers from those four plates was considered to be a single replicate. In this way "psuedoreplication" was avoided (Hurlburt 1984).

Data were analyzed using fixed effect analysis of variance procedures (SAS Institute 1988) on $\log_e (x+1)$ transformed data to meet assumptions of homoscedacity. Specific analyses are described below.

## RESULTS

### Assessment of variability in settlement

Variability in settlement during the before-drilling period was assessed by comparing settlement of red abalone larvae at the three reference sites (Table 1). Sites near the platforms were excluded from this analysis to avoid any confounding effects related to the platforms. In addition, the set of unfilmed plates was included in the analysis to determine the effect of no filming on larval settlement. Thus the three-way factorial ANOVA (filming site x incubation x plate height) had four treatments for the filming factor (three reference sites and one no-film treatment). With only three reference stations, and two sets of film conditions, the degrees of freedom were insufficient to test all of the interaction terms in the three-way factorial design. Consequently, interactions involving relief height were treated as part of the overall error term.

The ANOVA was followed by a Ryan-Einot-Gabriel-Welch multiple comparison test (REGWQ; SAS Institute 1988) to separate filming and incubation site means (Day and Quinn 1989).

Results indicated there were no effects of relief height or the interaction between filming and incubation location on settlement (Table 1). However, both filming location and incubation location affected settlement of red abalone. For the film location effect, plates with no microbial films had lower settlement than that found on plates from any of the reference sites. No differences in settlement were evident for films from different reference sites. The significant effect of incubation location was largely driven by Reference Site 3, which exhibited lower settlement than the other two sites. These results indicated: (1) filming increased settlement; (2) there was no strong evidence of differences in filming among locations that was sufficient to cause differences in settlement; and (3) there was significant among-site variability in settlement.

**Effect of drilling activity on settlement**

Drilling activities did not occur as anticipated at the three platforms; during the experimental period drilling occurred only at Platforms Hidalgo and Hermosa (Table 2). Therefore the "impact" site near Platform Harvest was dropped from the analysis.

The location of Reference Site 1, located >5 km northwest of Platform Hidalgo (Figure 1) received only low flux of drilling muds during the major drilling operations of Phase II (Hyland et al. 1994) and, based on extrapolation from deposition maps of Coats (1994), was expected to receive no flux during the limited drilling of Phase III . However, a second model applied to the actual amount and size of particles discharges in Phase III, indicated that low sediment fluxes and deposition was probable in the area of Reference Site 1 (see Appendix A in SAIC and MEC 1995). Since the present experiments were expected to be sensitive to low levels of depositional and waterborne effects, Reference Site 1 was excluded *a priori* from the analysis.

The result of these changes was an ANOVA model with two sites near platforms (impact sites, where drilling occurred during or just before the second half of the experiment) and two far from drilling activity (reference sites). A three-way factorial ANOVA was implemented with treatments of: (1) filming location (the "no film" level was excluded from this analysis), (2) incubation location, and (3) plate height. Each datum was the difference (delta) between the means of settling plate replicates in the pre-drilling and drilling periods. Using deltas resulted in removal from the analysis of potentially confounding effects of geographic location. The null hypothesis is that there is no difference in the deltas from platform or reference sites. The alternative hypothesis is that if there is a negative effect of drilling on settlement (either due to filming or waterborne effects), then the observed deltas from impact locations will be greater (in absolute terms) than those from reference locations. For example, there would be evidence for a negative effect if the predrilling-drilling delta was -35 (in mean number of settled larvae) for reference locations and -120 for impact locations.

The results of the analysis on red abalone settlement are clearly interpretable because there were no significant interactions (Table 3). Settlement was similar at high and low plate heights (Table 3A). However, the effects of both incubation and filming location were significant (Table 3A). Settlement on plates filmed and incubated close to drilling platforms had greater deltas than those filmed or incubated at reference sites (Table 3B). These results indicate that abalone settlement was generally reduced (for undetermined reasons) in the post-drilling period, but that the reduction in larval settlement was even greater on settling plates filmed or incubated at sites close to drilling platforms.

## DISCUSSION

Data presented in this study indicate that drilling activities in the Santa Maria Basin had a significant negative effect on the settlement of red abalone larvae (Table 3). Moreover, two separate, independent factors (filming and settling) were apparently related to these reductions. Microbial films that developed on settling plates located near platforms where drilling was occurring (Hidalgo) or where drilling had recently occurred (Harvest) induced less settlement than films developed far from drilling sites, regardless of whether settlement occurred near drilling platforms or at reference sites. Furthermore, settlement on plates located near platform sites was less than settlement far from platforms, regardless of where microbial films were developed.

An alternative explanation (i.e., that some other geographic-specific factor caused these effects) for these results is unlikely. If a platform-related characteristic other than drilling discharges induced a negative effect on settlement, the reductions would have been reflected in the pre-drilling as well as the drilling stage. Utilization of deltas (differences in settlement between pre-drilling and drilling periods) eliminated this type of effect. Reductions in settlement near platforms would have occurred in both periods such that the delta should have been no greater than that of reference stations.

The same logic applies to all potential influences other than those that were manifested only near drilling platforms in the during/after drilling period. Clearly, the most likely candidate that meets these criteria is platform drilling activity.

Competent red abalone larvae typically settle on surfaces covered with crustose coralline algae or bacterial films (Morse et al. 1979a, b). Once settled, metamorphosis of the adult form typically is completed within 24 hours (Morse et al. 1980). This larval settlement process is complex and may be associated with several mechanisms that account for the effects observed in the present study. Results showed that bacterial films greatly influenced the settlement of abalone larvae. When plates were filmed with bacteria prior to deployment, settlement was approximately twice as high as that observed when a film was not present (Table 1). This demonstrates the importance of filming to the larval settlement and recruitment process.

Marine larvae are known to be selective in their preference of a suitable habitat for settlement (Doyle 1975; Keough and Downes 1982; Rodriguez et al. 1993). This process often involves complex biochemical mechanisms (Morse et al. 1979a, 1979b; Morse 1990) that initiate the settlement process. Waterborne factors, including dissolved chemicals and suspended particulates, may interfere with physiological receptors of larvae that serve to identify suitable settlement sites or initiate the settlement process. In a similar manner, post-settlement processes (both physical and biochemical) that initiate metamorphosis from a free swimming larva to settled juvenile may be interrupted by waterborne factors. Newly settled abalone also feed on the microbial films present on the settlement surface (Raimondi, pers. obs.). Material incorporated into, or present on this matrix such as food particles, sediment particles, or adsorbed chemicals, may have a direct impact on the post-settlement survival of larvae.

Dissolved chemicals from effluents of drilling and production activities such as produced waters were thought to dilute rapidly below harmful levels (Montalvo and Brady 1979; Rose and Ward 1981; Middleditch 1984; Neff 1987). However, recent research has challenged this idea and demonstrated that dissolved chemicals may be responsible for toxicity of benthic invertebrate larvae observed in the water column (Krause et al. 1992; Raimondi and Schmitt 1992; Krause 1995) In similar work, Cherr et al. (1993) and Higashi and Crosby (1993) showed that dissolved petroleum products in produced waters were of primary importance in inducing chronic toxicity of marine organisms. The present study did not attempt to determine whether waterborne factors responsible for the observed effects on abalone settlement were derived from dissolved or particulate fractions, but the results observed are consistent with the previous studies on dissolved constituents, suggesting that they may play an important role as a mechanism for inducing effects.

Effects observed in this study focused on larval settlement, potentially one of the most ecologically important steps in the population dynamics of marine systems (Keough and Black 1995). Slight effects on larval settlement rates can result in significant reductions in recruits to settled populations of organisms and lead to wider spread population level changes (Murdoch et al. 1989; Nisbet et al. 1995). This may be especially true in areas of low natural settlement such as in the Santa Maria Basin (Barnett et al. 1995; see Appendix C-2 in SAIC and MEC 1995). Larval settlement results from the present study may correspond to observed effects in previous MMS sponsored studies of adult benthic invertebrates from the Santa Maria Basin. Hyland et al. (1994) found that 4 of 22 hard-bottom taxa showed significant decreases in mean abundance following drilling activities over a four year period. Nonetheless, processes linking larval and benthic dynamics are poorly understood and the ecological significance of decreased settlement rates remains an area of active research (Nisbet et al. 1995; Raimondi and Schmitt 1992).

Similar results to the present study were noted from a companion laboratory study (Raimondi et al., in preparation; see Appendix C-3 in SAIC and MEC 1995). These results indicated that expected field concentrations of drilling muds had negative effects on settlement of red abalone larvae and caused decreases in survivorship and increased tissue loss in a cup coral, *Paracyathus stearnsii.*

Further, similar experiments to the present study tested the effect of drilling activities on natural settlers in the Santa Maria Basin (Barnett et al. 1995; see Appendix C-2 in SAIC and MEC

1995). Because natural settlement rates in that experiment were low, it was not possible to assess as accurately the effects of drilling on settlement (as defined by Keough and Downes 1982) or on microbial inducers of settlement (microbial films). Barnett et al. (1995) investigated recruitment for durations greater than 300 days in the pre-drilling and drilling periods. These results suggested some drilling-related effects, even though the tests had low statistical power. However, in contrast to the present in situ study and the laboratory red abalone and cup coral studies, most of these effects were positive (enhanced recruitment). The basis for the difference between the studies is unresolved. Several hypotheses may be plausible to explain these differences: (1) species specific responses to drilling; (2) results of the natural settlement experiment are confounded by other (presently unknown) events that occurred during the long (>300 day) experimental periods; or (3) differences in effects at settlement and recruitment stages.

The design of the particular experiments used in this study showed the advantage of large-scale field experiments in detecting subtle effects in the field. In situ experiments can provide valuable information on the complex mechanisms associated with large-scale perturbations to ecosystems. These studies have the advantage of testing for responses in the field rather than in more artificial systems such as in the laboratory (Krause 1994). Laboratory testing often requires multiple systems to control naturally fluctuating variables such as temperature or salinity. Further, laboratory experiments that attempt to allow natural variance of abiotic variables are prohibitively expensive and generally impractical to perform. In situ studies allow the experimental manipulation a variable(s) of interest while still exposing the variable to natural fluctuations. The results are often very powerful aids in evaluating important phenomena such as environmental impacts.

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## LITERATURE CITED

Barnett, A.M., P.T. Raimondi, and P.R. Krause. 1995. Effects of offshore oil and gas development on larval recruitment: Field experiments on the outer continental shelf off Point Arguello, California. In: SAIC and MEC 1995. Monitoring assessment of long-term changes in biological communities in the Santa Maria Basin: Phase III. Appendix C-2. Final Report to the U.S. Department of the Interior, Minerals Management Service/National Biological Service. Contract No. 14-35-001-30584.

Brewer, G.D., J.L. Hyland, and D.D. Hardin. 1991. Effects of oil drilling on deepwater reefs offshore California. *Am. Fish. Soc. Symp.* 11:26-38.

Chelton, D.B., P.A. Bernal, and J.A. McGowan. 1982. Large-scale interannual physical and biological interactions in the California Current. *J. Mar. Res.* 40:1095-1125.

Cherr, G., R. Higashi, J. Shenker, and T. Fan. 1993. Assessment of chronic toxicity of petroleum and produced water components to marine organisms. Final Report for the Southern California Education Initiative. University of California, Davis and Minerals Management Service. Contract No. 30761.

Coats, D.A. 1994. Deposition of drilling particulates offshore Point Conception, California. *Mar. Env. Res.* 37:95-127

Connell, J.H. 1985. The consequences of variation in initial settlement vs. post-settlement mortality in rocky intertidal communities. *J. Exp. Mar. Biol. Ecol.* 93:11-45.

Crisp, D.J. 1974. Factors influencing the settlement of marine invertebrate larvae. In: Grant, P.T, and A.M. Mackie (eds.). Chemoreception in marine organisms. Academic Press. London. pp. 177-265.

Crisp, D.J. 1984. Overview of research on marine invertebrate larvae, 1940-1980. In: Costlow, J.D. and R.C. Tripper (eds.) Marine biodeterioration: An interdisciplinary study. Naval Inst. Press. Annapolis, MD. pp. 103-126.

Day, R.W. and G.P. Quinn. 1989. Comparisons of treatments after an analysis of variance in ecology. *Ecol. Monog.* 59:433-463.

Diener, D.R. and A.L. Lissner. In preparation. Long-term variability of hard-bottom epifaunal communities: Effects from offshore oil and gas production and development.

Doyle, R.W. 1975. Settlement of planktonic larvae: A theory of habitat selection in varying environments. *Am. Nat.* 109(966): 113-126.

Green, R. 1979. Sampling Design and Statistical Methods for Environmental Biologists. J. Wiley & Sons, New York. 257 pp.

Hardin, D.D., J. Toal, T. Parr, P. Wilde, and K. Dorsey. 1994. Spatial variation in hard-bottom epifauna in the Santa Maria Basin, California: The importance of physical factors. *Mar. Env. Res.* 37:165-193.

Higashi, R. and D. Crosby. 1993. Environmental degradation and identification of toxic compounds of petroleum and associated materials. Final Report for the Southern California Education Initiative. University of California, Davis and Minerals Management Service. Contract No. 30761.

Hunt, J.W. and B.S. Anderson. 1989. Sublethal effects of zinc and municipal effluents on larvae of the red abalone *Haliotis rufescens. Mar. Biol.* 101:545-552.

Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Mono.* 54:187-211.

Hyland, J., D. Hardin, E. Crecelius, D. Drake, P. Montagna, and M. Steinhauer. 1990. Monitoring long-term effects of offshore oil and gas development along the southern California outer continental shelf and slope: Background environmental conditions in the Santa Maria Basin. *Oil and Chem. Pollut.* 6:195-240.

Hyland, J., D. Hardin, M. Steinhauer, D. Coats, R. Green, and J. Neff. 1994. Environmental impact of offshore oil development on the outer continental shelf and slope off Point Arguello, California. *Mar. Env. Res.* 37:195-229.

Keough, M.J. and K.P. Black. 1995. Predicting the scale of marine impacts: Understanding planktonic links between populations. In: Schmitt, R.J. and C.W. Osenberg (eds). The design of ecological impact assessment studies: Conceptual issues and application. *In press.*

Keough, M.J. and B.J. Downes. 1982. Recruitment of marine invertebrates: The role of active larval choice and early mortality. *Oecologia.* 54:348-352.

Keough, M.J. and P.T. Raimondi. 1995. Responses of settling invertebrate larvae to bioorganic films: effects of different types of films. *J. Exp. Mar. Biol. Ecol.* 185:235-253.

Krause, P.R. 1994. Effects of an oil production effluent on gametogenesis and gamete performance in the purple sea urchin (*Strongylocentrotus purpuratus* Stimpson). *Environ. Tox. and Chem.* 13:1153-1161.

Krause, P.R. 1995. Spatial and temporal variability in receiving water toxicity near an oil effluent discharge site. *Arch. Env. Cont. Toxicol. In press.*

Krause, P.R., C.W. Osenberg, and R.J. Schmitt. 1992. Effects of produced water on early life stages of a sea urchin: Stage specific responses and delayed expression. In: J.P. Ray and F.R. Englehardt (eds). Produced water: Technological/environmental issues. Plenum, New York, NY, pp. 431-444.

Lissner, A., G. Taghon, D. Diener, S. Schroeter, and J. Dixon. 1991. Colonization and recovery of hard-substrate communities: Potential impacts from oil and gas development. *Ecolog. Appl.* 1:258-267.

Middleditch, B.S. 1984. Ecological effects of produced water discharges from offshore oil and gas production platforms. Final Report on API Project No. 248. American Petroleum Institute, Washington, D.C.

Montalvo, J.G. and V. Brady. 1979. Concentrations of Hg, Pb, Zn, Cd, and As in Tembalier Bay and the Louisiana oil patch. In: Ward C.H., M.E. Bender, and D.J. Reish (eds.). The offshore ecology investigation: Effects of oil drilling and production in a coastal environment. Rice University Studies. Texas.

Mooers, C.N. and A.R. Robinson. 1984. Turbulent jets and eddies in the California Current and inferred cross-shore transports. *Science.* 223:51-53.

Morris, R.H., D.P. Abbott, and E.C. Haderlie. 1980. Chapter 13 In: Intertidal Invertebrates of California. Stanford University Press, Stanford, California.

Morse, D.E. 1990. Recent progress in larval settlement and metamorphosis: Closing the gap between molecular biology and ecology. *Bull. Mar. Sci.* 46:465-483.

Morse D.E., H. Duncan, N. Hooker, A. Baloun, and G. Young. 1980. GABA induces behavioral and developmental metamorphosis in planktonic molluscan larvae. *Fed. Proc.* 39:3237-3241.

Morse, D.E., N. Hooker, H. Duncan, and L Jensen. 1979a. γ-aminobutyric acid, a neurotransmitter, induces planktonic abalone to settle and begin metamorphosis. *Science.* 204:407-410.

Morse, D.E., N. Hooker, L. Jensen, and H. Duncan. 1979b. Induction of larval abalone settling and metamorphosis by γ-aminobutyric acid and its congeners from crustose red algae: II. Applications to cultivation, seed production and bioassays: Principal causes of mortality and interference. *Proc. World Maricult. Soc.* 10:91-91.

Murdoch, W.W., R.C. Fay, and B.J. Mechalas. 1989. Final report of the Marine Review Committee to the California Coastal Commission. Marine Review Committee, Santa Barbara, CA.

Mullineaux, L.S. 1988. The role of settlement in structuring a hard-substratum community in the deep sea. *J. Exp. Mar. Biol. Ecol.* 120:247-261.

NRC (National Research Council). 1983. Drilling discharges in the marine environment. National Academy Press. Washington D.C.

Neff, J.M., J.W. Anderson, B.A. Cox, R.B. Laughlin, Jr., S.S. Rossi, and H.E. Tatum. 1976. Effects of petroleum on survival, respiration and growth of marine animals. In: Sources, effects and sinks of hydrocarbons in the aquatic environment. American Institute of Biological Sciences. Washington D.C., pp. 515-539.

Neff, J.M. 1987. Biological effects of drilling fluids, drill cuttings and produced waters. In: Boesch. D.F. and N.N. Rabalais (eds). Long-term environmental effects of offshore oil and gas development. Elsevier Applied Science, New York, NY, pp. 469-538.

Nisbet, R.M., W.W. Murdoch, and A. Stewart-Oaten. 1995. Consequences for adult fish stocks of human induced mortality on immatures. In: Schmitt, R.J. and C.W. Osenberg (eds). The design of ecological impact assessment studies: Conceptual issues and application. *In press.*

Piltz, F. 1986. Monitoring long-term changes in biological communities near oil and gas production platforms. In: Oceans '86. Proceedings Volume 3. Monitoring Strategies Symposium. Institute of Electrical and Electronics Engineers, New York, and Marine Tech. Soc., Washington, D.C., pp. 856-861.

Raimondi, P.T. 1990. Patterns, mechanisms and consequences of variability in settlement and recruitment of an intertidal barnacle. *Ecol. Monogr.* 60:283-309.

Raimondi, P.T. and R. J. Schmitt. 1992. Effects of produced water on settlement of larvae: Field tests using red abalone. In: J.P. Ray and F.R. Englehardt (eds). Produced water: Technological/environmental issues. Plenum, New York, NY, pp. 415-430.

Raimondi, P.T., A.M. Barnett, and P.R. Krause. 1995. The effects of drilling muds on marine invertebrate larvae and adults. In: SAIC and MEC 1995. Monitoring assessment of long-term changes in biological communities in the Santa Maria Basin: Phase III. Appendix C-3. Final Report to the U.S. Department of the Interior, Minerals Management Service/National Biological Service. Contract No. 14-35-001-30584.

Raimondi, P.T. and D.C. Reed. 1995. Determining the spatial extent of ecological impacts caused by local anthropogenic disturbances in coastal marine habitats. In: Schmitt, R.J. and C.W. Osenberg (eds). The design of ecological impact assessment studies: Conceptual issues and application. *in press.*

Rodriguez, S.R., F.P. Ojeda, and N.C. Inestrosa. 1993. Settlement of benthic marine invertebrates. *Mar. Ecol. Prog. Ser.* 97:193-207.

Rose, C.D. and T.J. Ward. 1981. Acute toxicity and aquatic hazard associated with discharge of formation water. In: Middleditch B.S. (ed.). Environmental effects of offshore oil production. The Buccaneer gas and oil field study. Plenum Press. N.Y.

SAIC (Science Applications International Corporation). 1986. Assessment of long-term changes in biological communities of the Santa Maria Basin and western Santa Barbara Channel - Phase I, Vol. II Synthesis of findings. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA. Contract No. 14-12-0001-30032.

SAIC and MEC (MEC Analytical Systems, Inc.). 1993. Monitoring and assessment of long-term changes in biological communities in the Santa Maria Basin: Phase III, Year One Report. Report to the U.S. Department of the Interior. Minerals Management Service, Pacific OCS Region, Camarillo, CA. Contract No. 14-35-0001-30584.

SAIC and MEC. 1995. Monitoring assessment of long-term changes in biological communities in the Santa Maria Basin: Phase III. Final Report to the U.S. Department of the Interior, Minerals Management Service/National Biological Service. Contract No. 14-35-001-30584.

SAS Institute. 1988. *SAS/STAT User's Guide, Release 6.03 Edition.* Cary, NC.

Steinhauer, M. and E. Imamura (eds). 1990. California OCS Phase II Monitoring Program: Year-three Annual Report. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA. Contract No. 14-12-0001-30262.

Steinhauer, W.G., E. Imamura, J.R. Barminski, and J.M. Neff. 1992. California study compares natural/drilling discharge contaminants offshore. *Oil & Gas J.* May 4, 1992.

Steinhauer, M., E. Crecelius, and W. Steinhauer. 1994. Temporal and spatial changes in the concentrations of hydrocarbons and trace metals in the vicinity of an offshore oil-production platform. *Mar. Env. Res.* 37:129-163.

Steinhauer, M. and W. Steinhauer. 1990. Chemical analysis of hydrocarbons in sediments, pore water, and animal tissue. California OCS Phase II Monitoring Program: Year-three Annual Report. Vol. I. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA. Contract No. 14-12-0001-30262.

Stewart-Oaten, A., W.W. Murdoch, and K. Parker. 1986. Environmental impact assessment: 'Pseudoreplication' in time? *Ecology.* 67:929-940.

Todd, C.D. and M.J. Keough. 1994. Larval settlement in hard substratum epifaunal assemblages: A manipulative field study of the effects of substratum filming and the presence of incumbents. *J. Exp. Mar. Biol. Ecol.* 181:159-187.

Underwood, A.J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. *Ecol. Applications*. 4(1):3-15.

Wilkinson, E.D. 1972. California offshore oil and gas seeps. California Division of Oil and Gas Pub. No. TR-08, 11p.

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**Table 1:** (A) Analysis of variance on numbers ($\log_e (x + 1)$ transformed) of abalone settlers in the pre-drilling period using reference site data (Sites 1, 2, and 3). Datum is the mean across similar treatment combinations at a settlement site. Log data are normally distributed. (B) Mean settlement of red abalone on plates at reference sites (untransformed data). Dashed lines indicate sites that are not significantly different as determined by REGWQ.

| (A) Source | SS | df | MS | F | p |
|---|---|---|---|---|---|
| Filming Site | 4.293 | 3 | 1.431 | 8.713 | 0.003* |
| Incubation Site | 5.601 | 2 | 2.801 | 17.050 | 0.000* |
| Filming Site x Incubation Site | 0.455 | 6 | 0.076 | 0.461 | 0.823 |
| Plate Height | 0.166 | 1 | 0.166 | 1.008 | 0.337 |
| Error | 1.807 | 11 | 0.164 | | |

* = statistical significance at p=0.05

| (B) Filming Site | Ref 1 | Ref 2 | Ref 3 | Unfilmed |
|---|---|---|---|---|
| Mean | 104.4 | 170.7 | 110.6 | 71.0 |
| SE | 14.4 | 23.5 | 13.1 | 9.1 |
| n | 12 | 12 | 12 | 12 |

| Incubation Site | Ref 1 | Ref 2 | Ref 3 |
|---|---|---|---|
| Mean | 142.3 | 149.0 | 61.6 |
| SE | 12.9 | 21.3 | 9.1 |
| n | 14 | 14 | 14 |

**Table 2:** Summary of drilling schedules and discharges from each platform during the experimental periods.

| Platform | Drilling Period | Drilling Duration (mo.) | No. of Wells | Platform Discharges: Total Muds ($m^3$) | Total Cuttings ($m^3$) | Produced Water (MGD) |
|---|---|---|---|---|---|---|
| Harvest | no drilling | no drilling | 0 | 0 | 0 | 0 |
| Hermosa | 9/93 - 11/93 | 2 | 1 | 822 | 136 | 0.592 |
| Hidalgo | 11/93 - 5/94 | 6 | 4 | 3850 | 739 | 1.72 |

MGD = millions of gallons per day

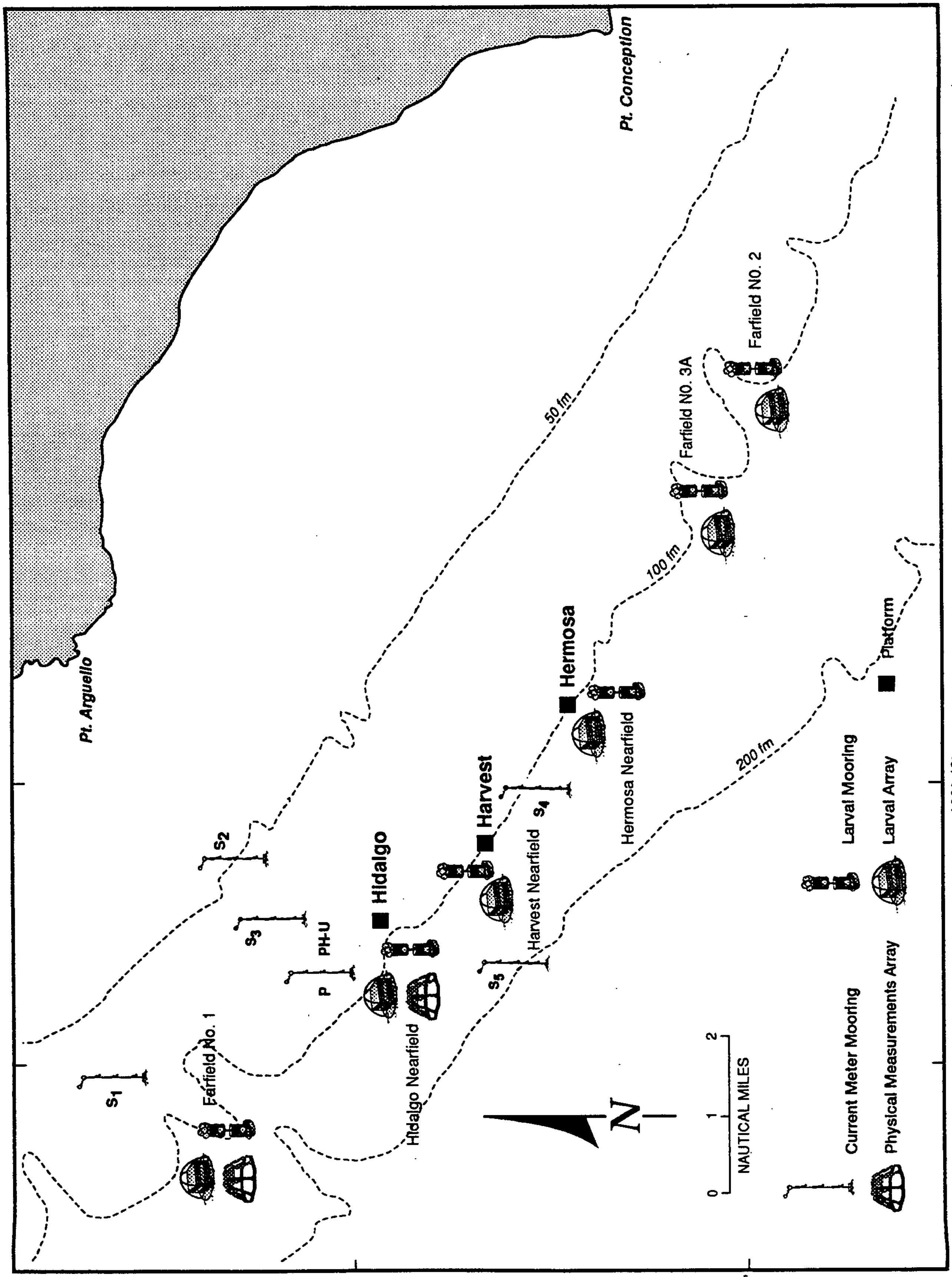
**Table 3:** (A) Analysis of variance of deltas ($\log_e (x + 1)$ transformed) using Reference Sites 2, 3, and Platforms Hidalgo and Hermosa. Datum is the mean across similar treatment combinations at a settlement site. Log deltas ($\log_e t2 - \log_e t1$) are normally distributed (where t1 = pre-drilling abundance and t2 = drilling abundance). (B) Mean deltas for settlement of red abalone (untransformed data).

| (A) Source | SS | df | MS | F | p |
|---|---|---|---|---|---|
| Filming Site | 6.792 | 1 | 6.792 | 4.74 | 0.040* |
| Incubation Site | 14.230 | 1 | 14.230 | 9.93 | 0.004* |
| Plate Height | 0.046 | 1 | 0.046 | 0.03 | 0.860 |
| Filming Site x Incubation Site | 2.454 | 1 | 2.454 | 1.71 | 0.203 |
| Filming Site x Plate Height | 0.002 | 1 | 0.002 | 0.00 | 0.969 |
| Incubation Site x Plate Height | 0.003 | 1 | 0.003 | 0.00 | 0.963 |
| Filming Site x Incubation Site x Plate Height | 0.123 | 1 | 0.123 | 0.09 | 0.772 |
| Error | 34.389 | 24 | 1.433 | | |

* = statistical significance at p=0.05

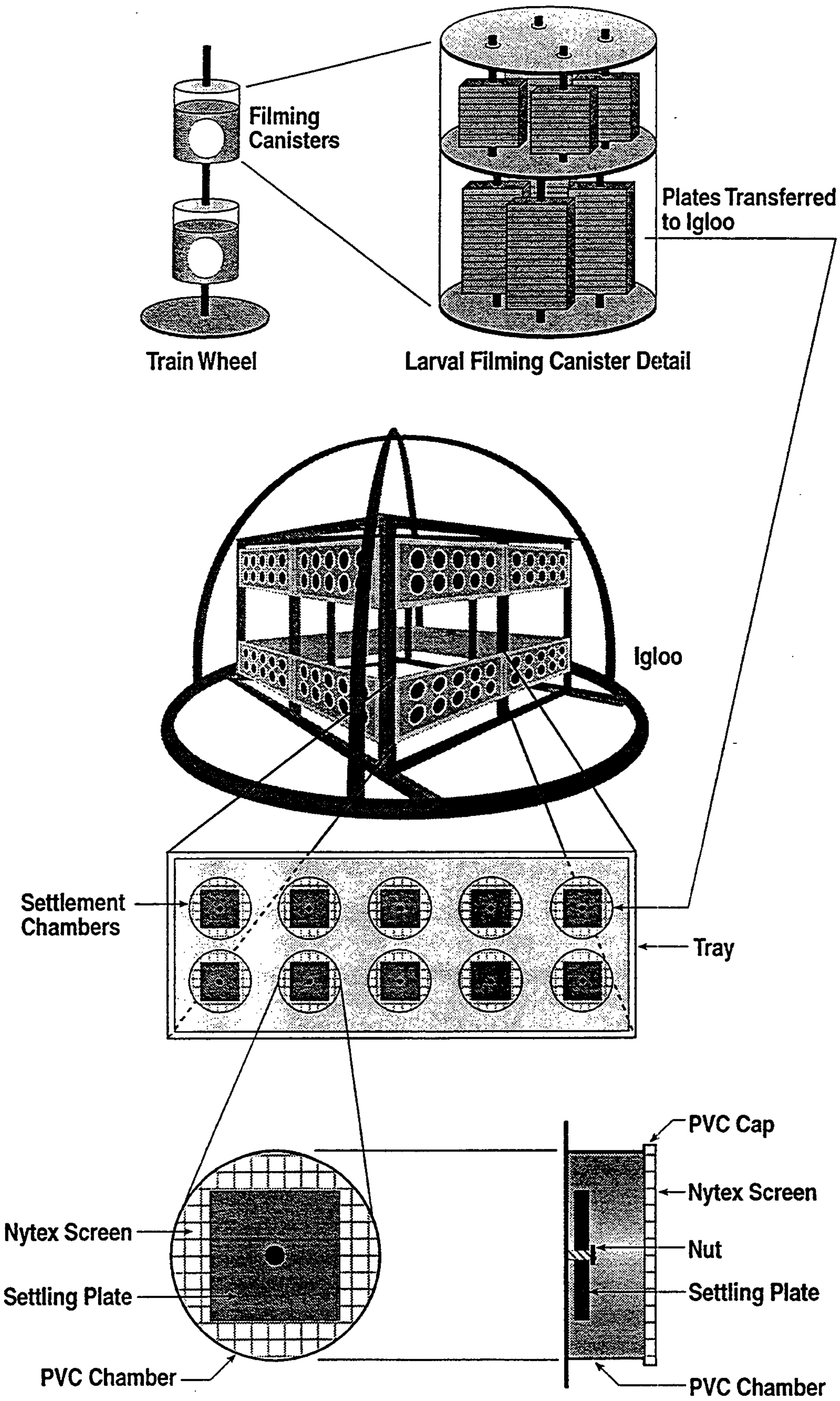
| (B) | Filming Site | | Incubation Site | |
|---|---|---|---|---|
| | Reference | Platforms | Reference | Platforms |
| Mean | -71.8 | -142.2 | -54.8 | -159.2 |
| SE | 28.2 | 34.8 | 26.4 | 33.4 |
| N | 16 | 16 | 16 | 16 |

Figure 1



Pt. Conception
Pt. Arguello
50 fm
100 fm
200 fm
Farfield No. 2
Farfield N0. 3A
Farfield No. 1
Hermosa
Hermosa Nearfield
Harvest
Harvest Nearfield
Hidalgo
Hidalgo Nearfield
Platform
$S_1$
$S_2$
$S_3$
$S_4$
$S_5$
P
PH-U
N
0 1 2
NAUTICAL MILES
Current Meter Mooring
Physical Measurements Array
Larval Mooring
Larval Array
34° 30'
34° 25'
120° 45'
120° 40'

**Figure 2**


Filming Canisters
Plates Transferred to Igloo
Train Wheel
Larval Filming Canister Detail
Igloo
Settlement Chambers
Tray
PVC Cap
Nytex Screen
Nut
Settling Plate
PVC Chamber
Nytex Screen
Settling Plate
PVC Chamber

# APPENDIX C-2

## IN SITU LARVAL SETTLEMENT EXPERIMENT MANUSCRIPT

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# EFFECTS OF OFFSHORE OIL AND GAS DEVELOPMENT ON LARVAL SETTLEMENT: FIELD EXPERIMENTS ON THE OUTER CONTINENTAL SHELF OFF POINT ARGUELLO, CALIFORNIA

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[To be submitted to: *Journal of Experimental Marine Biology and Ecology* or *Marine Environmental Research*]

## ABSTRACT

A series of field surveys and experiments were conducted to assess variability in recruitment of sessile marine invertebrates and potential impacts of offshore drilling activities to these organisms. These studies were performed on the California Outer Continental Shelf at depths of approximately 200 m. Sampling sites were near to, and far from (reference sites), three drilling/production platforms in the southern Santa Maria Basin between Pt. Arguello and Pt. Conception. Recruitment was assessed over a variety of temporal scales on 10 x 10 cm plexiglass settling plates. Results showed that the overall settlement rate was very low, compared to rates typical in shallower water, with little settlement occurring in the first 6 months of exposure. Settlement was higher during exposure periods between one and two years. Over 50 taxa were observed on the settling plates throughout the experimental period. There was considerable spatial variability in recruitment across sites and relief heights (0.35 and 1.25 m off the bottom). Growth, survivorship and fecundity were determined for some taxa on the plates. The potential effect of drilling at sites close to oil platforms was also assessed. Sets of plates were exposed for 300 days before drilling, and for 360 days during and just after drilling. Thus, the experimental design incorporated both "before" and "during/after" drilling periods. Some plates also were left in the field for the entire experimental period of up to 1000 days. Throughout the incubation periods, the settling plates were retrieved at specific intervals to determine the amount and type of organisms colonizing the plates. Upon retrieval, some plates were photographed and returned to the bottom, while others were returned to the laboratory for analysis. This allowed the effects of drilling to be tested on both existing benthic communities (those organisms established on the plates) and new settlement and recruitment (those organisms newly settling onto the plates) in the study area. Nine taxa (or groups of taxa) were present in sufficient numbers to facilitate statistical tests of drilling effects on new settlement and recruitment, while five taxa (or groups) were identified for effects on established organisms. Recruitment patterns of six taxa showed a response to drilling either as new recruits or established organisms. Five of the responses suggested a positive effect, while one suggested a negative effect. In addition, no difference was found in growth, survivorship or fecundity between organisms recruiting to either reference or drilling sites throughout the study. Thus, an

overall conclusion is that esentially no effects to natural larval settlement were evident from drilling activities during the study period.

## INTRODUCTION

Offshore oil and gas development may affect marine communities in several ways (for review see Capuzzo 1987). In particular, anthropogenic impacts that affect larval settlement may also influence the dynamics of populations and communities (Nisbet et al. 1995; Raimondi and Reed 1995). This may be especially true for sessile macrobenthic organisms inhabiting deep-water environments (Gage et al. 1980; Gage 1991). However, the extent to which waste plumes influence benthic population dynamics through impacts to larvae has not been fully determined, even for shallow water communities (Keough and Black 1995).

A variety of other factors can affect larval settlement and recruitment. These include the suitability of surfaces for settlement and post-settlement survivorship. Larvae are active samplers of benthic surfaces while searching for suitable settlement locations (Keough and Downs 1982; Rodriguez et al. 1993). Larvae respond to specific settlement cues including physical-chemical settlement inducers from microbial films (Morse et al 1984; Bonar et al. 1990; Todd and Keough 1994; Keough and Raimondi 1995), the presence of a food source (Morse and Morse 1984; Rowley 1989), or the occurrence of conspecific organisms (Highsmith 1982; Jensen and Morse 1984; Raimondi 1988). Wastes discharged into the marine environment can interfere with these settlement cues and disrupt larval settlement and recruitment processes (Raimondi and Schmitt 1992; Raimondi and Reed 1995).

Much of our understanding of settlement processes for benthic invertebrates comes from shallow water studies (<30 m depth), since working in deeper water usually requires special equipment (e.g., remotely operated vehicles, submarines, and large support ships), and larval settlement rates in deeper water are low compared to those in shallower water (Mullineaux and Butman 1990; Mullineaux et al. 1991; Kim et al. 1994; Mullineaux et al. 1995). However, the relative paucity of larvae at depth may increase the importance of settlement dynamics to adult community structure.

This study was designed to address natural variability in larval settlement and recruitment on hard surfaces in the southern Santa Maria Basin, CA, and to examine the effects of drilling activity on these processes. Field experiments were conducted to evaluate the variability of settlement and recruitment over time, space, and relief heights, and to assess the potential drilling effects on settlement, recruitment, survivorship, growth, and fecundity.

The study was performed in conjunction with the U.S. Department of the Interior (DOI), Minerals Management Service/National Biological Survey Phase III Study Program. This program was designed to conduct long-term studies on the cumulative effects of offshore drilling and production activities on the marine environments of the southern Santa Maria Basin (SAIC and MEC 1993). The DOI Phase III program follows earlier Phase I (SAIC 1986) and Phase II (Steinhauer and Imamura 1990) programs. The Phase I program gathered baseline information on hard-bottom communities prior to the onset of drilling activities, while the Phase II program included monitoring studies to address impacts to epifaunal communities from drilling operations (Steinhauer and Imamura 1990; Hyland et al. 1994).

## METHODS

### Study Area

The study was conducted along a portion of the southern Santa Maria Basin on the California Outer Continental Shelf (Fig. 1) between Pt. Conception (34° 28' N; 120° 28' W) and Pt. Arguello (34° 35' N; 120° 38' W). Three nearfield drilling/production platform sites and three farfield reference sites were located at depths between 160 and 210 m. Nearfield sites with adjacent hard strata were selected within 300 m of Platforms Hidalgo, Harvest, and Hermosa (Fig. 1). The reference sites were outside of the major influence of the expected Phase III drilling activity, based on dispersion and deposition estimates from previous studies (Coats 1994). One reference site was located north, and two others south of the platforms. Experiments were conducted at 0.35 m and 1.25 m above the bottom, which represented "low" and "high" relief heights, respectively, in the study region (Hardin et al. 1994; Hyland et al. 1994).

The general coastal axis in this area is southeast to northwest. Current patterns in the region are generally influenced by the California Current (Brink et al. 1984), and the study site is characterized by along-shelf surface flows that run parallel to the shoreline (Chelton et al. 1982). Previous studies in the area (Hyland et al. 1990; SAIC and MEC 1993) show a high-frequency tidal influence resulting in across-shelf currents that are particularly strong along the bottom. Because of these two predominant current regimes, patterns of circulation at the study site are complex, often resulting in eddies, swirls, filaments, meanders, and narrow jets (Mooers and Robinson 1984).

The general topography of the area includes both soft-bottom areas of mud and hard-bottom areas of rocky outcrops with varying relief height. Hardin et al. (1994) classified the hard substrates into two relief height groups, rocky areas of low relief (0.2–0.5 m) and higher relief reefs (>1.0 m). These were distinguished by differences in abundances of organisms throughout the area (Hardin et al. 1994; Diener and Lissner, in preparation). Natural oil seeps are not well characterized in the study area, but are known to be present along the southern California coast (Wilkinson 1972), and some seep areas have been noted in the vicinity of the Phase III hard-bottom areas (Lissner et al., personal observation). Microscopic tar particles have been observed in bottom sediments from the area (Steinhauer et al. 1994), although the hydrocarbon content is generally low (Steinhauer and Steinhauer 1990). Other potential sources of contaminants include a several million gallon spill between 1990 and 1991 of an oil distillate into the sea approximately 50 km north of the study area (C. Phillips, pers. comm.).

### Study Design

Field experiments were conducted through the deployment of settling plates for varying lengths of time before drilling and during/after drilling at the study platforms and reference areas. This two-way experimental design (Green 1979), with replication, allowed determination of effects on natural settlement and recruitment due to drilling activity.

The original design utilized three platform and three reference sites, with the expectation that drilling would occur simultaneously at the three platform sites to facilitate a true "before vs. after" controlled study. However, this study design had to be abandoned when it became apparent that drilling operations at the three sites would not be simultaneous. Drilling occurred at Platform Hermosa between September 1993, and October 1993, at Platform Hidalgo between October 1993 and May 1994, and did not occur at Platform Harvest. This differential drilling pattern provided a unique opportunity to study the natural pattern of effects over three distinctly different drilling regimes: active, recent, and none. Thus, all comparisons were made using each platform site individually and compared to the collective reference group.

The field exposure schedule for the experiments is summarized in Figure 2. Natural settlement experiments were conducted between April 1992 and January 1995. Exposure durations were very short (3–21 days) to test for filming related effects, medium (300–360 days) to assess effects of drilling on settlement, and long (480–1000 days) to test for effects on the established settled community. Recruitment to plates was compared at two distinct time intervals. The medium durations correspond to effects on recruitment of new individuals that were not present at the beginning of the time interval, and the long durations correspond to effects on organisms that comprised the settling plate community at the beginning of the time interval.

**Specific Methodology**

Surface Filming: plexiglass settling plates (10 x 10 cm) were used for the experiments. The surface of the plates was not roughened, although surface smoothness was altered by the development of a natural bacterial film prior to transplantation to larval settlement arrays in the field. Settling plates were filmed at two relief heights (0.35 and 1.25 m) above the sea floor using retrievable canisters (Fig. 3). For each canister, the settling plates (180 per canister) were attached to stainless steel rods and mounted in PVC cylinders. The lower portion of each canister was covered with 100 μm Nitex™ mesh to prevent natural settlement and predation during a 2–3 week filming period. Other plates were left uncovered to allow both filming and short-term settlement of invertebrate larvae.

Two filming moorings with two canisters each (one for each relief height) were deployed at the six study sites (three platform and three reference). Two moorings were used to ensure the likelihood that at least one would survive over the filming phase of the experiments. In almost every case both moorings were recovered, but only one was used, based on the availability of enough plates, for subsequent experiments. Upon retrieval the plates were kept cool, dark, and wet in a shipboard laboratory with a filtered running seawater system. The plates were then sorted by incubation site, and mounted onto deployable larval arrays, hereafter referred to as "igloos" because of their distinctive hemispherical shape (Fig. 3).

Deployment and In Situ Incubations: Each combination of filming site, incubation site, and relief height was replicated by four plates on each igloo. Plates were secured to the igloos in trays containing ten PVC cylinders, each holding one plate (Fig. 3). Trays were arranged on all four sides of the igloos to avoid problems associated with the orientation of deployment in the field.

On board the ship, the tray assembly was covered with a black lucite cover, designed to (1) retain water inside the tray, and (2) keep plates in dark conditions. Trays were stored in cold-water tanks to maintain ambient conditions. Plates were kept wet throughout manipulation on deck and deployment. Hoses were connected to the igloos to direct seawater into the trays. This allowed the trays and plates to be continuously submerged in cold seawater until deployment from the survey vessel, and prevented degradation of microbial films and settled organisms. For deployment, igloos were lifted off the deck with a crane and lowered into the ocean to a depth of approximately 10 m. SCUBA divers then decoupled the seawater hoses and removed the tray covers, and checked the integrity of the trays and plates before the igloos were deployed to the sea floor.

Retrieval: After the designated duration on the bottom, termed the "incubation time", the igloos were retrieved for plate processing. On site, an acoustic release system was used to release a surface buoy. The arrays were then lifted aboard ship and secured. The on-board filtered seawater system was re-attached to the settling trays to keep the plates cool and wet during processing as described above. In April and October 1992, short-term plates were preserved in formalin and returned to the laboratory for identification and enumeration of settled larvae. In August 1993 and January 1994, all plates were photographed using 35-mm slide film. Long-term plates were returned to the arrays, but a subset of the plates (medium-term exposures) were preserved and returned to the laboratory. In January 1994, a new set of filmed medium-term plates was deployed at each site to determine effects in the "during/after" drilling period. In January 1995 all plates were recovered, photographed, and preserved in formalin for laboratory analysis.

Deployment of Plankton Recorders: In addition to the in situ igloos, automated plankton recorders were deployed at high and low relief heights on their own igloos at one platform (Hidalgo) and one reference (northern) site. The concept of this igloo design followed the Hardy plankton recorder (Hardy 1936; Longhurst et al. 1966), with water drawn by battery pump into a 12 x 18 cm opening and through 60 m mesh at a rate of 56.7 L/min. The system was set to operate for 30 min every 16 hrs for 180 days. This would result in 270 1.73 $m^3$ samples, with sampling periods staggered through the day and night. Upon completion of each sample, the mesh was drawn beyond the filtering area and simultaneously merged with a second mesh which covered the sample. Finally, the combination was drawn onto a reel in a storage chamber containing formalin. To counteract any dilution, additional formalin was pumped into the storage container from a concentrated source vessel over the 180 day deployment period.

Unfortunately, mechanical problems with the mesh uptake system prevented more than 14 samples from being captured per deployment period. These data were not further analyzed.

Plate Surface Effects: Initial results indicated that either there was very low natural settlement or very high post-settlement mortality, because there were few recruits on experimental plates. One possibility was that the relatively smooth surface on the plates inhibited settlement or increased post-settlement mortality (Raimondi 1988). An additional experiment was conducted between August 1993 and January 1994 to determine if plate surface conditions (texture) might affect the settlement of larvae. Four replicate plates of three types (smooth, grooved, and roughened) were exposed at both high (1.25 m) and low (0.35 m) relief at each site throughout a 160 day exposure period. The response variable was mean recruitment to each type of plate. Smooth plates were consistent with those described above, grooved plates were made by cutting a series of grooves (1 mm deep, 0.5 cm apart) into the surface of the plates, and roughened plates were scuffed with sandpaper.

Laboratory Analyses: Settling plates and photographic slides of plates were examined under a dissecting microscope. The entire surface of the plate was examined and all organisms identified to the lowest possible taxon. Solitary organisms were counted, and percent cover was estimated for colonial organisms which could not be counted directly. A statistical (regression) comparison was done to determine if data from photographs were comparable to data collected from direct observation. This analysis was done on three taxa representing both colonial and solitary organisms.

Additionally, photographs were taken of the same plates over time and used to estimate the growth and survivorship for selected taxa that could be tracked photographically. Morphometric measurements were made using an optical micrometer at a magnification of 12X. Colonial organisms were measured by determining the area of the colony.

**Data Analysis**

All data were coded in the NODC taxonomic coding system, double-entry keypunched and subjected to a minimum 10% QA/QC check on all data fields. Data were stored in SAS databases and statistical analyses were performed in SAS (SAS Institute 1988). In general, analysis of variance (ANOVA) was performed on data from each set of incubation times to examine platform proximity and relief height effects. Treatment means were compared following the ANOVA using the Ryan-Einot-Gabriel-Welch multiple comparison test (REGWQ; SAS Institute 1988). The REGWQ test is effective for making pairwise comparisons of main effects following ANOVA (Day and Quinn 1989) and is applicable when replicates are unequal (SAS Institute 1988). This separation technique allowed better understanding of the direction and magnitude of changes between the periods (before vs. during/after drilling) at each of the sites.

Film effects were not observed in any initial analyses and were thus dropped as a factor in the ANOVA model in subsequent analyses. Only taxa that occurred on at least five percent of the plates were analyzed individually. In addition, taxonomic groups (e.g., total non-colonial organisms) that occurred on at least five percent of plates were also analyzed.

Natural Variability in Recruitment:

To address spatial and temporal variability in recruitment, data from the three reference sites were analyzed to avoid any platform-related effects. Data from long-term plates were tested with a 3-factor ANOVA with site (Reference Sites 1, 2 and 3), incubation time (3, 42, 180, 480, 640, or 1000 days), and relief height as factors. The significance of the relief height term was evaluated to determine effects of plate height above the bottom on settlement over the entire 1000 day exposure period. If no relief height effect was observed the reference site data were pooled for further comparisons. If there was a significant relief height effect the data were analyzed separately by height (high or low). The data were then re-analyzed with a 2-factor ANOVA using site and drilling period as the factors, followed by a REGWQ test (Day and Quinn 1989) to separate the incubation site means. For each taxon (or taxonomic group), if the data from a single reference site was statistically different from the other reference sites, it was treated as an outlier and dropped from the reference site pool. If all three sites were statistically different from one another, these sites were pooled, and the results of the subsequent analyses were interpreted with caution, because of the increased variability indicated between sites. Thus, if a given reference site was acting independently of the other two it was dropped, but if all three sites acted independent of one another then they were kept in the analysis.

Drilling Related Effects:

*Detection of drilling related effects on recruitment*

Data from long term settling plates deployed for either 480 days (before drilling) or 1000 days (during/after drilling) were used to test effects on the established settling community (Fig. 2). Because these plates were incubated for long periods they contained higher numbers of organisms than those with shorter duration exposure plates. Medium term exposure plates (300 days before drilling and 360 days during/after drilling) were used to test for drilling effects on newly recruited organisms. Because these incubation periods were relatively short they often contained small numbers of settlers.

To test for drilling effects on the established benthic community, mean abundance data from plates exposed for 480 days in the before-drilling period were compared to data from the same plates at the end of the 1000 day incubation. This was tested by a 2-factor ANOVA using incubation period (480 or 1000 days) and incubation location (pooled reference sites, Hidalgo, Harvest, Hermosa) as factors, and by observing the interaction term. A significant interaction between period and location would indicate that the abundances of organisms present on the plates changed differently at the sites between periods (before drilling vs. during/after drilling). Those taxa that showed significant interactions in the 2-factor ANOVA were then tested using a 1-factor ANOVA with settlement at each site for each of the time periods as the only factor. Following this analysis each of the means were separated using the REGWQ test.

Effects on new recruitment were tested using a similar approach as noted above. Recruitment data from settling plates incubated for 300 days in the period before drilling, and settlement onto new plates incubated for 360 days in the period during/after drilling, were used in the analyses.

*Physical parameters*

To address physical factors that may influence recruitment variability within the Santa Maria Basin system, recruitment data from the northern reference site (Reference Site 1) and from Platform Hidalgo were used in a stepwise multiple regression model. This technique was used in an exploratory manner to determine the major source of variation (Sokal and Rohlf 1981). The regression model used several physical oceanographic variables. Data for the variables were collected from physical measurements arrays (SAIC and MEC 1995, Appendix A) deployed at the same time periods and near the recruitment igloos at the respective sites (Fig. 1). Variables available for testing were temperature, salinity, current velocity, total suspended solids, surficial particulate loading (measured as optical fouling), and drilling. Temperatures, salinities, and current velocities averaged over each incubation time were nearly constant (9 $\pm$ 0.5° C, 32.5 $\pm$ 0.1 ppt, 25 $\pm$ 1 cm $sec^{-1}$), and thus were excluded from the regression since they offered little predictive power. Consequently, variables tested in the stepwise multiple regression model included: total suspended solids (average, maximum, and time weighted by exposure period); optical fouling rate (the time in months to foul optical backscatter instruments); and drilling (presence or absence). Measures of these variables were available under six of the eight possible conditions (2 sites x 2 periods x 2 relief heights; measures from lower relief height in the during/after drilling condition were missing). Therefore, the results from this analysis are considered preliminary.

*Performance measures*
Fecundity was estimated for "dense" hydroid colonies by observing plates with high (>50%) coverage following a 360 day during/after drilling exposure period. The proportion of reproductive zooids in each colony were determined for 10 plates from the reference sites, and 14 plates from the platform sites. Data for each group were tested with a Student's *t*-test (Sokal and Rohlf 1981).

## RESULTS

More than 50 taxa were observed in the study (Appendix C-2A), although only seven were present on at least 5% of all plates (Table 1). In general, only these taxa and certain group totals (e.g., total colonial and total non-colonial organisms) were used in the data analysis for the recruitment experiments. Other organisms could be analyzed when individual performance measures were tracked.

Photographic methods comparisons: Data from photographs of settling plates corresponded well with direct plate observations for both colonial and solitary organisms. Regressions comparing the slope and intercept of photographic or plate data found no significant difference from a 1:1 relationship for three taxa with sufficient pairs to be tested. Mat forming protozoa (Komokoiacea) showed the strongest relationship ($F_{1,21}$=508.6; p<0.0001; $r^2$=0.962). The slope of the regression was not significantly different from 1 ($F_{1,20}$=0.53; p=0.48), and the intercept was not different from zero ($F_{1,20}$=0.69; p=0.41). The colonial hydroid, *Oplorhiza gracilis,* showed similar results with a strong relationship between the percent cover determined from both photographs and plates ($F_{1,7}$=52.3; p<0.0004; $r^2$=0.897). Both slope ($F_{1,6}$=1.68; p=0.24) and intercept ($F_{1,6}$=1.02; p=0.35) values were not significantly different from a 1:1 relationship. Counts of the solitary mollusc, *Delectopecten* sp., exhibited a slightly weaker yet significant relationship ($F_{1,13}$=40.6; p<0.001; $r^2$=0.772). As with the other species tested, the relationship observed was not different from 1:1 ($F_{1,12}$=2.85; p=0.12) with a zero intercept ($F_{1,12}$=1.00; p=0.34). These results indicate that data recovered from the photographs were of similar quality to those data recovered from direct observations of the settling plates, and could be substituted where necessary.

## Natural Recruitment Processes

Plate surface effects: Five taxa were found on the plates used for the surface-effects experiment. Settlement on smooth, rough, and grooved surfaces was tested by a two-factor ANOVA using plate surface and relief height. Each taxon, total multicellular organisms, and total organisms on each plate were tested separately. Taxa or taxonomic groups did not appear to favor a single plate type. Overall, there was no significant difference between the mean numbers of total organisms or total multicellular organisms settling on any type of plate (Table 2). However, some effects of either plate surface or height were detected for individual taxa: *Oplorhiza gracilis* showed a preference for smooth plates, and *Delectopecten* sp. exhibited the highest settlement on grooved or rough plates.

Natural Variability in Recruitment: Natural variability in recruitment was determined based on data from reference site results. Recruitment rates were very low throughout the early experimental periods and no appreciable settlement occurred on plates with incubation times up to 180 days. After this time appreciable increases occurred. This temporal variability was most notable in the total number of non-colonial organisms for which low recruitment was found in the first 300 days, followed by large increases (Fig. 4). Because there was virtually no recruitment in the early period, differences that occurred in plate filming prior to conducting cross-transplants were not measurable. Therefore, filming effects on natural settlement could not be assessed.

Recruitment on plates at the three reference sites showed that there was considerable spatial variability at the reference sites. This was characterized by differences in the recruitment at the two relief heights (Table 3) and differences between reference sites (Table 4). Comparisons of settlement at the three reference sites showed significant relief height differences in settlement for four of the nine taxa or groups (Table 3). The remaining five taxa showed no relief height difference; plates from both heights were combined in subsequent analyses of these taxa.

Large-scale spatial variability was considered in a preliminary assessment of whether a reference site was an outlier and therefore should be dropped from reference vs. platform site comparisons. An example of a high degree of variability at the reference sites introduced by a single site outlier is exemplified by the response of serpulid worms (Table 4; Fig. 4). Serpulids settled in high numbers at the southern reference site (Reference Site 2), but fairly evenly at the other reference sites and at the platform sites (not shown or tested). Consequently, Reference Site 2 was not used in subsequent comparisons for serpulid worms.

Total colonial organisms exhibited extreme variability between reference sites (Fig. 4), with over two orders of magnitude greater variability found between sites than within a site (Table 4). Subsequent analysis by REGWQ showed that all three reference sites were statistically different from one another. However, because no site was identified as an outlier, all three were pooled for subsequent comparisons.

*Oplorhiza gracilis*, Cyclostomata, and total colonial organisms showed no differences in settlement between relief heights. *Delectopecten* sp., Komokoiacea, colonial hydroid colonies, and total non-colonial organisms showed significant differences between relief heights; thus, analyses of these taxa or groups were done separately for each relief height. Variability in settlement between sites was high for organisms on lower plates; all of the taxa showed differential settlement for at least one reference site (Table 4). *Delectopecten* sp. and total non-colonial organisms had significantly higher settlement on plates at the southern reference site (Reference Site 2), while dense hydroid colonies showed higher settlement at the middle reference site (Reference Site 3). Komokoiacea mats on the lower plates were much more variable between than within sites (MSB=1126 v. MSE=87; Table 4); this was influenced by very low settlement at Reference Site 1. Similarly, Komokoiacea mats on the upper plates had significantly lower recruitment at the northern reference site. These outlier reference sites were dropped from subsequent analyses.

Total non-colonial organisms on upper plates had a high degree of variability (between site MSB=7699; within site MSE=141) (Table 4). All reference stations were significantly different from one another and none was considered an outlier.

Performance Measures (Growth, Survivorship, and Fecundity): Organisms on plates exposed less than 400 days were considered new recruits (e.g., Fig. 4). Growth data for these organisms were obtained by dividing the organism size at the end of the period by the total number of months the plate was in the field. This yields a proportional growth rate measured as an increase factor per month (i.e., x times larger per month). For example, a growth rate of 0.75 means that the organism increased three-quarters of its original size each month. This assumes that the organisms settled at the beginning of the period and represents a measure of minimum growth rate.

Five taxa of newly recruited organisms were evaluated for growth of colonies or individuals. Because the growth of new recruits was measured by observation of individual organisms or colonies over time, new taxa were included that otherwise were not tested in this study; however, these represented species of the larger groups included throughout this study. These new taxa were the bryozoans *Cabera ellisi* and *Microporella* sp., the sponges (Porifera) as a group, and the solitary serpulid polychaete, *Haplopomatus biformus*. Average growth for newly recruited colonial organisms at the reference sites was variable, ranging between 0.792 for Porifera to 5.00 for the Cyclostomata (Table 5). The polychaete *H. biformus* showed an increase of 0.914, almost doubling in size each month. Although the sample sizes were small, these growth estimates represent the first measure for these taxa in deep waters.

Established organisms were defined as those that had recruited to the settling plates by 480 days of exposure in the field. Only colonial forms were available for growth measurements of established organisms. Since a record existed (photographs) of the organism size at the beginning of each period a more accurate growth record could be established. Therefore, growth data for established organisms were obtained by dividing the difference between the colony size from one time period to another by the total number of months between periods. This yielded a proportional growth rate per month that could be compared across taxa.

Colonies on settling plates were evaluated for five taxa that were represented by the colonial organisms used throughout this study (Table 5). Average growth was generally similar for all taxa and ranged from 0.278 for dense hydroid colonies to 0.874 for colonies of Komokoiacea.

As with the growth for newly recruited organisms, measurements for established colonies were limited and most sample sizes were small.

Survivorship for newly recruited organisms was high with most organisms showing 100% survival over the entire 5 month tracking period (August 1993 to January 1994). Only the polychaete *H. biformus* showed decreased survival with 42% of 12 individuals surviving throughout the tracking period (Table 5). Survivorship of established colonies, tracked over 17 months (August 1993, January 1994, and January 1995), was lower than that for new colonies. The hydroid *Oplorhiza gracilis* showed low but even survivorship over time with 25–33% survival over the 17 month period. Survivorship of the Komokoiacea was higher initially with 87% after 5 months declining to approximately 50% up to 17 months.

Only one species exhibited measurable reproductive activity in this study. Fecundity of dense hydroids, as measured by the density of reproductive zooids in the colony, was low with an average of 11.53% (SE=0.960, n=14). Fecundity was measured in January 1995 following a 360 day incubation period on plates, and may represent a seasonal (winter) low. No other measurements from this study or data from other studies were available to compare the seasonality of reproductive zooid density in deep-water hydroids.

**Detection of Drilling-Related Effects**

Drilling at the study area platforms was not synchronous and did not occur at Platform Harvest. Drilling at Platform Hermosa was conducted between September and November 1993 and resulted in the discharge of approximately 800 $m^3$ of drilling muds, 130 $m^3$ of drill cuttings, and an average of 0.59 million gallons per day (MGD) of produced waters. Drilling operations at Platform Hidalgo occurred between November 1993 and May 1994, and discharged over 3800 $m^3$ of muds, 730 $m^3$ of cuttings, and 1.72 MGD of produced water.

Two distinct biological responses of the biota (positive or negative) at the study sites could be indicative of drilling-related effects, whether persistent or short-term. These outcomes would be reflected in the response pattern found at the platform sites in relation to the response at the reference sites. Patterns can be discerned by observing the difference, commonly referred to as the "delta (Δ)" (Green 1979; Stewart-Oaten et al. 1986; Underwood 1994), between time periods (before vs. during/after drilling) at each site. Since drilling activity was different at the three platforms throughout the study (active drilling at Platform Hidalgo, previous drilling at Platform Hermosa, and no drilling at Platform Harvest), the degree of effect might be expected to follow a similar pattern. Four specific scenarios that describe potential positive and negative outcomes are outlined below. Since no drilling occurred at Platform Harvest, all scenarios would be independent of changes occurring there.

<u>Scenario 1A (persistent negative effect of drilling)</u>:

$$\Delta \text{ Reference} > \Delta \text{ Hidalgo and } \Delta \text{ Hermosa}$$

This pattern would be observed when the temporal change (Δ) at the reference site is greater than that observed at both Platforms Hidalgo and Hermosa. It would indicate that relative to the reference sites, organisms at platforms that underwent drilling exhibited decreased performance regardless of the history of the drilling, and that even when drilling ceased (Hermosa) performance at that platform continued to be diminished compared to the reference sites.

Scenario 1B (short-term negative effect of drilling):

$\Delta$ Reference = $\Delta$ Hermosa
$\Delta$ Reference > $\Delta$ Hidalgo

This result would occur when the temporal change at Platform Hermosa was similar to that at the reference sites, and the changes at both the reference sites and Hermosa were greater than those at Hidalgo. This would indicate that organisms at sites with ongoing drilling activity (Hidalgo) performed relatively poorly, while sites with recent drilling (Hermosa) responded similarly to the reference sites. Therefore the negative effect of drilling is transitory in nature.

Scenario 2A (persistent positive effect of drilling):

$\Delta$ Reference < $\Delta$ Hidalgo and $\Delta$ Hermosa

This scenario is similar to the first, with the exception of the direction of response. Responses that are greater at both Platforms Hidalgo and Hermosa than at reference sites would indicate a net enhancement of performance regardless of the temporal scale of drilling.

Scenario 2B (short-term positive effect of drilling):

$\Delta$ Reference < $\Delta$ Hidalgo
$\Delta$ Reference = $\Delta$ Hermosa

This last scenario shows that a positive effect of drilling (enhancement of performance) is detected only when drilling is underway (Hidalgo); it is not observed after drilling ceases (Hermosa). Like Scenario 1B it would show the transitory nature of the effect.

Effects were identified through a two-step process. First a 2-factor ANOVA using drilling period (Before and During/After drilling) and site (Reference, Hidalgo, Harvest, and Hermosa) was performed on each taxon or taxonomic group. A significant interaction term suggested a potential drilling discharge effect. The pattern of the temporal changes (deltas) at the different sites were then compared, to a delta range corresponding to a 50% change at the reference sites ($\Delta$ Reference $\pm$ 50%). This level was used as a conservative indicator for the detection of environmental impacts in a recent field study of invertebrate populations near a nuclear generating station (Schroeter et al. 1993). Several authors have advocated using a conservative indication level when determining environmental impacts to increase the confidence of any impacts concluded from such studies (Osenberg et al. 1993; Schroeter et al. 1993; Underwood 1994). Deltas from platform sites outside this conservative range were considered representative of real drilling related effects. Any response pattern that did not fit within one of the above scenarios was considered inconclusive or indicated that there was no detected effect of drilling activities.

Effects on new recruitment: As above, organisms on plates exposed less than 400 days were considered new recruits. Seven taxa and two groups of taxa showed significant interactions between experimental site and period (Table 6). These organisms represented both solitary and colonial forms.

Comparisons of delta patterns revealed drilling-related effects on four taxa/groups. Three taxa showed patterns consistent with positive effects and one with a negative effect (Table 7). The colonial hydroid *Oplorhiza gracilis* and dense hydroid mats both showed similar patterns with greater increase in cover occurring at both platform sites than at the reference (2A persistent positive effect). *Oplorhiza gracilis* displayed increases at the platforms that were over two times that of the reference, while dense hydroids increased by up to two orders of magnitude over the reference. Total non-colonial organisms showed a short-term positive effect with the delta at Platform Hidalgo over two times that of the reference, while the delta at Hermosa was within 50% of the reference site.

Komokoiacea showed the only negative effect of drilling observed in this study and this was a short-term effect (Table 7). Coverage of these mat-forming protozoans at Platform Hidalgo decreased (over 4 times lower) compared to a net increase at the reference site. However, the delta at Platform Hermosa was within the range of the reference. Thus, Komokoiacea performance was worse when drilling was active, but no change was evident at the site where drilling had ceased for a period of time.

Effects on established organisms: Established organisms (defined as those organisms that had recruited to the settling plates by 480 days) were censused in the before drilling period after they had become established on the plates. The objective was to evaluate how drilling activities may have affected these established recruits over time in the during/after drilling period. They were recensused after the plates had been incubated for 1000 days.

Only two taxa (Cyclostomata and dense hydroids) and two groups (non-colonial organisms and colonial organisms) showed significant interactions between experimental site and drilling period, indicating a change in the relationship of the established community between the periods (Table 6). Dense hydroids showed significant interactions for both high and low relief heights while total non-colonial organisms showed a significant term for low relief plates only. All of the organisms that showed interactions between 480 and 1000 days exposure were colonial forms. All other taxa (or groups of taxa) showed no effect.

Response patterns based on analysis of the difference (deltas) between the recruitment at 1000 days and 480 days revealed effects only to Cyclostomata and total non-colonial organisms (Table 7). Both taxa/groups showed patterns consistent with enhancement of recruitment in response to drilling activity.

Total non-colonial organisms recruiting to lower plates showed a pattern consistent with a persistent positive effect (2A) with deltas at both Platforms Hidalgo and Hermosa being much greater than that at the reference site. In fact, total non-colonial organisms decreased (negative delta) at the reference site, while both platform sites experienced as much as 28-30 times the originally censused recruitment between the 480 and 1000 day incubation times (Table 7).

Cyclostomata showed a large increase in coverage at Platform Hidalgo relative to the reference, but no change at Platform Hermosa. The pattern in Cyclostomata was consistent with a short-term positive effect (2B).

Relation to Oceanographic Variables: Stepwise multiple regression on recruitment of organisms at the northern reference site (Site 1) and Platform Hidalgo revealed several physical oceanographic variables that may be responsible for the recruitment patterns at the two sites. For example, four of the eight taxa tested (Cyclostomata, *Oplorhiza gracilis*, *Triticella* sp., and total colonial organisms) showed that the presence of drilling explained most of the variation (Table 8). For two taxa (Serpulidae and total non-colonial organisms) incubation time (either 300 days or 360 days) explained most of the variation observed. The total suspended material, weighted for the incubation time (300 or 360 days), was the factor most associated with recruitment of *Delectopecten* sp. Recruitment of Komokoiacea was explained best by the length of time it took to foul optical instruments on the physical measurements arrays. This suggests that biofilming of hard substrate led to a more suitable recruitment site for Komokoiacea. The relationship may also have resulted from differential recruitment of Komokoiacea to the optical instruments themselves, leading to fouling of the optics. However, this was never tested directly and no samples of the matter on the optical instruments were collected (SAIC and MEC 1995).

Effects on Performance Measures (Growth, Survivorship, and Fecundity): Average monthly growth of newly recruited organisms at the platform sites was generally similar to that observed from the reference sites. Growth at platform sites ranged from 1.01 times (an approximate doubling per month) for the polychaete *Haplopomatus biformus* to 4.25 times for Cyclostomata (Table 5). Statistical comparisons of platform and reference growth rates for *Haplopomatus biformus*, Cyclostomata, and Porifera showed no significant difference. While sample sizes were larger than those for the reference sites, due to higher recruitment at the platform sites, sample sizes were still small.

Growth for established colonial organisms (Table 5) was also similar between reference and platform groups. It ranged from 0.04 times for Cyclostomata to 2.89 times for dense hydroid colonies at platform sites. No statistical difference was detected between sites for any taxon/group.

Survivorship varied for both new recruits and established colonies. For 70% of the taxa, greater than 80% of the organisms survived for as least 5 months (Table 5). Survivorship ranged from 33–66% for the others. Survival of new Porifera colonies dropped off from 100% at 5 months to only 20% by 17 months. Established colonies of the hydroid *Oplorhiza gracilis* was generally low but relatively even (10–25%) over the entire 17 month tracking period. Survivorship at platform sites was either higher (e.g., Komokoiacea for 12 months) or not significantly different (e.g., *Oplorhiza gracilis*) than the survivorship observed at reference sites for the same taxon/group.

Mean fecundity of dense hydroid colonies at reference sites was 11.53% (SE=0.960, n=14) while that at platform sites was 9.41% (SE=1.375, n=10). There was no difference between reference sites and platform sites (t-test; $t_{22}$=1.31; p=0.20), although the sample size tested was very small and yielded rather low power (0.54) to detect differences.

## DISCUSSION

### Recruitment of Hard Bottom Organisms in the Santa Maria Basin

Numerous experimental studies have shown that plate surface roughness can influence the micro-hydrodynamics around a settlement surface, thereby influencing the degree of recruitment (Mullineaux and Butman 1990). Mullineaux (1988) demonstrated that while surface roughness did not influence the density of recruits, it did influence the number of taxa recruiting to each type of surface. In the present study, plate surface roughness was found to be a factor that influenced recruitment in four of the seven cases tested (Table 2); however, there was no pattern of recruitment influence among taxa or taxonomic groups. Members of the same general taxonomic group (e.g., colonial organisms) demonstrated strikingly different recruitment patterns. When all non-colonial organisms were pooled, no significant difference in recruitment to different surface conditions was observed. Although roughness was found to be a factor, its effect was constant for each taxon because a single plate type (smooth) was used throughout the study. Recruitment estimates or organisms that preferentially settle onto grooved or roughened surfaces (e.g., *Delectopecten* sp.) might be lower in this study.

Recruitment to settling plates exhibited a high degree of spatial and temporal variability throughout the study. This was especially evident based on recruitment results from the reference sites since they were not confounded by effects from drilling activities. Spatial variability was evident on both vertical and horizontal scales. For example, taxa settled differentially onto plates at varying heights from the sea floor (Table 3) and at different reference sites (Table 4), often by factors of 2 and 10, respectively. However, no obvious spatial pattern in settlement was discerned for specific taxa or for taxonomic groups. Some solitary taxa preferentially settled onto high or low plates, while others settled in relatively equal numbers between plate heights. This was true for the colonial organisms as well and demonstrates the high degree of variability observed throughout these experiments.

The observations from this study are similar to several literature reports of natural recruitment in the deep sea. Mullineaux (1988) showed that early recruitment of deep sea larvae (primarily Formanifera) onto hard surfaces was strongly influenced by elevation of the surface above the sea floor. Her study was performed at a much greater depth (1300 m) than the present study (about 200 m), although the recruitment levels were similar. In a similar study, Keough and Downes (1982) showed that spatial variation in recruitment of marine larvae to different surfaces (rocks with refuges vs. flat rocks) could be explained by the active selection of microhabitats by some species, possibly to avoid predation.

A high degree of temporal variation in recruitment to settling plates was also observed in this study. Not only did it take a long time (> 180 days) for substantial recruitment to occur, but recruitment was different among the reference sites. No reference site showed consistently low (or high) recruitment across all taxa. For example, Reference Site 2 in the south had relatively higher recruitment for solitary (non-colonial) organisms, while colonial organisms at the same site showed an intermediate degree of recruitment compared to the other reference sites (Table 4). The patchy nature of this recruitment possibly may reflect local oceanographic conditions. Several researchers have linked recruitment of benthic invertebrates in the deep sea to local, small-scale, turbulent hydrodynamic events such as eddies or jets (Eckman 1983; Mullienaux 1988; Grassle and Morse-Porteous 1987; Mullineaux 1995). Oceanographic measurements in the area showed a predominant yearly summer/winter cycle in the general current patterns (SAIC and MEC 1995), although small-scale eddy conditions near the bottom were not measured or observed due to the scale of sampling during the present study.

A long period of exposure was required before substantial numbers of recruits were observed on the settling plates in this experiment. In general, greater than 180 days was necessary before plates had consistently observable recruits (Fig. 4). The most probable reasons suggested by Mullineaux (1988) are very low larval and/or food availability at these depths. This was addressed using automated plankton recorders, but due to mechanical problems those data were unavailable to corroborate this hypothesis.

Several studies of recruitment in the deep sea have observed similar periods to achieve sustainable recruitment. Kukert and Smith (1992) found that experimental plots on the Santa Catalina Basin (>1200 m depth) required more than 23 months before colonizing organisms displayed enhanced species diversity. In a study of macrofanual colonization of disturbed sediments in the deep sea, Grassle and Morse-Porteous (1987) found that over a five-year period organisms colonizing azoic trays never reached the density of the natural community. These studies indicate that natural colonization rates in the deep sea may be very long and not inconsistent with those observed in the Santa Maria Basin.

Very few estimates of survival, growth, or fecundity exist for deep-sea benthic organisms, and the estimates presented here are the first for organisms of the Santa Maria Basin. In general, survival of colonial organisms recruiting to plates was high for both initial recruits, and established colonies over the study period (Table 5). Both colonial and solitary new recruits survived well for the early period following recruitment (≤ 5 mo), but significant losses occurred after that. No comparative survivorship information is available.

It has been reported that many encrusting organisms, such as hydroids (Braverman 1963; Jormalaien et al., 1994), sponges (Johnson 1979), and polychaetes (Qian and Chia, 1994) can grow to become reproductive within the first five months of settlement, although these studies focused on shallow water species only. Survival for up to five months in the deep sea may not be long enough for many recruiting organisms to become fully reproductive. Estimates of fecundity for hydroids at the Santa Maria Basin study site showed that only 11% of the zooids were reproductive after one year in the field. For comparison, Jormalaien et al. (1994) demonstrated that a colonial hydroid at peak reproductive output had an estimated 80% of the zooids that were reproductive.

It is likely that lower temperature or food limitation, or both, may be responsible for delayed reproductive output in benthic organisms at depth; however, growth estimates obtained for organisms in this study were comparable to those reported in the literature for similar organisms in shallower water. As an example, Quian and Chia (1994) showed growth rates of a capitellid polychaete in temperate waters to be approximately equal (1–2 times increase per month) to those observed here. Similarly, hydroids from temperate fouling communities approximately doubled in size over a yearly growing period (Schmidt and Warner 1991). One notable exception is the Porifera. Newly recruited sponges (as a group) in this study increased in size by 0.792 times per month whereas Bergquist (1978) reported a growth rate of approximately 6 times per month for *Haliconia* sp., a ubiquitous sponge.

**Drilling-Related Effects**

Because drilling at the study site was variable and recruitment was very low, the present experimental design had low power to detect effects. However, the overall pattern of recruitment at the platform compared to the reference sites suggests some possible effects of drilling. If activities associated with operations at the drilling sites were contributing to changes in the recruitment (or performance) of organisms then it should be evident when observing the differences (deltas) in the response variables between the before and during/after periods. This technique has been advocated by several authors as the most powerful technique to demonstrate environmental impacts in field studies where replication in space is likely to be limited (Green 1979; Hurlburt 1984; Stewart-Oaten et al. 1986; Underwood 1994). Because the pattern analysis utilized in this study relied only on statistically significant interactions between site (reference vs. drilling) and period (before vs. during/after) (Table 5), and was restricted to patterns relative to a delta of 50% change at the reference sites (Table 6), there is confidence that the patterns are truly indicative of the effects of drilling at the study site.

The responses observed for established organisms showed that when the pattern was indicative of an effect, it was primarily positive (Table 6B). Enhancement of recruitment was observed for both the Cyclostomata (bryozoan) and the group of all non-colonial organisms. All other organisms (3 of 5) showed a pattern that was not consistent with an effect (either positive or negative). Similarly, when effects were noted for newly recruited organisms, the patterns were generally positive (Table 6A). The notable exception was for the mat-forming protozoans of the Komokoiacea, which showed the only negative effect associated with drilling activities. However, even that negative effect was considered short-term since it was observed only at Platform Hidalgo where drilling was on-going, and not at Platform Hermosa where drilling had occurred recently, but was not active. The most logical conclusion is that effects from the activities at Platform Hidalgo (e.g., drilling, effluent discharges, or unknown activities) partly restricted new recruitment of Komokoiacea, but once they were established at Platform Hidalgo, no further effects were observed.

Based on step-wise multiple regression analysis on the relationship between recruitment and oceanographic/drilling variables (Table 8), drilling activities were further implicated as an important factor in the observed patterns. While this analysis was limited, drilling activity was suggested as the primary source of recruitment variability in 50% of the species tested.

Measures of the performance (growth, survivorship, and fecundity) of recruited organisms were similar between platform sites as a group and reference sites as a group. The lack of a significant difference between these two groups suggest no significant effect of drilling activity on these parameters in the field. The major limitation of these analyses was that the study was limited to small sample sizes and, therefore, low statistical power to detect differences. The low sample size was a consequence of low and patchy recruitment throughout the study. This is always a risk when conducting a natural experiment in the field. Laboratory studies in which important variables such as toxicant dose, larval availability, or the ability to accurately track individual performance are highly controlled and may lead to better estimates of drilling effects; however, this would be at the expense of a higher degree of reality as represented by the present type of natural experiment (Raimondi et al., in preparation; see Appendix C-3 in SAIC and MEC 1995).

### Conclusions and Recommendations for Future Research

This study suggests that natural recruitment of hard-bottom organisms in the Santa Maria Basin is extremely variable in both time and space. Patchy distribution may reflect low larval abundance and/or food availability, as also influenced by physical oceanographic factors. The high degree of natural variability in recruitment made it extremely difficult to detect drilling-related effects (observed in 6 of 22 tests in 4 of 11 taxa/groups), regardless of the direction (positive or negative). However, the results suggest that when drilling activities were associated with changes in recruitment, they generally acted to enhance settlement.

The study was restricted in its ability to detect drilling effects due to low or variable rates of natural recruitment. Given the large number of taxa observed (>50; Appendix C-2A), relatively few (11) were able to be tested, either because of low settlement at most sites or high recruitment of a taxon at only one or two sites with no recruitment at others.

Larger, less variable sample sizes of settlement and recruitment were possible based on the design of an additional study using in situ settlement conducted at the Santa Maria Basin study sites (Raimondi et al., in preparation; see Appendix C-1 in SAIC and MEC 1995). In this study larval availability was controlled by manipulating the density of larvae (red abalone, *Haliotis rufescens*). Trading off a level of natural realism for increased control may prove to be a more powerful technique in addressing environmental impacts than using natural experiments.

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## LITERATURE CITED


Bergquist, P.R. 1978. Sponges. University of California Press. Berkeley, CA., p.106.

Bonar, D.B., S.L. Coon., M. Walch, R.M. Weiner, and W. Fitt. 1990. Control of oyster settlement and metamorphosis by endogenous and exogenous chemical cues. *Bull. of Mar. Sci.* 46:484-498.

Braverman, M.H. 1963. Studies on hydroid differentiation, II. Colony growth and the initiation of sexuality. *J. Embryol. Exp. Morph.* 11(1):239-253.

Brink, K.H., D.W. Stewart, and J.C. Vanleer. 1984. Observations of the coastal upwelling region near 34° 30' N off California: Spring 1981. *J. Phys Oceanogr.* 14:378-391.

Capuzzo, J.M. 1987. Biological effects of petroleum hydrocarbons: Assessments from experimental results. Pages 343-410, In: Boesch. D.F. and N.N. Rabalais (eds). *Long-term environmental effects of offshore oil and gas development.* Elsevier Applied Science, New York, NY.

Chelton, D.B., P.A. Bernal, and J.A. McGowan. 1982. Large-scale interannual physical and biological interactions in the California Current. *J. Mar. Res.* 40:1095-1125.

Coats, D.A. 1994. Deposition of drilling particulates offshore Point Conception, California. *Mar. Env. Res.* 37:95-127.

Crisp, D.J., and J.S. Ryland. 1960. Influence of filming and of surface texture on the settlement of marine organisms. *Nature.* 185(4706):119.

Day R.W. and G.P. Quinn. 1989. Comparisons of treatments after an analysis of variance in ecology. *Ecol. Monog.* 59(4):433-463.

Eckman, J.E. 1983. Hydrodynamic processes affecting benthic recruitment. *Limnol. Oceanogr.* 28(2):241-257.

Gage, J.D., R.H. Ligntfoot, M. Pearson, and P.A. Tyler. 1980. An introduction to a sample time-series of abyssal macrobenthos: Methods and principal sources of variability. *Oceanol. Acta.* 3:169-176.

Gage, J.D. 1991. Biological rates in the deep sea: A perspective from studies on processes in the benthic boundary layer. *Rev. Aqua. Sci.* 5:49-100.

Grassle, J.F. and L.S. Morse-Porteous. 1987. Macrofaunal colonization of disturbed deep-sea environments and the structure of deep-sea benthic communities. *Deep-Sea Res.* 34(12):1911-1950.

Green, R. 1979. Sampling Design and Statistical Methods for Environmental Biologists. J. Wiley & Sons, New York. 257pp.

Hardin, D.D., J. Toal, T. Parr, P. Wilde, and K. Dorsey. 1994. Spatial variation in hard-bottom epifauna in the Santa Maria Basin, California: The importance of physical factors. *Mar. Env. Res.* 37:165-193.

Hardy, A.C. 1936. The continuous plankton recorder. *Discovery Rep.* 11:457-510.

Highsmith, R.C. 1982. Induced settlement and metamorphosis of sand dollar (*Dendraster excentricus*) larvae in predator-free sites: Adult sand dollar beds. *Ecology* 63:329-337.

Hurlbert, S.J. 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Monographs.* 54:187-211.

Hyland, J., D. Hardin, E. Crecelius, D. Drake, P. Montagna, and M. Steinhauer. 1990. Monitoring long-term effects of offshore oil and gas development along the southern California outer continental shelf and slope: Background environmental conditions in the Santa Maria Basin. *Oil and Chem. Pollut.* 6:195-240.

Hyland, J., D. Hardin, M. Steinhauer, D. Coats, R. Green, and J. Neff. 1994. Environmental impact of offshore oil development on the outer continental shelf and slope off Point Arguello, California. *Mar. Env. Res.* 37:195-229.

Jensen, R.A. and D.E. Morse. 1984. Intraspecific facilitation of larval recruitment: Gregarious settlement of the polychaete *Phragmatopoma californica* (Fewkes) *J. Exp. Mar. Biol. Ecol.* 83:107-126.

Johnson, M.F. 1979. Recruitment, growth, mortality, and seasonal variations in the calcareous sponges *Clathrina coriacea* (Montagu) and *C. blanca* (Miklucho-Maclay) from Santa Catalina Island, California. In: Levi, C. and N. Boury-Esnault (eds.). Sponge Biology *Colloques internationaux du C.N.R.S.* 291:325-334.

Jormalainen, V., T. Honkanen, T. Vuorisalo, and P. Laihonen. 1994. Growth and reproduction of an estuarine population of the colonial hydroid *Cordylophora caspia* (Pallas) in the northern Baltic Sea. *Helgoländer Meersunters.* 48:407-418.

Keough, M.J. and K.P. Black. 1995. Predicting the scale of marine impacts: Understanding planktonic links between populations. In: Schmitt, R.J. and C.W. Osenberg (eds). The design of ecological impact assessment studies: Conceptual issues and application. *in press.*

Keough, M.J. and B.J. Downs. 1982. Recruitment of marine invertebrates: The role of active larval choices and early mortality. *Ecology.* 54:348-352.

Keough, M.J. and P.T. Raimondi. 1995. Responses of settling invertebrate larvae to bioorganic films: Effects of different types of films. *J. Exp. Mar. Biol. Ecol.* 185:235-253.

Kim, S.L., L.S. Mullineaux, and K.R. Helfrich. 1994. Larval dispersal via entrainment into hydrothermal vent plumes. *J. Geophys. Res.* 99(C6):12655-12665.

Kukert, H. and C.R. Smith. 1992. Disturbance, colonization and succession in a deep-sea sediment community: Artificial-mound experiments. *Deep Sea Res.* 39(7/8):1349-1371

Longhurst, A.R., A.D. Reith, R.E. Bower, and D.L.R. Seibert. 1966. A new system for the collection of multiple serial plankton samples. *Deep Sea Res.* 13:213-222.

Mooers, C.N. and A.R. Robinson. 1984. Turbulent jets and eddies in the California Current and inferred cross-shore transports. *Science.* 223:51-53.

Morse, A.N.C., C.A. Floyd, and D.E. Morse. 1984. Molecules from cyanobacteria and red algae that induce larval settlement and metamorphosis in the mollusc *Haliotis rufescens. Mar. Biol.* 81:293-298.

Morse, A.N.C. and D.E. Morse. 1984. Recruitment and metamorphosis of *Haliotis* larvae induced by molecules uniquely available at the surfaces of crostose red algae. *J. Mar. Biol. Ecol.* 75:191-215.

Mullineaux, L.S. 1988. The role of settlement in structuring a hard-substratum community in the deep sea. *J. Exp. Mar. Biol. Ecol.* 120:247-261.

Mullineaux, L.S. 1995. Implications of mesoscale flows for dispersal of deep-sea larvae. In: Young, C.M. and K.J. Eckelbarger (eds.). Reproduction, larval biology, and recruitment of the deep-sea benthos. Columbia University Press. NY, pp. 201-222.

Mullineaux, L.S. and C.A. Butman. 1990. Recruitment of encrusting benthic invertebrates in boundary-layer flows: A deep-water experiment on Cross Seamount. *Limnol. Oceanogr.* 35(2):409-423.

Mullineaux, L.S., P.H. Wiebe, and E.T. Baker. 1991. Hydrothermal vent plumes: Larval highways in the deep sea? *Oceanus.* 1991:64-68.

Mullineaux, L.S., P.H. Wiebe, and E.T. Baker. 1995. Larvae of benthic invertebrates in hydrothermal vent plumes over Juan de Fuca Ridge. *Mar. Biol.* 122:585-596.

Nisbet, R.M., W.W. Murdoch, and A. Stewart-Oaten. 1995. Consequences for adult fish stocks of human induced mortality on immatures. In: Schmitt, R.J. and C.W. Osenberg (eds). The design of ecological impact assessment studies: Conceptual issues and application. *in press.*

Osenberg, C.W., R.J. Schmitt, S.J. Holbrook, K.E. Abu-Saba, and A.R. Flegal. 1994. Detection of environmental impacts: Natural variability, effect size, and power analysis. *Ecol. Appl.* 4(1):16-30.

Qian, P-Y and F-S Chia. 1994. In situ measurement of recruitment, mortality, growth, and fecundity of *Capitella* sp. (Annelida: Polychaeta). *Mar. Ecol. Prog. Ser.* 111:53-62.

Raimondi, P.T. 1988. Rock type affects settlement, recruitment, and zonation of the barnacle *Chthamalus anisopoma* Pilsbury. *J. Exp. Mar. Biol. Ecol.* 123:253-267.

Raimondi, P.T., A. Barnett, and P. Krause. The effects of drilling muds on marine invertebrate larvae and adults. *in preparation.*

Raimondi, P.T., A. Barnett, and P. Krause. Effects of offshore oil and gas development on marine larval settlement: In situ manipulated field experiments. *in preparation.*

Raimondi, P.T. and D.C. Reed. 1995. Determining the spatial extent of ecological impacts caused by local anthropogenic disturbances in coastal marine habitats. In: Schmitt, R.J. and C.W. Osenberg (eds). The design of ecological impact assessment studies: Conceptual issues and application. *in press.*

Raimondi, P.T. and R.J. Schmitt. 1992. Effects of produced water on settlement of larvae: Field tests using red abalone. In: J.P. Ray and F.R. Englehardt (eds). Produced water: Technological/Environmental issues. Plenum, New York, NY, pp. 415-430.

Rodriguez, S.R., F.P. Ojeda, and N.C. Inestrosa. 1993. Settlement of benthic marine invertebrates. *Mar. Ecol. Prog. Ser.* 97:193-207.

Rowley, R.J. 1989. Settlement and recruitment of sea urchins (*Strongylocentrotus* spp.) in a sea-urchin barren ground and a kelp bed: Are populations regulated by settlement or post-settlement processes? *Mar. Biol.* 100:485-494.

SAIC (Science Applications International Corporation). 1986. Assessment of long-term changes in biological communities of the Santa Maria Basin and western Santa Barbara Channel: Phase I, Vol. II Synthesis of Findings. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30032.

SAIC and MEC (MEC Analytical Systems, Inc.). 1993. Monitoring and Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III, Year One Report. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, CA, under Contract No. 14-35-0001-30584.

SAIC and MEC. 1995. Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III, Final Report. Report to the U.S.

Department of the Interior, Minerals Management Service/National Biological Service, under Contract No. 14-35-0001-30584.

SAS Institute. 1988. *SAS/STAT User's Guide, Release 6.03 Edition*. Cary, NC.

Schmidt, G.H. and G.F. Warner. 1991. The settlement and growth of *Sertularia cupressina* (Hydrozoa, Sertulariidae) in Langstone Harbour, Hampshire, UK. *Hydrobiologia*. 216/217:215-219.

Schroeter, S.C., J.D. Dixon, J. Kastendiek, R.O. Smith, and J.R. Bence. 1993. Detecting the ecological effects of environmental impacts: A case study of kelp forest invertebrates. *Ecol. Appl.* 3(2):331-350.

Sokal, R.R. and F.J. Rohlf. 1981. *Biometry,* 2nd Edition. W.H. Freeman and Co., San Francisco, CA.

Steinhauer, M. and W. Steinhauer. 1990. Chemical analysis of hydrocarbons in sediments, pore water, and animal tissue. California OCS Phase II Monitoring Program: Year-Three Annual Report. Vol. I. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30262.

Steinhauer, M., E. Crecelius, and W. Steinhauer. 1994. Temporal and spatial changes in the concentrations of hydrocarbons and trace metals in the vicinity of an offshore oil-production platform. *Mar. Env. Res.* 37:129-163.

Steinhauer, M. and E. Imamura (eds). 1990. California OCS Phase II Monitoring Program: Year-Three Annual Report. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30262.

Stewart-Oaten, A., W.M. Murdoch, and K.R. Parker. 1986. Environmental impact assessment: "pseudoreplication" in time? *Ecology*. 67:929-940.

Todd, C.D. and M.J. Keough. 1994. Larval settlement in hard substratum epifaunal assemblages: a manipulative field study of the effects of substratum filming and the presence of incumbents. *J. Exp. Mar. Biol. Ecol.* 181:159-187.

Underwood, A.J. 1994. On beyond BACI: Sampling designs that might reliably detect environmental disturbances. *Ecol. Applications*. 4(1):3-15.

Wilkinson, E.D. 1972. California offshore oil and gas seeps. California Division of Oil and Gas Pub. No. TR-08, 11p.

## LIST OF TABLES

**Table 8**: Stepwise multiple regression analysis of selected physical oceanographic variables and settlement at the northern reference site (#1) and at Platform Hidalgo. Physical oceanographic variables are from SAIC and MEC (1995). All variables shown in the multiple regression model are statistically significant at the $\alpha$=0.15 level. No other variables met the $\alpha$=0.15 significance level for inclusion in the model.

**APPENDIX C-2A.** Complete taxonomic list of organisms observed on all settling plates throughout this study. Taxa were identified to the lowest practical level.

## LIST OF FIGURES

**Table 1:** Taxonomic list of organisms observed on at least five percent of all settling plates. These taxa or groups were used in settlement/recruitment analyses at reference stations. Taxa were identified to the lowest practical level.

| Taxon | Faunal Type |
|---|---|
| Cyclostomata | Bryozoa |
| *Delectopecten* sp. | Mollusca (Bivalvia) |
| Dense Hydroids | Coelenterata |
| Komokoiacea | Protozoa |
| *Oplorhiza gracilis* | Coelenterata (Hydroid) |
| Serpulidae | Polychaeta |
| *Triticella* sp. | Bryozoa (colonial) |
| **Taxonomic Groups** | |
| Total non-colonial organisms | |
| Total colonial organisms | |

**Table 2:** Mean numbers of solitary organisms, percent cover of colonial organisms per plate and results of ANOVA for plate surface experiment. ANOVA probabilities of rejection of $H_0$: no difference in settlement; ns = p > 0.05. Rankings of settlement surface type were determined through REGWQ analyses following the ANOVA.

| | Lower Plates (0.35 m from bottom) | | | Upper Plates (1.25 m from bottom) | | |
|---|---|---|---|---|---|---|
| | | Surface | | | Surface | |
| **Taxon** | **Grooved** | **Rough** | **Smooth** | **Grooved** | **Rough** | **Smooth** |
| Cyclostomata | 0.6 | 0.1 | 0.0 | 0.1 | 0.0 | 0.0 |
| *Delectopecten* sp. | 1.0 | 0.5 | 0.3 | 1.9 | 13 | 0.0 |
| Komokoiacea | 1.0 | 1.0 | 0.9 | 1.0 | 0.9 | 1.0 |
| *Oplorhiza gracilis* | 0.0 | 0.1 | 0.8 | 0.3 | 0.3 | 0.8 |
| *Triticella* sp. | 0.8 | 0.1 | 0.1 | 0.1 | 0.3 | 0.4 |
| Total non-colonial organisms | 2.4 | 0.9 | 1.6 | 2.4 | 1.8 | 1.3 |
| Total organisms | 3.4 | 1.9 | 2.5 | 3.4 | 2.6 | 2.3 |

| **Taxon** | **Plate Surface** | **Relief Height** | **Surface x Height** | **Description of Difference** |
|---|---|---|---|---|
| Cyclostomata | p<0.01 | <0.01 | ns | Grooved > Smooth, Rough |
| *Delectopecten* sp. | p<0.01 | ns | ns | Grooved, Rough > Smooth |
| Komokoiacea | ns | ns | ns | |
| *Oplorhiza gracilis* | p<0.01 | ns | ns | Smooth > Grooved, Rough |
| *Triticella* sp. | ns | ns | p<0.01 | Lower: Grooved > Smooth, Rough<br>Upper: Rough, Smooth > Grooved |
| Total non-colonial organisms | ns | ns | ns | |
| Total organisms | ns | ns | ns | |

**Table 3:** Results of 3-factor ANOVA (site, relief height, and deployment period) for effects of relief height (RH) on settlement of taxa observed on five percent or more of plates at reference sites only. Reference data for taxa that did not show significant differences were pooled for subsequent comparisons.

| Taxa | Lower Plates | Upper Plates | df | MS(RH) | F | p |
|---|---|---|---|---|---|---|
| Cyclostomata | 0.07 | 0.07 | 1,70 | 0.015 | 0.33 | 0.5701 |
| *Delectopecten* sp. | 3.3 | 5.3 | 1,222 | 1681 | 4.62 | 0.0337* |
| Dense Hydroids | 4.4 | 12.3 | 1,70 | 1768 | 7.88 | 0.0065* |
| Komokoiacea mat | 9.4 | 18.6 | 1,70 | 168 | 10.66 | 0.0017* |
| *Oplorhiza gracilis* | 2.3 | 5.0 | 1,70 | 132 | 10.2 | 0.3155 |
| Serpulidae | 0.9 | 0.8 | 1,122 | 0.09 | 0.07 | 0.7970 |
| *Triticella* sp. | 11.3 | 4.6 | 1,70 | 355 | 1.62 | 0.2069 |
| | | | | | | |
| Total non-colonial organisms | 6.0 | 10.8 | 1,274 | 1958 | 21.16 | 0.0001* |
| Total colonial organisms | 39.0 | 34.8 | 1,158 | 636 | 1.26 | 0.2628 |

df = degrees of freedom (factor, error)
MSE = mean square error
F = F-ratio [MS(RH)/MSE]
p = probability of accepting null hypothesis
* = statistical significance at p=0.05

**Table 4:** Results from 2-factor ANOVA (reference site by deployment period) indicating the degree of variability in recruitment on settling plates at reference (Ref) sites. Significant results from REGWQ test were determined at a significance level of p=0.05. If single reference sites were determined to be outliers, relative to the other two reference sites and the platform sites, they were dropped from further analyses. Retained reference sites were pooled in before and during/after groups.

| Taxa | Reference Site 1 | Reference Site 2 | Reference Site 3 | Within Site MSE | Between Site MSE | REGWQ Separation | Conclusions |
|---|---|---|---|---|---|---|---|
| **Lower Plates (0.35 m)** | | | | | | | |
| *Delectopecten* sp. | 0.7 | 7.0 | 1.8 | 22 | 331 | 2 > 3,1 | Ref. site #2 is outlier |
| Dense Hydroids | 0.0 | 2.0 | 33.3 | 229 | 7424 | 3 > 2,1 | Ref. site #3 is outlier |
| Komokoiacea | 1.5 | 16.3 | 9.3 | 87 | 1126 | 2,3 > 1 | Ref site #1 is outlier |
| Total Non-colonial Organisms | 1.0 | 13.6 | 2.5 | 43 | 3648 | 2 > 3,1 | Ref. site #2 is outlier |
| **Upper Plates (1.25 m)** | | | | | | | |
| *Delectopecten* sp. | 0.3 | 9.9 | 5.6 | 22 | 716 | 2 > 3 > 1 | All sites are different |
| Dense Hydroids | 0.0 | 0.3 | 12.2 | 219 | 1096 | 1 = 2 = 3 | All sites are similar |
| Komokoiacea | 2.1 | 26.2 | 25.9 | 224 | 3156 | 2,3 > 1 | Ref. site #1 is outlier |
| Total Non-colonial Organisms | 2.0 | 21.2 | 9.0 | 141 | 7699 | 2 > 3 > 1 | All sites are different |
| **Combined Plates** | | | | | | | |
| Cyclostomata | 0.03 | 0.07 | 0.1 | 0.05 | 0.07 | 1 = 2 = 3 | All sites are similar |
| *Oplorhiza gracilis* | 0.3 | 6.5 | 4.1 | 127 | 188 | 1 = 2 = 3 | All sites are similar |
| Serpulidae | 0.04 | 2.1 | 0.3 | 1.3 | 65.4 | 2 > 3,1 | Ref. site #2 is outlier |
| *Triticella* sp. | 17.3 | 5.1 | 0.2 | 272 | 1437 | 3 > 2,1 | Ref. site #3 is outlier |
| Total Colonial Organisms | 2.6 | 35.3 | 68.3 | 599 | 69877 | 3 > 2 > 1 | All sites are different |

**Table 5:** Growth and survivorship of new recruits (tracked as individuals or colonies) and established colonial organisms (tracked as percent cover of colony on entire plate). Growth is expressed as proportional increase per month and survivorship as percent surviving over a given time period. Plates were observed in August 1993, January 1994, and January 1995. Data were combined for plate height and plates were grouped as either reference or platform sites. Where applicable, growth data for groups are tested against each other with either a Student's *t*-test or Mann-Whitney Rank Sum Test. Both statistical tests are evaluated at a level of $\alpha = 0.05$. When tested, no significant differences in growth rates were found between reference and platform sites for any taxa.

| **A. Newly Recruited Organisms** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | *Haplopomatus biformus* | | Cyclostomata | | Porifera | | *Cabera ellisi* | | *Microporella* sp. | |
| | Reference | Platform | Reference | Platform | Reference | Platform | Reference | Platform | Reference | Platform |
| Growth | | | | | | | | | | |
| Mean | 0.914 | 1.014 | 5.00 | 4.25 | 0.792 | 1.223 | N/P | 2.54 | 4.28 | N/P |
| Standard Error | 0.180 | 0.148 | N/A | 0.876 | 0.324 | 0.172 | -- | 1.54 | -- | -- |
| n | 5 | 6 | 1 | 16 | 3 | 6 | -- | 5 | -- | -- |
| Survivorship | | | | | | | | | | |
| 5 months (n) | 42% (12) | 43% (14) | 100% (1) | 100% (± 15) | 100% | 100% (5) | -- | 100% (1) | 100% | -- |
| 12 months (n) | -- | 33% (3) | -- | 100% (1) | -- | 50% (4) | -- | 100% (4) | -- | -- |
| 17 months (n) | -- | -- | -- | -- | -- | 20% (1) | -- | -- | -- | -- |

| **B. Established Colonies** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Komokoiacea | | Cyclostomata | | Dense Hydroid | | *Triticella* sp. | | *Oplorhiza gracilis* | |
| | Reference | Platform | Reference | Platform | Reference | Platform | Reference | Platform | Reference | Platform |
| Growth | | | | | | | | | | |
| Mean | 0.874 | 0.491 | N/P | 0.041 | 0.278 | 2.889 | 0.83 | 0.00 | 0.563 | 0.571 |
| Standard Error | 0.225 | 0.108 | -- | 0.041 | -- | 2.51 | -- | -- | 0.422 | 0.368 |
| n | 25 | 41 | -- | 2 | 1 | 3 | 1 | 1 | 3 | 5 |
| Survivorship | | | | | | | | | | |
| 5 months (n) | 87% (15) | 81% (13) | -- | 66% (3) | 33% (3) | 100% (3) | -- | 100% (1) | 25% (4) | 25% (8) |
| 12 months (n) | 53% (15) | 93% (14) | -- | -- | -- | -- | 11% (9) | -- | 33% (6) | 10% (10) |
| 17 months (n) | 50% (17) | 69% (11) | -- | -- | -- | -- | -- | -- | 25% (4) | 25% (8) |

N/P = Not Present

**Table 6:** Results of 2-factor ANOVA on (A) established organisms and (B) new recruits showing results of testing the interaction of settlement location (Reference, Hidalgo, Harvest, and Hermosa) and incubation period (480 days [before drilling] vs. 1000 days [during/after drilling]) for effects. Reference locations used in the individual analyses correspond to those determined to be most relevant (see Table 4). Plate heights were combined when no difference due to plate height (high vs. low) was determined (Table 3).

**A. Newly Recruited Organisms**

| Taxa | Height | df | MSE | F | p |
|---|---|---|---|---|---|
| Cyclostomata | Combined | 3,704 | 0.24 | 8.78 | 0.0001* |
| *Delectopecten* sp. | Low | 3,290 | 2.11 | 4.58 | 0.0054* |
| *Delectopecten* sp. | High | 3,348 | 9.26 | 1.77 | 0.1520 |
| Dense Hydroid | Low | 3,296 | 456 | 5.79 | 0.0007* |
| Dense Hydroid | High | 3,355 | 225 | 1.49 | 0.2182 |
| Komokoiacea | Low | 3,348 | 126 | 4.37 | 0.0049* |
| Komokoiacea | High | 3,289 | 195 | 2.42 | 0.0667 |
| *Oplorhiza gracilis* | Combined | 3,704 | 285 | 8.13 | 0.0000* |
| Serpulidae | Combined | 3,587 | 0.19 | 4.27 | 0.0054* |
| *Triticella* sp. | Combined | 3,587 | 113 | 2.91 | 0.0339* |
| Total non-colonial organisms | Low | 3,595 | 701 | 1.85 | 0.0001* |
| Total non-colonial organisms | High | 3,711 | 903 | 2.48 | 0.0590* |
| Total colonial organisms | Combined | 31,423 | 14243 | 19.19 | 0.0001* |

**B. Established Organisms**

| | | | | | |
|---|---|---|---|---|---|
| Cyclostomata | Combined | 3,129 | 3.19 | 9.90 | 0.0001* |
| *Delectopecten* sp. | Low | 3,49 | 7.15 | 1.63 | 0.1938 |
| *Delectopecten* sp. | High | 3,61 | 27.9 | 6.31 | 0.9730 |
| Dense Hydroid | Low | 3,56 | 3914 | 25.58 | 0.0001* |
| Dense Hydroid | High | 3,68 | 3181 | 10.80 | 0.0001* |
| Komokoiacea | Low | 3,57 | 355 | 1.68 | 0.1822 |
| Komokoiacea | High | 3,58 | 806 | 2.02 | 0.1230 |
| *Oplorhiza gracilis* | Combined | 3,129 | 150 | 0.99 | 0.3972 |
| Serpulidae | Combined | 3,107 | 0.34 | 1.42 | 0.2399 |
| *Triticella* sp. | Combined | 3,106 | 28.3 | 1.54 | 0.2087 |
| Total non-colonial organisms | Low | 3,113 | 1576 | 8.58 | 0.0001* |
| Total non-colonial organisms | Upper | 3,137 | 365 | 0.81 | 0.4904 |
| Total colonial organisms | Combined | 3,273 | 17850 | 19.86 | 0.0001* |

* = statistical significance at p = 0.05

**Table 7:** Ranking of observed responses of (A) established organisms and (B) new recruits following drilling activities. Responses are ranked based on comparison of the delta values for Platform Hidalgo and Hermosa relative to a 50% change from the delta observed from the reference. Response scenarios correspond to one of the four patterns outlined in the text.

**A. Newly Recruited Organisms**

| | | Deltas | | | Pattern at 50% change from reference | | | Response |
|---|---|---|---|---|---|---|---|---|
| **Taxa** | **Height** | **Reference** | **Hidalgo** | **Hermosa** | **Reference Range** | **Hidalgo** | **Hermosa** | **Scenario** |
| Cyclostomata | Combined | 0.13 | 0.14 | 0.60 | 0.07 to 0.20 | Same | Greater | No Effect |
| *Delectopecten* sp. | Low | 0.23 | -0.52 | 0.93 | 0.11 to 0.34 | Less | Greater | No Effect |
| Dense Hydroid | Low | 0.02 | 0.16 | 10.94 | 0.01 to 0.02 | Greater | Greater | 2A |
| Komokoiacea | Low | 4.53 | -0.43 | 3.19 | 2.26 to 6.76 | Less | Same | 1B |
| *Oplorhiza gracilis* | Combined | 6.65 | 16.65 | 19.15 | 3.27 to 9.98 | Greater | Greater | 2A |
| Serpulidae | Combined | 0.28 | 0.40 | 0.12 | 0.14 to 0.42 | Same | Less | No Effect |
| *Triticella* sp. | Combined | 6.32 | 5.35 | 7.39 | 3.16 to 9.50 | Same | Same | No Effect |
| Total non-colonial organisms | High | 7.88 | 16.99 | 6.58 | 3.94 to 11.83 | Same | Same | 2B |
| Total colonial organisms | Combined | 24.63 | 26.64 | 40.02 | 12.31 to 36.94 | Greater | Greater | No Effect |

**B. Established Organisms**

| | | Deltas | | | Pattern at 50% change from reference | | | Response |
|---|---|---|---|---|---|---|---|---|
| **Taxa** | **Height** | **Reference** | **Hidalgo** | **Hermosa** | **Reference Range** | **Hidalgo** | **Hermosa** | **Scenario** |
| Cyclostomata | Combined | 0.20 | 0.50 | 0.25 | 0.10 to 0.30 | Greater | Same | 2B |
| Dense Hydroid | Low | 0 | 0 | 75.00 | 0 | Same | Greater | No Effect |
| Dense Hydroid | High | 18.13 | 0 | 73.75 | 10.06 to 27.19 | Less | Greater | No Effect |
| Total non-colonial organisms | Low | -1.20 | 28.88 | 31.63 | -1.8 to -0.6 | Greater | Greater | 2A |
| Total colonial organisms | Combined | 42.63 | 55.00 | 117.75 | 21.31 to 63.94 | Same | Greater | No Effect |

**Table 8:** Stepwise multiple regression analysis of selected physical oceanographic variables and settlement at the northern reference site (#1) and at Platform Hidalgo. Physical oceanographic variables are from SAIC (1995). All variables shown in the multiple regression model are statistically significant at the α=0.15 level. No other variables met the α=0.15 significance level for inclusion in the model.

| Taxon | Variable | Partial $r^2$ | Model $r^2$ | F | P |
|---|---|---|---|---|---|
| Cyclostomata | | | | | |
| | Drilling | 0.939 | 0.939 | 62.1 | 0.0014* |
| | $TSS_{max}$ | 0.047 | 0.986 | 10.21 | 0.0495* |
| *Delectopecten* sp. | | | | | |
| | $TSS_{wtd}$ | 0.466 | 0.466 | 3.49 | 0.1352 |
| Komokoiacea | | | | | |
| | Sedrate | 0.766 | 0.766 | 13.07 | 0.0225* |
| *Oplorhiza gracilis* | | | | | |
| | Drilling | 0.838 | 0.838 | 20.64 | 0.0105* |
| | $TSS_{avg}$ | 0.110 | 0.948 | 6.31 | 0.0868 |
| Serpulidae | | | | | |
| | Incubation | 0.958 | 0.958 | 91.45 | 0.0007* |
| | Sedrate | 0.032 | 0.990 | 9.689 | 0.0528 |
| *Triticella* sp. | | | | | |
| | Drilling | 0.996 | 0.996 | 1062 | 0.0001* |
| Total non-colonial organisms | | | | | |
| | Incubation | 0.7912 | 0.7912 | 15.16 | 0.0176* |
| Total colonial organisms | | | | | |
| | Drilling | 0.714 | 0.714 | 10.01 | 0.0341* |

Variables:
Drilling - no drilling or drilling
TSS - Total suspended solids (average, maximum, and time weighted)
Sedrate - Sedimentation rate (time in months to foul optical instruments)
Incubation - Incubation Period (before or during/after drilling)
Temperature
Current Velocity (average and maximum)
Relief Height (High or Low).

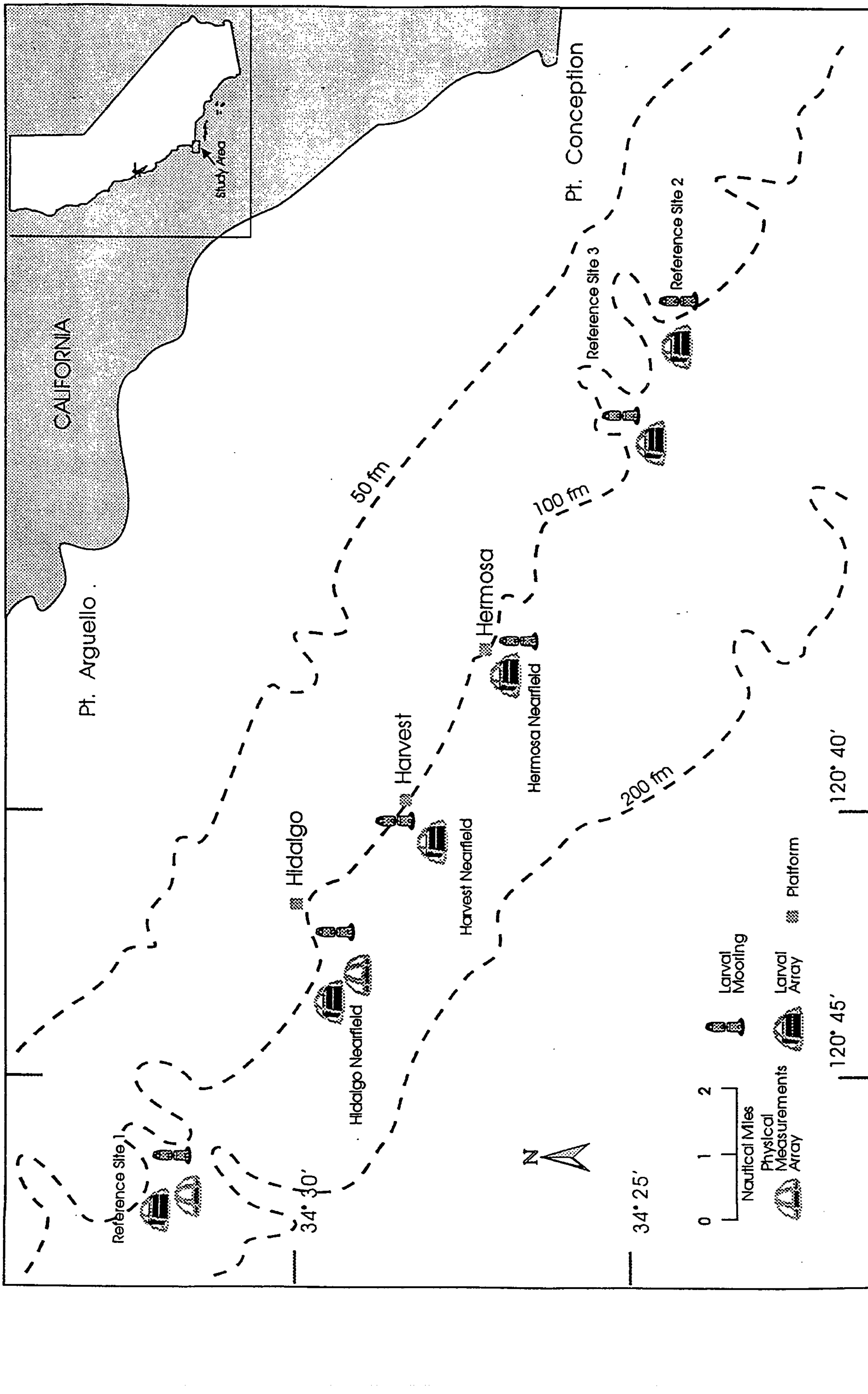
* = statistical significance at α=0.05.

**APPENDIX C-2A.** Complete taxonomic list of organisms observed on all settling plates throughout this study. Taxa were identified to the lowest practical level.

| Taxon | Faunal Type |
|---|---|
| Eggs | Unidentified Eggs |
| Egg capsule | |
| Arenaceous Foraminifera | Protozoan |
| Folliculinidae | |
| Foraminifera | |
| Komokoiacea (colonial) | |
| Stalked ciliate | |
| Stalked ciliate sp. A | |
| Porifera | Poriferan |
| Star Sponge | |
| Anemone, unid. frag. | Cnidarian |
| Bougainvillidae (colonial) | |
| Campanulariidae (colonial) | |
| Campanulinidae (colonial) | |
| *Clava* sp. (colonial) | |
| Clavidae | |
| Coral | |
| *Corymorpha* sp. A | |
| Dense hydroid (colonial) | |
| *Eudendrium* sp. | |
| *Halecium* sp. | |
| Hydrozoa (colonial) | |
| *Oplorhiza gracilis* (colonial) | |
| *Oplorhiza polynema (colonial)* | |
| *Pandea* sp. | |
| *Plumularia mobilis* | |
| Star hydroid | |
| Flatworm | Flatworm |
| *Notoplana* sp. | |
| *Stylochus* sp. | |
| Nemertea | Nemertean |
| *Glycera* sp. | Polychaete |
| Hirudinea | |
| Polychaeta | |
| Serpulidae | |
| Spirorbid | |
| Trochophore larvae | |
| Worm tube | |
| *Calliostoma platinum* | Gastropod |
| *Dendronotus* sp. | |
| Gastropoda | |
| *Haliotis* sp. | |
| *Mangelia* sp. | |

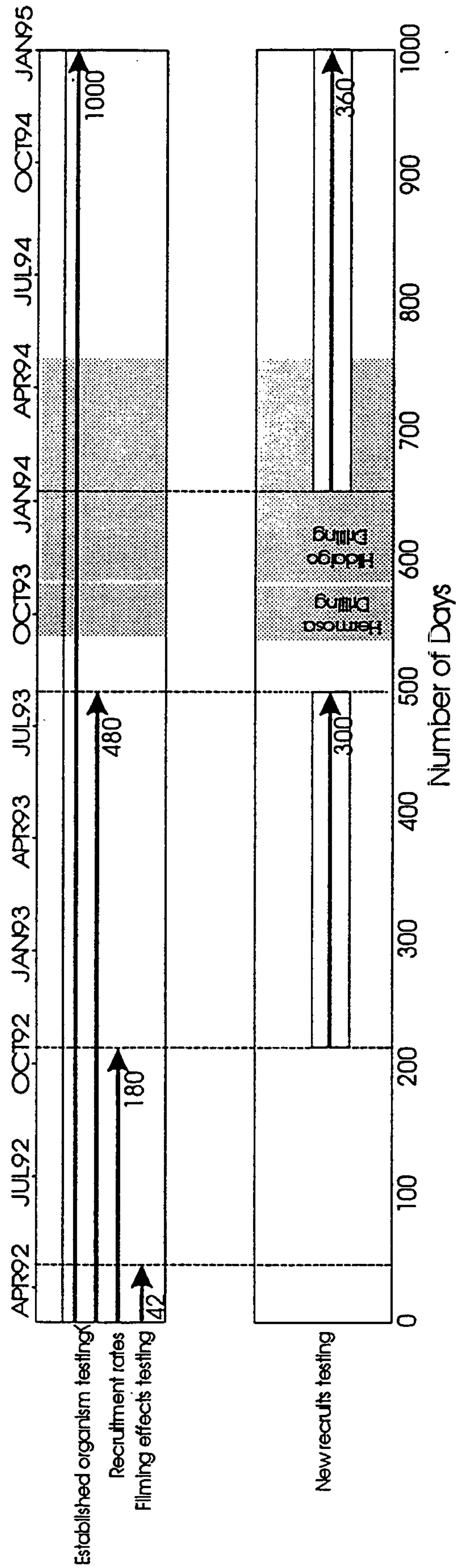
| Taxon | Faunal Type |
|---|---|
| *Mitrella* sp. | |
| Mollusc egg capsule | Gastropod, continued |
| Nudibranchia | |
| *Onchidoris bilamellata* | |
| *Onchidoris hystricina* | |
| Bivalvia | Bivalve |
| *Delectopecten* sp. | |
| *Mytilus* sp. | |
| Pectinidae | |
| Acarina | Arachnid |
| Pycnogonida | Pycnogonid |
| Amphipod tube | Crustacean |
| *Arcoscalpellum californicum* | |
| Cumacea | |
| Gammaridea | |
| Harpacticoida | |
| *Alcyonidium* sp. (colonial) | Bryozoan (colonial) |
| Bryozoa (colonial) | |
| *Caberea ellisi* (colonial) | |
| *Caulibugula californica* (colonial) | |
| *Caulibugula* sp. | |
| *Crisia* sp. (colonial) | |
| Cyclostomata (colonial) | |
| Ectoprocta (colonial) | |
| *Membranipora villosa* (colonial) | |
| *Microporella columbiana* (colonial) | |
| *Microporella* sp. (colonial) | |
| *Porella columbiana* (colonial) | |
| *Scrupocellaria* sp. (colonial) | |
| *Triticella* sp. (colonial) | |
| Vesiculariidae | |
| Loxosomatidae (colonial) | Entoproct |
| Asteroid | Echinoderm |
| *Florometra serratissima* | |
| Ophiuroidea | |
| Aplousobranchi | Urochordate |
| Boltenia echinata | |
| *Botryllus* sp. (colonial) | |
| *Chelyosoma productum* | |
| *Chelyosoma* sp. | |
| *Didenmum* sp. | |
| *Tridideminum strangulatum* | |
| Tunicate | |
| Organism, unid. | Unidentifiable |
| Unid. spherical colonies | |
| Whips (colonial) | |

Figure 1



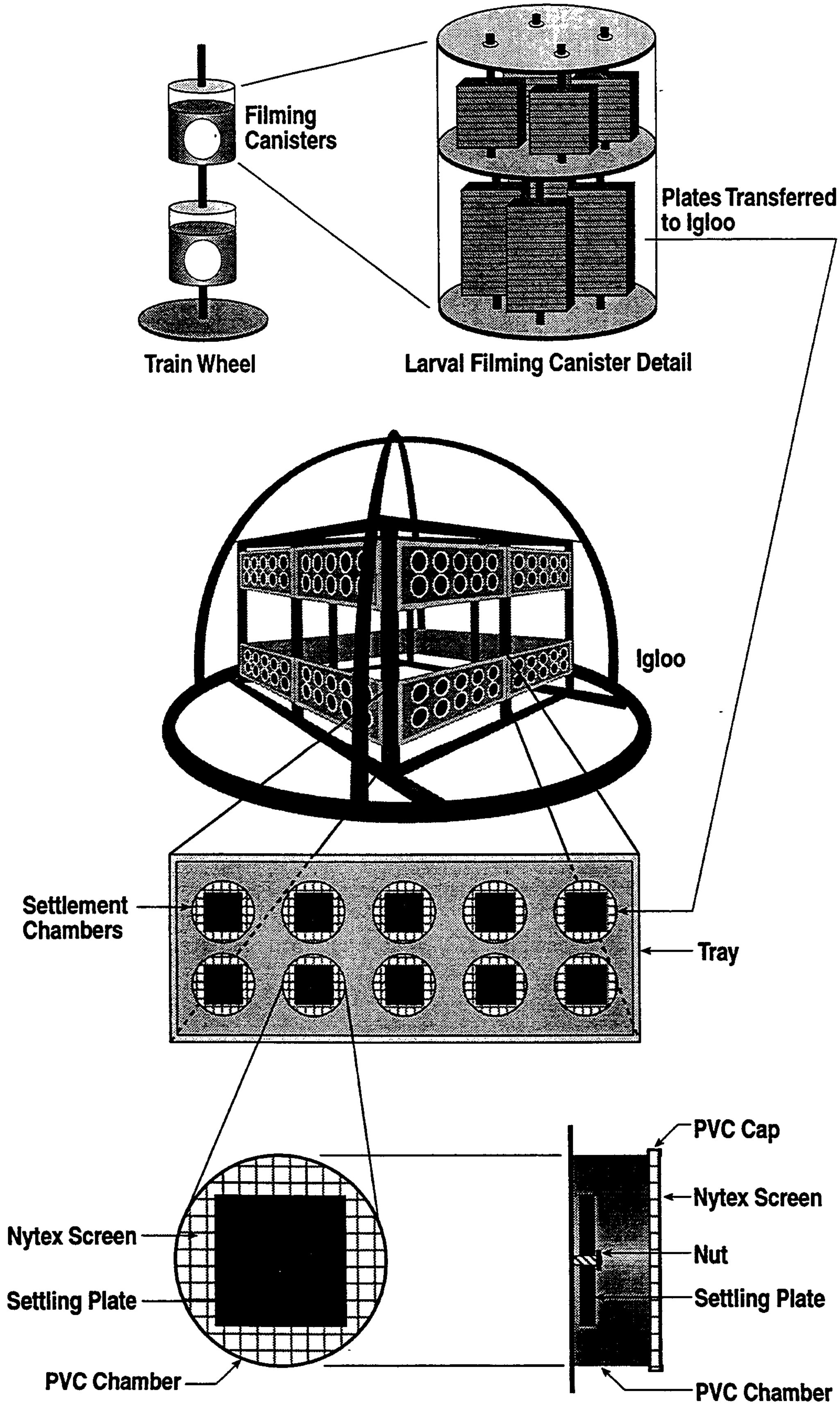
CALIFORNIA
Study Area
Pt. Conception
Pt. Arguello
50 fm
100 fm
200 fm
Reference Site 1
Reference Site 2
Reference Site 3
Hidalgo
Harvest
Hermosa
Hidalgo Nearfield
Harvest Nearfield
Hermosa Nearfield
N
0
1
2
Nautical Miles
Physical Measurements Array
Larval Mooring
Larval Array
Platform
34° 30′
34° 25′
120° 40′
120° 45′

Figure 2



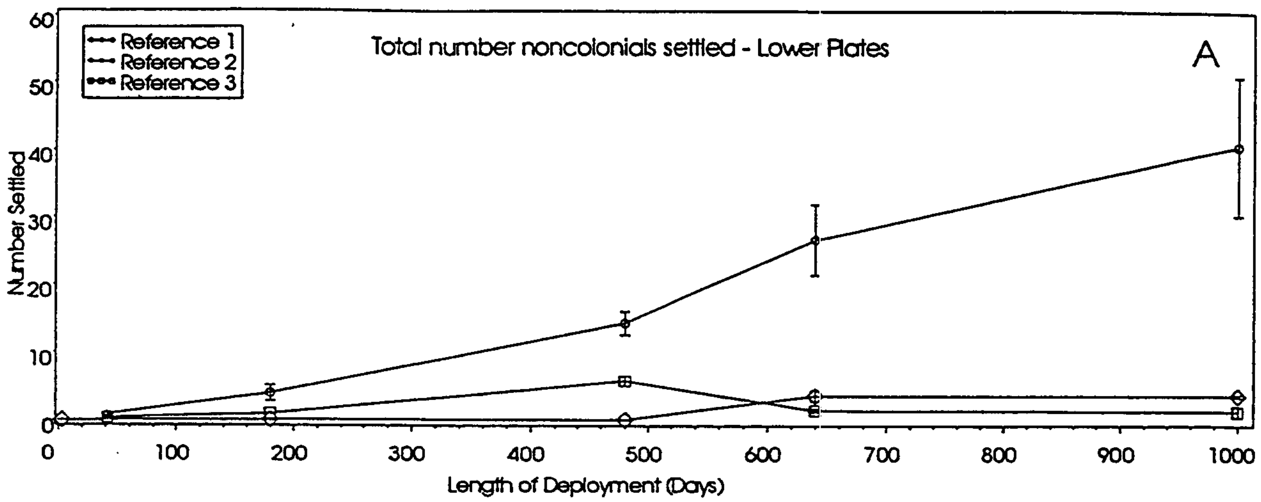
APR92
JUL92
OCT92
JAN93
APR93
JUL93
OCT93
JAN94
APR94
JUL94
OCT94
JAN95
Established organism testing
Recruitment rates
Filming effects testing
42
180
480
1000
New recruits testing
300
360
Hermosa Drilling
Hidalgo Drilling
0
100
200
300
400
500
600
700
800
900
1000
Number of Days

Figure 3

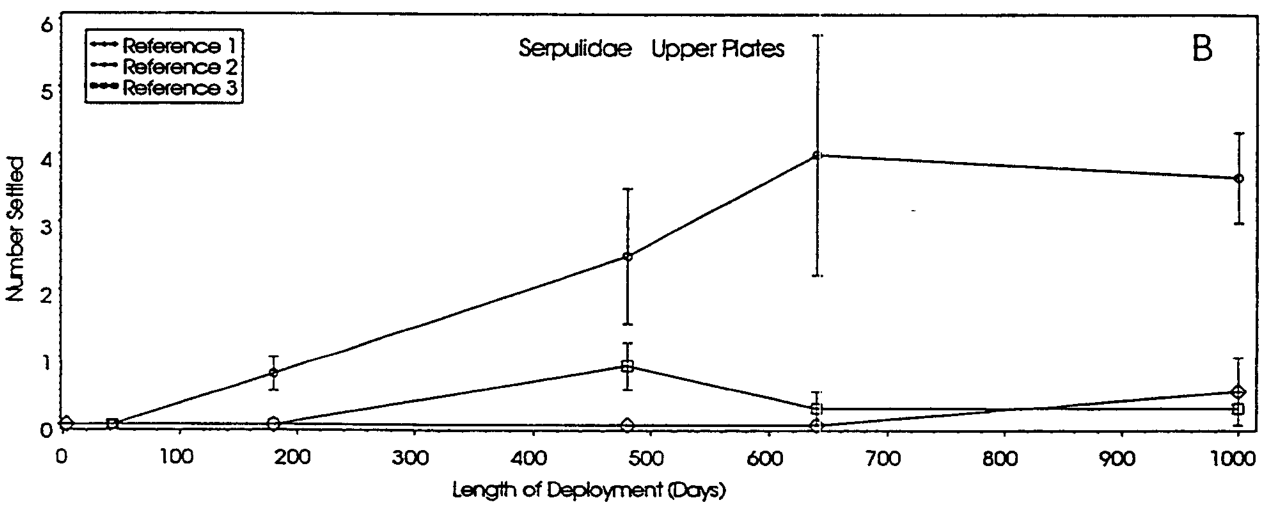


Filming Canisters
Plates Transferred to Igloo
Train Wheel
Larval Filming Canister Detail
Igloo
Settlement Chambers
Tray
PVC Cap
Nytex Screen
Nut
Settling Plate
PVC Chamber
Nytex Screen
Settling Plate
PVC Chamber

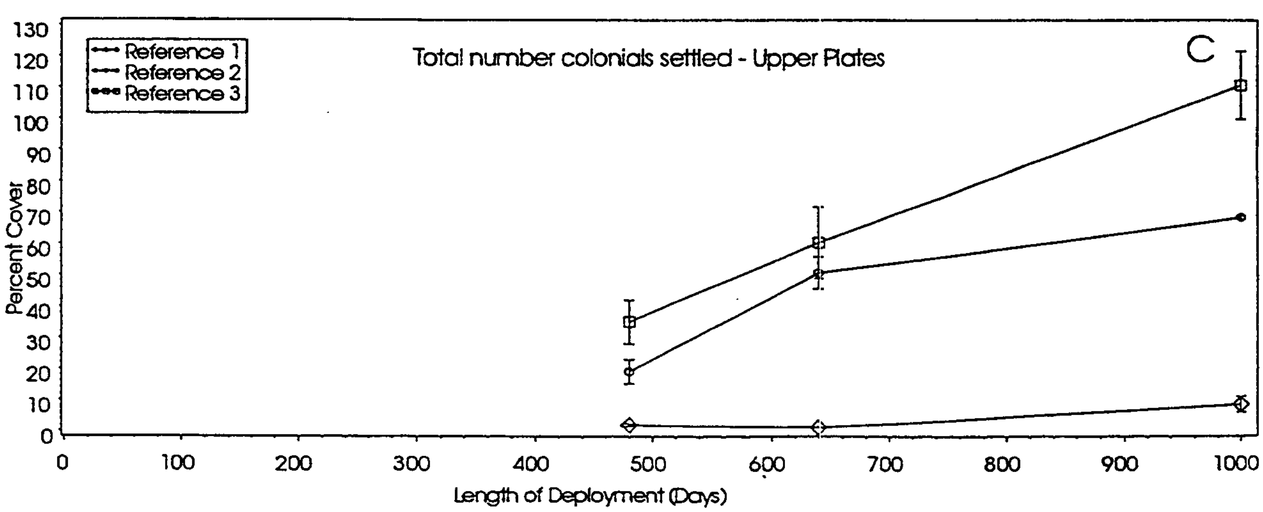
**Figure 4**



Total number noncolonials settled - Lower Plates
A
Reference 1
Reference 2
Reference 3
Number Settled
Length of Deployment (Days)

Serpulidae Upper Plates
B
Reference 1
Reference 2
Reference 3
Number Settled
Length of Deployment (Days)

Total number colonials settled - Upper Plates
C
Reference 1
Reference 2
Reference 3
Percent Cover
Length of Deployment (Days)

# APPENDIX C-3

## LABORATORY TOXICITY TESTS MANUSCRIPT

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# THE EFFECTS OF DRILLING MUDS ON MARINE INVERTEBRATE LARVAE AND ADULTS

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## ABSTRACT

A series of laboratory experiments were conducted to determine the effects of drilling muds on marine invertebrate larvae and adults. Experiments were conducted with the gametes and larvae of the red abalone (*Haliotis rufescens*) and adult brown cup corals (*Paracyathus stearnsii*). Red abalone experiments tested effects of exposure to drilling muds on fertilization, early development, survivorship, and settlement. Larval viability, calculated from survivorship and settlement, and the degree to which drilling muds might interfere with settlement inducers (those chemicals that promote larval settlement) also were assessed. Experiments on adult brown cup corals tested effects of exposure to suspended and settled drilling muds on adult survivorship, viability, and tissue loss. Drilling muds used in all experiments were collected from an active drilling platform in the southern Santa Maria Basin, offshore southern California. Laboratory exposure conditions (duration and temperature) were comparable to field conditions in the Santa Maria Basin. Concentrations of suspended drilling muds used in experiments included those expected to occur in the field as determined by a plume model. Exposures to drilling muds did not show an effect on abalone fertilization or early development. However, exposures of precompetent and competent larvae (planktonic larval stages that are not and are physiologically able to settle, respectively), indicated effects on their ability to survive or settle. Several exposures resulted in weak, but significant positive effects of drilling muds on both survivorship (in precompetent larvae) and settlement (in competent larvae). In contrast, settlement of red abalone larvae on natural coralline algal crusts decreased with increasing concentrations of drilling muds. This suggests that drilling muds affect either the abalone's ability to detect natural settlement inducers, or the inducer itself. Exposure of brown cup corals to concentrations of drilling muds adversely impacted their survivorship and viability. These effects were likely caused by increased tissue mortality of the coral polyps. Results of these studies suggest that exposure to drilling muds at environmentally realistic concentrations, in a controlled laboratory setting, can result in impacts to marine invertebrates at both the larval and adult levels.

## INTRODUCTION

Offshore oil and gas development activities can result in the discharge of large amounts of drilling wastes to the marine environment. During drilling activities, drilling fluids (muds) are used to facilitate the operation of the drilling machinery and transport the drill cuttings to the surface of the well. Typical drilling muds used in southern California are water-based fluids (Steinhauer et al. 1992) that represent mixtures of clays and/or synthetic weighting agents that are diluted with either fresh or salt water (EHA 1990). The major weighting agent used in typical water-based drilling fluids is barium sulfate ($BaSO_4$), resulting in a fine grained mud with a characteristically high density (4.5 g/mL). Barium sulfate is added to drilling muds in amounts that range from 1% to up to 85%, although the exact make-up of drilling muds is specific to the drilling operation and type of substrate through which the drilling will occur (EHA 1990).

Current and projected offshore drilling in the southern California area has prompted interest in the ecological effects of the discharge of these drilling wastes to the marine environment (Steinhauer et al. 1992). This is especially true for areas where the discharge of drilling muds may influence organisms associated with hard bottom structures such as rocky outcrops and reefs, which are commonly found in the Santa Maria Basin, California (Hyland et al. 1990; Brewer et al. 1991; Lissner et al. 1991; Hyland et al. 1994). This study was designed to examine the effects of environmentally realistic concentrations of drilling muds on several aspects of the life history of hard-bottom organisms native to deep offshore regions where drilling has occurred. Organisms chosen for these experiments were larvae of the red abalone (*Haliotis rufescens*) and adult brown cup coral (*Paracyathus stearnsii).*

The study was performed in conjunction with additional studies as part of the U.S. Department of the Interior, Minerals Management Service (MMS)/National Biological Survey (NBS) Phase III Study Program. The Phase III program was designed to conduct long-term studies on the cumulative effects of offshore drilling and production activities on the marine environment of the southern Santa Maria Basin, CA (SAIC and MEC 1993).

### Study Organisms

#### Larvae of the red abalone (*Haliotis rufescens* Swainson)

Red abalone is a long-lived (up to 15 years), dioecious (separate sexes), commercially important species that lives on rocky reefs between the intertidal zone to depths exceeding 180 m on the west coast of the United States (Morris et al. 1980). Spawning abalone can be found year round, but the height of the spawning occurs in the spring and summer months (Morris et al. 1980). This species is common in the Santa Barbara Channel, a region of considerable offshore oil production, and adults can be found on submerged pipelines that link offshore platforms with onshore processing facilities (S. Anderson, University of California, Santa Barbara, personal observations). Abalone have free-swimming lecithotrophic larvae that enter the water column and subsequently settle and metamorphose into the adult body form. At 15° C the planktonic phase can be divided into an initial period of 5 – 7 days when the larva is developmentally incapable of settling (= precompetent stage), followed by a 2 – 5 week period when it is competent to settle in response to an inducer (Morse et al. 1979a; Morse 1990). Because of the short pre-competent period and behavioral mechanisms, such as active swimming and response to diel cycles (Prince et al. 1987, 1988), the distances that abalone larvae disperse from the point of origin are likely to be relatively short. The average dispersal distance for red abalone larvae may be about 1–10 km (M. Tegner, Scripps Institution of Oceanography, personal communication).

Larvae were chosen to study the effects of drilling muds because these early developmental stages are thought to be more sensitive to petroleum hydrocarbons and other contaminants than older life stages (for review see Capuzzo 1987; Neff 1987). Specifically, normal development of "wild" larvae that encounter waste plumes can be greatly altered. For example, Weis et al. (1989) and Kingsford (1995) found that natural stocks of fish larvae encountering treated municipal wastewaters had higher incidences of deformations than did laboratory reared or natural stocks of fishes from uncontaminated areas. There is also evidence that brief exposure of early life stages to low concentrations of petroleum wastes (produced water) can result in a developmental response at later larval stage (Krause et al. 1992; Raimondi and Schmitt 1992). Furthermore, effects of toxicants may be most pronounced at transition phases in an organism's life history when biochemical pathways are initiated or repressed. For many larvae, an important transition phase involves settlement and metamorphosis in the adult habitat.

Competent red abalone larvae typically settle on surfaces covered with crustose coralline algae or bacterial films (Strathmann 1987). In addition to natural settlement inducers, they can also be induced to settle and metamorphose by an analog of the natural inducer, γ-aminobutyric acid (GABA) (Morse et al. 1979a, 1979b, 1980). Morse et al. (1979a) found that $10^{-6}$ molar GABA resulted in 98% settlement in 18 hours. Once settled, metamorphosis to the adult body form typically is completed within 24 hr (Morse et al. 1980). This potent inducer allows measurement of the effect of different exposure regimes on settlement. Competent larvae settle in the presence of GABA. This technique has been used to assess interference of settlement of red abalone by pesticides and other contaminants (Morse et al. 1979b) and by produced water (a by-product of oil production; Raimondi and Schmitt 1992).

**Brown cup coral (*Paracyathus stearnsii* Verrill)**
The brown cup coral is a fairly large (polyps sometimes > 4 cm diameter), solitary coral that lives on rocky reefs from 7 to at least 900 meters deep (Fadlallah and Pearse 1982). It is a dioecious, obligately sexual species with gonads on all septa. Fertilization is external and zygotic development culminates in a planula larva about 160 μm long (Fadlallah and Pearse 1982). It is not known if brown cup coral larvae, like those of many other coral species (Morse et al. 1994) use specific inducers to cue settlement. In culture, individuals persist without settling for up to 4 weeks before perishing, an indication that external induction of settlement may be required. Populations of brown cup corals are common organisms found on hard surfaces of both platforms and local rocky reefs throughout the Santa Maria Basin (SAIC 1986; Brewer et al. 1991; Lissner et al. 1991; Hardin et al. 1994).

## METHODS

*Collection and handling of drilling muds*

The study was conducted using drilling muds collected from Platform Hidalgo. This drilling/production platform is one of a series of three platforms (Hidalgo, Hermosa, and Harvest) operating along a portion of the southern California continental shelf between Pt. Conception (34° 28' N; 120° 28' W) and Pt. Arguello (34° 35' N; 120° 38' W). Drilling muds used in these experiments were water-based muds, and samples were collected from active drilling platforms before discharge to the ocean. Drilling mud samples were collected by platform personnel and shipped in PVC containers on ice to the bioassay laboratory at the University of California, Santa Barbara (UCSB). At the laboratory they were stored in a cold (4° C) room until used in experiments. All experiments were conducted within 14 days of collection of the drilling muds.

### Study Design

*Determination of exposure periods and dose*

In order to utilize realistic drilling mud concentrations in the laboratory, a series of assumptions and calculations were made based on existing data on current patterns and the concentrations of drilling particulates recorded from previous studies (SAIC and MEC 1993; Coats 1994). First, it was assumed that competent larvae drift into the study area at an average near-bottom current speed of 7 cm $sec^{-1}$ (SAIC and MEC 1993; E. Waddell, SAIC, personal communication). Second, based on Coats (1994), it is assumed that the drilling mud footprint from the three production platforms (Hidalgo, Hermosa, and Harvest) is an ellipsoid about 13 km in major axis (longshore), based on concentrations of 200 mg $m^{-2}$ $day^{-1}$ particulate flux due to the initial deposition of daily discharges of drilling muds. Using these assumptions it would take a larva about 26 hours to reach the center from the edge of the footprint and approximately 51.6 hours to travel along the axis of the ellipsoid.

Most competent larvae can settle within 2-3 days (Morse et al. 1979a, b). While larvae are planktonic (about 7-8 days for red abalone at 15° C) in the footprint area they would be exposed to a solution that contains about 10 mg/L total suspended solids (SAIC and MEC 1993) of which about 2% or 0.2 mg/L is drilling mud (Coats 1994). When they settle onto a hard surface, the sedentary stage will be exposed to drilling mud fluxes of between 200 and 500 mg $m^{-2}$ $day^{-1}$ (Coats 1994). Therefore, concentrations of drilling muds used in experiments were set from 0.002 mg/L to 200 mg/L plus controls, except as noted. In the field, concentrations greater than 200 mg/L would be expected only very close to the platform discharge (Coats 1994).

*Collection and laboratory handling of test organisms*

Stocks of adult red abalone are maintained in a flow-through seawater system at UCSB. Methods for spawning, fertilization and larval culturing are described in Morse et al. (1977, 1979b, 1980). Stock animals were collected originally from a subtidal reef near Santa Barbara, CA and have been maintained as spawning animals for ongoing studies over several years. In order to mimic conditions that exist at 200 m, some experiments were conducted, as feasible, at 9° C in the dark. However, because the results of preliminary experiments indicated that development times for cultures were unstable at 9 degrees, parallel experiments were also performed at 15° C, the typical rearing temperature for red abalone. To help prevent bacterial infection in the laboratory, antibiotics (2 mg/l Rifampicin) were added to laboratory vessels holding larvae; antibiotics do not interfere with normal settlement of red abalone larvae (Morse et al. 1979b). If individuals in any replicate container appeared to be severely affected by bacterial infection that replicate was not used. Typically 2-3 replicates per treatment (concentration) have been used for survivorship and settlement assays with red abalone larvae (Morse et al. 1979a; Raimondi and Schmitt 1992), and variability is generally low among replicates. Experiments described in this study used between 3 and 10 replicates per treatment (concentration); the number was in large part dictated by logistical constraints of the experiment. Due to limited holding times for the drilling muds, as noted above, most of the experiments were carried out concurrently.

Individual adult brown cup corals were collected by scuba divers from subtidal rocky reefs near Santa Barbara, CA, at depths between 10 and 20 m and maintained in the UCSB laboratory. Until use, corals were kept at 9° C in the dark in a flow-through seawater system. The corals were not fed during the experiments.

**Specific Methodology of Experiments**

PHYSIOLOGICAL EFFECTS OF DRILLING MUDS ON RED ABALONE

*Gametes - (fertilization)*
This experiment tested the relationship between the concentration of drilling muds and the fertilization success of abalone, expressed as a percentage of eggs showing evidence of fertilization (Figures 1 and 2). At least 2 male and 2 female adult red abalone were spawned using the method of Morse et al., (1977). Sperm were collected via pipette from spawned abalone. Sperm concentration was determined by first diluting a sample of concentrated sperm 1:10,000 in sterile sea water, then counting 10 μL samples of the diluted sperm solution on a hemocytometer. Freshly spawned eggs were allowed to settle in 50 mL conical tubes. To determine settled egg density, a 20 μL sample of settled eggs was mixed in 1 mL of sterile sea water, and 20 μL samples of the suspended eggs were counted on depression slides.

Concentrations of drilling muds tested were: 200, 20, 2, 0.2. 0.02, and 0.002 mg/L. Clean, sterile sea water (0 mg/L) was used for control conditions. Subsamples (10 mL) of each drilling fluid dilution were pipetted into individual wells of Falcon six-well tissue culture plates. Ten replicates of each concentration and ten replicates of control conditions were included in this experiment.

Approximately 500 settled eggs were pipetted into each well of the Falcon tissue culture plates, and freshly diluted sperm at a ratio of approximately 800 sperm per egg were added to each well. Fertilization was allowed to proceed at 15° C for 5 hours on a shaker apparatus. At the end of 5 hours, fertilization was stopped by the addition of approximately 1 mL of 10% formalin. Maximum resolution of fertilization success was achieved by sampling 5 hours after gametes had been mixed. Tests for fertilization were only conducted at 15° C because that was the temperature at which the fertilization protocol was established. Due to logistical constraints, it was not feasible to complete the fertilization tests at 9° C. Fertilization success was measured by observing the presence of polar bodies or cell division under a microscope (Hunt and Anderson 1989). At least 100 eggs were counted per well for each replicate.

*Zygotes - (development)*
Experiments on zygotes tested the relationship between drilling mud concentration and early larval development (Figures 1 and 2). Freshly spawned red abalone eggs were fertilized at 15° C. Fertilized eggs were examined under the microscope to ensure the presence of between 10 to 50 sperm per egg. Drilling muds were diluted, using sterile sea water, to the following concentrations: 200, 20, 2, 0.2, 0.02, and 0.002 mg/L (plus control; 0 mg/L). Approximately 500 fertilized eggs were added per well of Falcon six-well culture dishes, into which 10 mL of each drilling mud dilution was pipetted. Ten replicates were conducted per concentration, and sixteen replicate controls in sterile sea water were performed. Development was allowed to proceed at 15° C on a shaker apparatus for 52 hours.

At the end of 52 hours, approximately 1 mL of 10% formalin was added to each well. At least 100 individuals were scored for normalcy of development. Larvae were defined as "normal", based on characteristic calcified, striated, snail-shaped shells with smooth borders, as identified in Hunt and Anderson (1989). "Abnormal" shells showed deviations such as indentations in the shell margins or mis-shapened shells (Hunt and Anderson 1989).

*Larvae - (survivorship, settlement, and viability)*
Survivorship was measured as the proportion of organisms alive at the end of the test. Settlement was measured as the proportion of survivors that settled. Viability is the product of the proportion of individuals that survived and the proportion that settled. It is an estimate of the proportion of individuals that successfully made the transition from the planktonic to the benthic stage.

*Precompetent larvae*
This experiment tested the relationship between exposure of precompetent larvae to varying concentrations of drilling muds and subsequent survival to competency, settlement (as competent larvae), or viability (Figures 1 and 2). Approximately 500 precompetent abalone larvae were placed in 800 mL of drilling mud solution, and maintained at 9° or 15° C for 52 hours. The precompetent stage was defined as those larvae under 7 days post fertilization for individuals reared at 15° C and under 10-12 days for individuals reared at 9°; the length of the precompetent period is more variable at lower temperatures. Drilling mud was diluted to the following concentrations: 200, 20, 2, and 0.2 mg/L (plus control; 0 mg/L) for the 9° C experiment , and 200, 20, 2, 0.2, 0.02, and 0.002 mg/L (plus control) for the 15° C experiment. Different concentrations were used for the 9° C experiment for two reasons. First, the results of the 15° C experiment (done first) indicated that the lowest concentrations tested (0.002 and 0.02 mg/L) had no effect on larval performance. Second, because only a limited numbers of larvae were available for testing, all treatment conditions could not be performed. Consequently, it was decided to forego the lower concentrations in the subsequent 9° C experiments.

After 52 hours of exposure to the various drilling mud dilutions, larvae were transferred to 800 mL fresh, sterile sea water containing 2 mg/L Rifampicin and were maintained at either 9° or 15° C (in closed systems). Upon reaching competency, approximately 75 of the exposed individuals were transferred into 20 mL disposable beakers and challenged with GABA plus 2 mg/L Rifampicin for 24 hours. There were 3 and 9 replicates per concentration for the 9° and 15° C experiments, respectively. Temperatures were maintained as described for the precompetent phase. Larvae were scored as settled (attached to the beaker), not settled (lying on their side), or dead (movement could not be detected).

*Competent larvae*

These experiments tested the relationship between exposure of competent larvae to varying concentrations of drilling muds, and their survival, settlement, or viability (Figures 1 and 2). These tests were done to examine the effects of longer term exposure to drilling muds, including the ability to settle and survive during the period of exposure. They were included to evaluate how larvae drifting into, and remaining in, an area of impact might be affected by exposure to drilling muds.

*Settlement ability of abalone larvae exposed to drilling muds at 9° and 15° C during the competent stage: 28h exposure to drilling muds*

Competent abalone larvae, reared at 9° or 15° C were exposed to dilutions of drilling fluids, ranging from 200 mg/L down to 0.002 mg/L (plus control), for 28h at 9° or 15° C. Approximately 400 individuals were exposed in 800 mL volumes of the dilutions, replicated two times per dilution for the 9° C experiment and three times per dilution for the 15° C experiment. After 28h, approximately 50 larvae per replicate were transferred to 20 mL disposable beakers containing 10 mL fresh sterile sea water. They were then challenged with 2 mg/L GABA plus 2 mg/L Rifampicin. For the 9° C experiments, three replicates per exposure group were set up for a total of six replicates per dilution. Only one replicate per exposure group (three replicates total) was used for experiments at 15° C. Larvae were scored as described for the precompetent larvae experiments.

*Settlement ability of abalone larvae exposed to drilling muds at 9° and 15° C during the competent stage: 52h exposure to drilling muds and settlement challenge in the presence of drilling muds*

Competent abalone larvae, reared at 9° or 15° C in a closed system (see above), were exposed to dilutions of drilling fluids ranging from 200 mg/L down to 0.002 mg/L (plus control) for 52h at 9° or 15° C. Approximately 400 individuals were exposed in 800 mL volumes of the dilutions, replicated two times per dilution for the 9° C experiment and three times per dilution for the 15° C experiment. For the 9° C experiment, before the last 24h of exposure, as many larvae as were available per replicate were split among three 20 mL disposable beakers along with 10 mL of the drilling fluid dilution. Larvae were challenged to settle by the addition of 2 mg/L GABA plus 2 mg/L Rifampicin. A total of six GABA challenge replicates per dilution were performed. For the 15° C experiment, before the last 24h of exposure, 50-150 larvae from each replicate were put into 20 mL disposable beakers along with 10 mL of the drilling fluid dilution. Larvae were challenged to settle by the addition of 2 mg/L GABA plus 2 mg/L Rifampicin. A total of three GABA challenge replicates per dilution were run. Larvae were scored as defined for the precompetent larvae and 28h exposures.

*Interference with settlement inducers*

This experiment was designed to test whether settlement of larval red abalone was affected by alteration of settlement surfaces due to deposition of drilling muds. As such, this experiment differed fundamentally from the other tests using larval red abalone. The other experiments tested whether drilling muds had direct physiological effects that translated into loss of larval performance: fertilization, development, and the ability to settle. In contrast, this experiment tested indirect effects on the performance of individuals (ability to settle) through interference with a necessary step in the settlement process (contact with an inducer). With this treatment the reaction of competent abalone larvae to fouled surfaces was examined. The focus was to determine how larvae might react to potentially inductive surfaces occurring in a zone of drilling mud particles. This treatment was intended to mimic short-term exposure of these inductive surfaces.

Coralline crusts (known to induce red abalone larvae to settle; Strathmann 1987) were placed in solutions of drilling muds for 28 hours at 9° C in the dark at the following concentrations (see Figure 1): 200, 2, and 0.02 mg/L (plus control; 0 mg/L). After 28 hours, crusts were transferred to small containers (8 crusts per concentration) containing a new solution of drilling muds that was identical in concentration to that used in the initial 28 hr period. New solutions were used to reduce the possibility of contamination when the abalone larvae were added. Approximately 500 competent abalone larvae were added to each container. After 24 hr the crusts were sampled microscopically to determine the density of settlers on coralline crusts as well as the percent of the crust surface that was clear of drilling muds. The latter parameter was sampled to separate interference with settlement due to effects on the inductive quality of the surface (e.g., chemical effects on the inducers) from interference with settlement due to physical covering of the surface with mud.

However, this experiment alone was not sufficient to distinguish interference with inducers from physiological effects of larvae. To evaluate this distinction, it was necessary to determine whether exposure to drilling muds during the competency phase affected larval settling ability. This was tested in the previously described experiment on competent larvae using GABA as an inducer. In this experiment, the GABA induced settlement was repeated and, additionally, coralline crusts were used to induce settlement. Coralline crusts and GABA were both used to determine if larvae exposed to natural and artificial inducers responded differently.

For this test, larvae were placed into solutions of the same concentrations as noted above (five replicates each), but without coralline crusts for 28 hours. After 28 hours, larvae were removed from the drilling mud solutions and put into containers of clean seawater. The larvae from each of the replicates were split into two containers: one containing clean coralline crusts, the other containing 2 mg/L GABA solution. Settlement was scored as noted above after 24 hours in these containers.

## PHYSIOLOGICAL EFFECTS OF DRILLING MUDS ON THE BROWN CUP CORAL: ADULT MORTALITY AND TISSUE LOSS

This experiment was designed to test whether adult *Paracyathus* are affected by exposure to realistic concentrations of drilling muds (see earlier discussion of rationale for the concentrations). The effect could result from either of two sources: 1) toxicity from a chemical or biological component of the drilling muds, or 2) toxicity from the fine particulate matter in drilling muds that might interfere with physiological processes (e.g., feeding or respiration) of a filter feeder such as *Paracyathus*. Survivorship and tissue loss in adult cup corals were examined as endpoints. For corals such as *Paracyathus*, tissue loss has a direct bearing on reproduction because gonads are located in external tissue in the septa.

Individual *Paracyathus*, 11 per concentration, were randomly selected from a population of adults and placed in solutions of drilling muds with the following concentrations: 200, 2, and 0.02 mg/L (plus control; 0 mg/L). Experiments were maintained in a cold room at 9° C. Every two days for 10 days individuals were examined microscopically for survivorship and tissue loss (sub-lethal effects). Individuals were scored as either exhibiting or not exhibiting tissue loss. An additional variable, relative viability, was calculated as the product of survivorship and the proportion of individuals showing tissue loss. Relative viability should be a good predictor of the likelihood of continued survival and reproduction under exposure to drilling muds. New solutions were made of the experimental concentrations of drilling muds every two days (all concentrations were made using drilling muds that were less than 14 days post-collection). Following examination, individuals were replaced into the appropriate fresh experimental concentrations of drilling muds. Since adult *Paracyathus* are sessile, the period that they could be affected by drilling muds is longer than for a larvae. Consequently, this experiment was carried out over a longer period of time. This time frame was within the average period for discharge of drilling muds during drilling activity at the Santa Maria Basin platforms, which usually lasts for several weeks or months (Steinhauer et al. 1992; Raimondi et al. in preparation) for each well drilled.

*Data Analysis*

Results from the experiments are expressed as percent fertilization, survivorship, etc., compared to a control. All values were standardized to the mean for the control set of replicates (the 0 mg/L treatment), including each of the control replicates. This approach allows direct comparisons of results from different experiments with differing units or measured parameters.

Regression analyses were used for all experiments testing for physiological effects of drilling muds on gametes, zygotes, or larval red abalone (Figure 1). All statistical analyses were performed using SAS software (SAS Institute 1988). Separate analyses were done using the concentration and the log of the concentration of drilling muds as the independent variable. This was done because dose response curves have been shown to follow both linear and log-linear trajectories, and there was no objective reason to predict which, if any, was the probable model for biological response to drilling muds.

Experiments testing for interference with inducers of settlement (Figure 1) used both multiple and simple regression models. Analysis of covariance models were used to evaluate results from experiments designed to test for the effects of drilling muds on adult brown cup corals (Figure 1).

## RESULTS

### PHYSIOLOGICAL EFFECTS OF DRILLING MUDS ON RED ABALONE

*Fertilization and development*
The results of the fertilization and development assays are presented in Table 1 and Figure 3. There was no significant relationship between concentration of drilling muds and fertilization in red abalone. Similarly, there was no significant relationship between concentration of drilling muds and development of red abalone zygotes. Fertilization and development was similar across all drilling mud concentrations, including the controls.

*Precompetent larvae*
It was not possible to calculate settlement and survivorship compared to controls for the 9° C experiments due to bacterial contamination of the drilling mud control (0 mg/L). Relative measures were considered important because they allowed direct comparisons among different experiments. Therefore, for the experiments where controls were contaminated, survivorship and settlement were calculated relative to the mean of the 0.2 and 2 mg/L treatments. The mean of the two lowest concentrations was used because preliminary experiments showed that concentrations $\leq$ 2 mg/L are not significantly different from the control for either settlement or survivorship. Experiments at 15° C were standardized to the control mean as explained in the methods. Survivorship and viability were not assessed in the 15° C experiment because experimental chambers were lost after settlement was evaluated.

The only performance parameter showing a significant relationship with concentration of drilling muds in precompetent larvae was survivorship in experiments done at 9° C (Table 1; Figure 4). However, the relationship is positive indicating that survival increased as a function of increasing concentrations of drilling muds.

*Competent larvae*
Results from experiments involving competent larvae are presented in Figures 5-7 for survivorship, settlement, and viability, respectively. This grouping was done to facilitate comparisons among measures of performance. The only parameter that was significantly correlated with concentration of drilling mud was settlement, for which 3 of the 4 experiments showed a significant effect. However, in two of these experiments (28 and 52 hr exposure to drilling muds at 9° C) the relationship was positive (for log-transformed concentrations only),

while in the other (28 hr exposure to drilling muds at 15° C) the relationship was negative (for non-transformed concentrations only; P=0.023) (Table 1). Therefore, even these results were somewhat equivocal.

*Interference with inducers of settlement*
Settlement of red abalone larvae on coralline crusts decreased with increasing concentrations of drilling muds (Figures 8a and 8b), although the effect was not attributable to physical masking of the crust surface by muds. This conclusion was based on the results of the multiple regression analysis, which indicated that only the concentration of drilling muds and not the percentage of free space was significantly correlated with settlement (Table 2a), although this relationship was weak ($r^2$=0.493). Additionally, there was no evidence that physiological effects on larvae due to their exposure to drilling muds were responsible for the pattern shown in Figure 8a. Settlement of individuals that were exposed to drilling muds and then removed and put in containers with either coralline crusts or GABA did not vary with initial concentration of drilling muds (Figures 8c and 8d; Table 2b). Moreover, results from experiments described earlier demonstrated that larval settlement was unaffected by even continuous exposure to high concentrations of drilling muds. The most reasonable explanation for these results is that drilling muds negatively affected the quality of the inducer.

### PHYSIOLOGICAL EFFECTS OF DRILLING MUDS ON THE BROWN CUP CORAL: ADULT MORTALITY AND TISSUE LOSS

Results of the analysis of covariance (ANCOVA) for all parameters measured (survivorship, proportion of individuals showing tissue loss, and relative viability) indicated that there was a significant interaction between concentration of drilling muds and exposure time (days; Table 3). This indicates that slopes of the response curves were not homogeneous (Figure 9), and is important because it shows that the response did not vary over time in a similar manner between dose conditions (drilling mud concentrations). Survivorship decreased, proportion of individuals showing tissue loss increased, and relative viability decreased over time with increasing concentration of drilling muds, although the response was slightly different at each concentration.

## DISCUSSION

Exposure of abalone larvae to drilling muds revealed that there was no statistically significant effect on the fertilization mechanism, or the early developmental stages of abalone larvae (Figure 3). Experiments on precompetent larvae showed that drilling mud exposure may have enhanced the survivorship of abalone larvae. This relationship was driven primarily by the results of the treatment with 200 mg/L drilling muds which showed much greater survivorship than other treatments (Figure 4). However, this result may be an artifact of the way the data were treated when the controls were lost. It is not possible to know from the data presented whether the relative increase in survivorship observed at high concentrations is real or a result of the data manipulation without proper controls.

Similar positive relationships were found at 9° C for settlement of competent larvae (Table 1 and Figure 6). However, the relationship is probably of little ecological significance. The increase observed, while statistically significant, shows that settlement increased only by approximately 2-3% over the range of concentrations tested. In comparison, the similar treatment with competent larvae at 15° C showed a negative relationship. These results suggest that there may be some enhancement of survivorship and/or settlement in abalone larvae with drilling muds, at least for the range of experimental concentrations, but the specific mechanism remains unknown.

In contrast, significant strong, negative effects were found on the ability of larvae to respond to a natural settlement inducer (Figure 8). This type of effect may be very important in influencing population dynamics for some marine organisms (Keough and Black 1995). Effects such as these on larval settlement could result in significant reductions in recruits to settled populations, and lead to more widespread population level changes throughout a benthic community (Murdoch et al. 1989; Nisbet et al. 1995). However, because the ecological processes that link larval dynamics and benthic populations are still poorly understood, the significance of changes in settlement rates remains largely unknown (Raimondi and Schmitt 1992; Nisbet et al. 1995).

Somewhat in contrast to most of the red abalone results, experiments on adult cup corals showed that under environmentally realistic exposure conditions there was increased mortality due to progressive tissue loss (Figure 9). Unlike the larval effects noted above, this would have a direct impact on adult coral populations in the vicinity of drilling mud discharges. Experiments showed that even under the lowest drilling mud concentration tested (0.02 mg/L) relative viability of adult corals dropped to only 60% after eight days of exposure, and at a high concentration of 200 mg/L all adults died after only 6 days of exposure (Figure 9).

Throughout this study controls were maintained that consisted of only clean seawater. An additional control for sediment load or particle size in the absence of the other fractions of drilling muds may have been appropriate as well. This was not done because of the difficulty in maintaining a drilling mud substitute that contained only the particulate load expected from the drilling mud samples. It is possible that the effects observed in this study are not caused by the dissolved fraction of the muds but rather by the particulate material carried by the muds. A thorough search of the literature yielded no studies that have addressed this hypothesis directly. Future studies need to distinguish the differences between this particulate load and direct toxicity from dissolved fractions to better address the mechanisms of effect that were noted here and elsewhere. Dissolved petroleum fractions have been shown to be the primary toxic agent in several studies of oil-field effluents, particularly produced waters (Neff et al. 1992; Cherr et al. 1993; Higashi and Crosby 1993). Field and laboratory studies of produced water toxicity have shown impairment in fertilization and development of marine invertebrates and plants (Krause et al. 1992; Raimondi and Schmitt 1992; Reed 1993; Krause 1995). The results of these studies further raise questions of the mechanism(s) of toxicity observed in the present study and emphasize the need to separate effects from dissolved and particulate fractions.

The majority of recent laboratory studies on drilling muds have addressed lethal effects on adult organisms (Neff 1983; Neff et al. 1989; Daan et al. 1994; Payne et al. 1989; Parrish et al. 1989), while fewer studies have addressed sublethal effects on more sensitive larval forms (Crawford and Gates 1981; Carls and Rice 1984; Conklin and Rao 1984). Laboratory bioassays have shown that, in general, drilling fluids can cause acute toxicity in high concentrations (1,000 – 10,000 mg/L), and chronic toxicity at lower concentrations (10–100 mg/L) to a variety of organisms (Neff 1983). Results of the present study show the importance of addressing effects on both sensitive larval stages and adults in toxicity testing. Data presented here suggest that drilling muds used in the Santa Maria Basin may elicit indirect effects (on settlement inducers; Figure 8), and direct effects (on sessile adults; Figure 9).

As noted above, while these results suggest that drilling muds interfere with the settlement inducer mechanism, it was not possible to determine whether the observed effect was the result of a toxicological response to the drilling mud or a physical interaction with drilling mud particulates. Barium sulfate has been shown to cause toxic effects in fertilization and early developmental stages of sea urchin larvae at concentrations as low as 23 mg/L (Schatten et al. 1982). Barium has also been implicated in developmental effects associated with the discharge of produced water from production platforms (Krause et al. 1992). Somewhat in contrast, in a field study near Santa Barbara, CA, Jenkins et al. (1989) concluded that barium from deposited drilling muds is probably not soluble enough to contribute to toxicity. However, Jenkins et al. (1989) did not address physical processes that may result in mortality or reduced physiological performance, or produce toxicological effects to sensitive larvae. It remains possible that barium in the drilling muds contributed to the overall observed effects reported here for both abalone larvae and adult cup corals. Future work should focus on separating the physical and toxicological nature of effects observed here, as well as helping to understand the possible toxicological impacts of chronic low level barium exposure in marine systems.

This investigation has shown that drilling muds may contribute to impacts on important larval processes, and have direct effects on sessile adult organisms typical of hard-bottom communities of the Santa Maria Basin. Drilling muds that are discharged from drilling\production platforms may hinder larval recruitment by interference with natural settlement inducers of marine organisms. Furthermore, drilling muds may directly cause mortality to sessile organisms that are not able to escape the exposure through mobility. The use of environmentally realistic test concentrations emphasizes that effects found in this study are of the magnitude likely to occur in the field.

## ACKNOWLEDGMENTS

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## LITERATURE CITED


Brewer, G.D., J.L. Hyland, and D.D. Hardin. 1991. Effects of oil drilling on deepwater reefs offshore California. *Am. Fish. Soc. Symp.* 11:26-38.

Capuzzo, J.M. 1987. Biological effects of petroleum hydrocarbons: Assessments from experimental results. In: Boesch. D.F. and N.N. Rabalais (eds). Long-term environmental effects of offshore oil and gas development. Elsevier Applied Science, New York. pp. 343-410.

Carls, M.G. and S.C. Rice. 1984. Toxic contributions of specific drilling mud components to larval shrimp and crabs. *Mar. Env. Res.* 12:45-62.

Cherr, G., R. Higashi, J. Shenker, and T. Fan. 1993. Assessment of chronic toxicity of petroleum and produced water components to marine organisms. Final Report for the Southern California Education Initiative. University of California, Davis and Minerals Management Service. Contract No. 30761.

Conklin, P.J. and K.R. Rao. 1984. Comparative toxicity of offshore and oil-added drilling muds to larvae of the grass shrimp (*Palaemonetes intermedius*). *Arch. Environ. Contam. Toxicol.* 13:685-690.

Coats, D.A. 1994. Deposition of drilling particulates offshore Point Conception, California. *Mar. Env. Res.* 37:95-127

EHA (Espy, Houston and Associates, Inc.). 1990. A review of drilling mud research. Prepared for Mobil Oil Exploration and Producing Southeast, Inc. New Orleans, LA. Document No. 890601.

Fadlallah, Y.H. and J.S. Pearse. 1982. Sexual reproduction in solitary corals: Synchronous gametogenesis and broadcast spawning in *Paracyathus stearnsii. Mar. Biol.* 71:233-239.

Hardin, D.D., J. Toal, T. Parr, P. Wilde, and K. Dorsey. 1994. Spatial variation in hard-bottom epifauna in the Santa Maria Basin, California: The importance of physical factors. *Mar. Env. Res.* 37:165-193.

Higashi, R. and D. Crosby. 1993. Environmental degradation and identification of toxic compounds of petroleum and associated materials. Final Report for the Southern California Education Initiative. University of California, Davis and Minerals Management Service. Contract No. 30761.

Hunt, J.W. and B.S. Anderson. 1989. Sublethal effects of zinc and municipal effluents on larvae of the red abalone *Haliotis rufescens. Mar. Biol.* 101:545-552.

Jenkins, K.D., S.H. Howe, B.M. Sanders, and C. Norwood. 1989. Sediment deposition, biological accumulation and subcellular distribution of barium following the drilling of an exploratory well. In: F.R. Engelhardt, J.P. Ray, and A.H. Gilliam (eds.). Drilling Wastes. Elsevier Applied Science. New York. pp. 587-608.

Kingsford, M.J. 1995. Influence of pollutants and oceanography on abundance and deformities of wild fish larvae. In: R.J. Schmitt and C.W. Osenberg (eds.). The design of ecological impact assessment studies: Conceptual issues and applications. in press.

Krause, P.R. 1995. Spatial and temporal variability in receiving water toxicity near an oil effluent discharge site. *Arch. Env. Cont. Toxicol. In press.*

Krause, P.R., C.W. Osenberg, and R.J. Schmitt. 1992. Effects of produced water on early life stages of a sea urchin: Stage specific responses and delayed expression. In: J.P. Ray and F.R. Englehardt (eds.). Produced water: Technological/Environmental issues. Plenum, New York, NY. pp. 431-444.

Lissner, A.L., G.L. Taghon, D.R. Diener, S.C. Schroeter, and J.D. Dixon. 1991. Recolonization of deep-water hard-substrate communities: Potential impacts from oil and gas development. *Ecol. Appl.* 1(3):258-267.

Morris, R.H, D.P. Abbott, and E.C. Haderlie. 1980. *Intertidal invertebrates of California.* Stanford University Press. Stanford, CA.

Morse, D.E. 1990. Recent progress in larval settlement and metamorphosis: Closing the gap between molecular biology and ecology. *Bull. Mar. Sci.* 46:465-483.

Morse, D.E., H. Duncan, N. Hooker, and A. Morse. 1977. Hydrogen peroxide induces spawning in molluscs, with activation of prostoglandin endoperoxide synthetase. *Science* 196:298-300.

Morse, D.E., H. Duncan, N. Hooker, A. Baloun, and G. Young. 1980. GABA induces behavioral and developmental metamorphosis in planktonic molluscan larvae. *Fed. Proc.* 39:3237-3241.

Morse, D.E., N. Hooker, H. Duncan, and L Jensen. 1979a. $\gamma$-aminobutyric acid, a neurotransmitter, induces planktonic abalone to settle and begin metamorphosis. *Science* 204:407-410.

Morse, D.E., N. Hooker, L. Jensen, and H. Duncan. 1979b. Induction of larval abalone settling and metamorphosis by $\gamma$-aminobutyric acid and its congeners from crustose red algae: II. Applications to cultivation, seed production and bioassays: Principal causes of mortality and interference. *Proc. World Maricult. Soc.* 10:91-91.

Morse, D.E., A. Morse, N. Hooker, and P.T. Raimondi. 1994. Morphogen-based chemical flypaper for *Agaricia humilis* larvae. *Biol. Bull.* 186:172-181.

Neff, J. 1983. The biological effects of drilling discharges. In: Drilling Discharges in the Marine Environment. National Academy Press, Washington D.C. pp. 75-128.

Neff, J.M. 1987. Biological effects of drilling fluids, drill cuttings and produced waters. In: Boesch. D.F. and N.N. Rabalais (eds.). Long-term environmental effects of offshore oil and gas development. Elsevier Applied Science, New York. pp. 469-538.

Neff, J.M., T.C. Sauer, Jr., and M. Maciolek. 1992. Composition, fate and effects of produced water discharges to nearshore marine waters. In: J.P. Ray and F.R. Englehardt (eds). Produced water: Technological/Environmental issues. Plenum, New York, NY. pp. 371-385.

Prince, J.D., T.L. Sellers, W.B. Ford, and S.R. Talbot. 1987. Experimental evidence for limited dispersal of haliotid larvae (genus *Haliotis*: Mollusca: Gastropoda). *J. Exp. Mar. Bio. Ecol.* 106:243-263.

Prince, J.D., T.L. Sellers, W.B. Ford, and S.R. Talbot. 1988. Confirmation of a relationship between the localized abundance of breeding stock and recruitment for *Haliotis rubra* Leach (Mollusca: Gastropoda). *J. Exp. Mar. Biol. Ecol.* 122:91-104.

Raimondi, P.T. and R. J. Schmitt. 1992. Effects of produced water on settlement of larvae: Field tests using red abalone. In: J.P. Ray and F.R. Englehardt (eds). Produced water: Technological/Environmental issues. Plenum, New York, NY. pp. 415-430.

Reed, D. 1993. Potential biogenic habitat alteration by OCS activities: Adverse effects to early life stages of giant kelp from chronic disturbances. Final Report for the Southern California Education Initiative. University of California, Davis and Minerals Management Service. Contract No. 30761.

SAIC (Science Applications International Corporation). 1986. Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin and Western Santa Barbara Channel. Final Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30032.

SAIC and MEC (MEC Analytical Systems, Inc.). 1993. Monitoring and Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III, Year One Report. Report to U.S. Deptartment of the Interior. Minerals Management Service, Pacific OCS Region, Camarillo, CA, under Contract No. 14-35-0001-30584.

SAS Institute. 1988. *SAS/STAT User's Guide, Release 6.03 Edition.* Cary, NC.

Schatten, G., C. Simerly, and H. Schatten. 1982. Effects of barium sulfate on sea urchin fertilization and early development. In: Duedall, I.W., D.R. Kester, P.K. Park, and B.H. Ketchum (eds.). Energy wastes in the ocean. John Wiley and Sons, New York. pp. 233-239.

Strathmann, M.F. 1987. Reproduction and development of marine invertebrates of the northern Pacific coast: Data and methods for the study of eggs, embryos, and larvae. University of Washington Press. Seattle, WA. pp 220-267.

Steinhauer, W.G., E. Imamura, J.R. Barminski, and J.M. Neff. 1992. California study compares natural/drilling discharge contaminants offshore. *Oil and Gas J.* May 4:74-93.

Weis, P., S.J. Weis, and A. Greenburg. 1989. Treated municipal wastewaters: Effects on development and growth of fishes. *Mar. Env. Res.* 28:527-532.

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**Figure 6:** Settlement (proportion of survivors that settled) of red abalone exposed as competent larvae to varying concentrations of drilling muds. Data are mean ( $\pm$ SE). Data were normalized to the control mean (see text). See Table 1 for statistics. **(A)** Settlement at 9° C of larvae exposed to drilling muds for 28 hours followed by exposure of 24 hours in clean seawater with GABA. **(B)** Settlement at 9° C of larvae exposed to drilling muds for 28 hours followed by an additional exposure of 24 hours in drilling muds with GABA. **(C)** Settlement at 15° C of larvae exposed to drilling muds for 28 hours followed by exposure of 24 hours in clean seawater with GABA. **(D)** Settlement at 15° C of larvae exposed to drilling muds for 28 hours followed by an additional exposure of 24 hours in drilling muds with GABA.

**Figure 7:** Viability (survivorship x settlement) of red abalone exposed as competent larvae to varying concentrations of drilling muds. Data are mean ( $\pm$ SE). Data were normalized to the control mean (see text). See Table 1 for statistics. **(A)** Viability at 9° C of larvae exposed to drilling muds for 28 hours followed by exposure of 24 hours in clean seawater with GABA. **(B)** Viability at 9° C of larvae exposed to drilling muds for 28 hours followed by an additional exposure of 24 hours in drilling muds with GABA. **(C)** Viability at 15° C of larvae exposed to drilling muds for 28 hours followed by exposure of 24 hours in clean seawater with GABA. **(D)** Viability at 15° C of larvae exposed to drilling muds for 28 hours followed by an additional exposure of 24 hours in drilling muds with GABA.

**Figure 8:** Interference with settlement inducer for red abalone as a function of concentration of drilling muds. Data (mean $\pm$ SE) were normalized to the control mean for Figures 8a, 8c, and 8d (see Results). See Table 2 for statistics. **(A)** Settlement, while exposed to drilling muds, on coralline crusts as a function of concentration of drilling muds. **(B)** Percent free space (mean $\pm$ SE) on coralline crusts (area not covered by mud) as a function of concentration of drilling muds (these data are from the same experiment as in 8a). **(C)** Settlement, on coralline crusts, following exposure to varying concentrations of drilling muds. **(D)** Settlement, in the presence of GABA, following exposure to varying concentrations of drilling muds.

**Figure 9:** Survivorship **(A)**, proportion of live individuals showing tissue loss **(B)**, and relative viability (survivorship x proportion of live individuals showing tissue loss) **(C)** of brown cup corals as a function of concentration of drilling muds and exposure period. See Table 3 for statistics.

**Table 1:** Summary of regression analyses for experiments testing for physiological effects on red abalone larvae due to exposure to varying concentrations of drilling muds. P-values using concentration and log(concentration) as the independent variable are given. If the relationship between the dependent variable and concentration or log(concentration) was significant ($P<0.05$) the direction of the slope is shown (+ or -). Non-significant results are denoted by "ns" See Figures 3-7.

| | | | P-Value | | |
|---|---|---|---|---|---|
| **Experiment** | **Dependent Variable** | **df** | **Concentration** | **Log Concentration** | **Slope** |
| Fertilization | Fertilization | 1,69 | 0.397 | 0.069 | ns,ns |
| Development | Development | 1,74 | 0.909 | 0.325 | ns,ns |
| Precompetent Larvae-9° C | Survivorship | 1,10 | *0.001* | *0.002* | +,+ |
| | Settlement | 1,10 | 0.497 | 0.641 | ns,ns |
| | Viability | 1,10 | 0.880 | 0.994 | ns,ns |
| Precompetent Larvae-15° C | Settlement | 1,61 | 0.186 | 0.191 | ns,ns |
| Competent Larvae-9° C | Survivorship | 1,40 | 0.613 | 0.602 | ns,ns |
| 28 hr drilling mud | Settlement | 1,40 | 0.259 | *0.043* | ns,+ |
| 24 hr GABA/Clean SW | Viability | 1,40 | 0.398 | 0.080 | ns,ns |
| Competent Larvae-9° C | Survivorship | 1,39 | 0.848 | 0.918 | ns,ns |
| 28 hr drilling mud | Settlement | 1,39 | 0.362 | *0.048* | ns,+ |
| 24 hr GABA/drilling mud | Viability | 1,39 | 0.248 | 0.069 | ns,ns |
| Competent Larvae - 15° C | Survivorship | 1,19 | 0.387 | 0.130 | ns,ns |
| 28 hr drilling mud | Settlement | 1,19 | *0.023* | 0.057 | -,ns |
| 24 hr GABA/Clean SW | Viability | 1,19 | 0.093 | 0.249 | ns,ns |
| Competent Larvae-15° C | Survivorship | 1,19 | 0.137 | 0.861 | ns,ns |
| 28 hr drilling mud | Settlement | 1,19 | 0.703 | 0.086 | ns,ns |
| 24 hr GABA/drilling mud | Viability | 1,19 | 0.884 | 0.122 | ns,ns |

**Table 2A:** Results of multiple regression analysis for experiments testing for effects on inductive quality of surfaces by drilling muds. Results did not differ qualitatively if log (concentration of drilling muds) was used as the independent variable. Asterisk (*) indicates a significant result ($P<0.05$). ANOVA results are depicted for the regression line of concentration of drilling mud.

| Variable | Coefficient | P |
|---|---|---|
| Intercept | -0.551 | 0.833 |
| Concentration of Drilling Muds | -0.002 | *0.016** |
| Percent free space | 0.014 | 0.605 |

**Analysis of Variance**

| Source | SS | df | F | P |
|---|---|---|---|---|
| Regression | 2.055 | 2 | 16.062 | *0.001** |
| Residual | 1.855 | 29 | | |

Adjusted squared multiple R: 0.493

**Table 2B:** Summary of regression analyses for control experiments testing for physiological effects on red abalone larvae due to exposure to varying concentrations of drilling muds. P-values using concentration and log (concentration) as the independent variable are given. If the relationship between the dependent variable and concentration or log (concentration) was significant the direction of the slope is shown (+ or -). Non-significant results are denoted by "ns". See Figure 8.

| | | | P-Value | | |
|---|---|---|---|---|---|
| **Experiment** | **Dependent Variable** | **df** | **Concentration** | **Log Concentration** | **Slope** |
| 28 hr drilling muds 24 hours Coralline crusts/clean SW | Settlement | 1,18 | 0.586 | 0.454 | ns |
| 28 hr drilling muds 24 hours GABA/clean SW | Settlement | 1,18 | 0.386 | 0.333 | ns |

**Table 3**: Results for analysis of covariance for effects of drilling muds (categorical variable) over time (day = covariate) on several measures of performance for the brown cup coral, *Paracyathus stearnsii.* For all performance parameters (survival, individuals exhibiting tissue loss, and viability) there was a significant ($P<0.05$) interaction term in the analysis. This indicates that the slopes were not homogeneous. Significant terms are denoted by asterisks (*). See Figure 9.

**Analysis of covariance - *Survival***

| **Source** | **df** | **SS** | **F** | **P** |
|---|---|---|---|---|
| Concentration of drilling muds | 3 | 0.0002 | 0.10 | 0.960 |
| Day | 1 | 0.062 | 107.59 | *<0.001** |
| Interaction | 3 | 0.116 | 66.37 | *<0.001** |
| Residual | 16 | 0.009 | | |

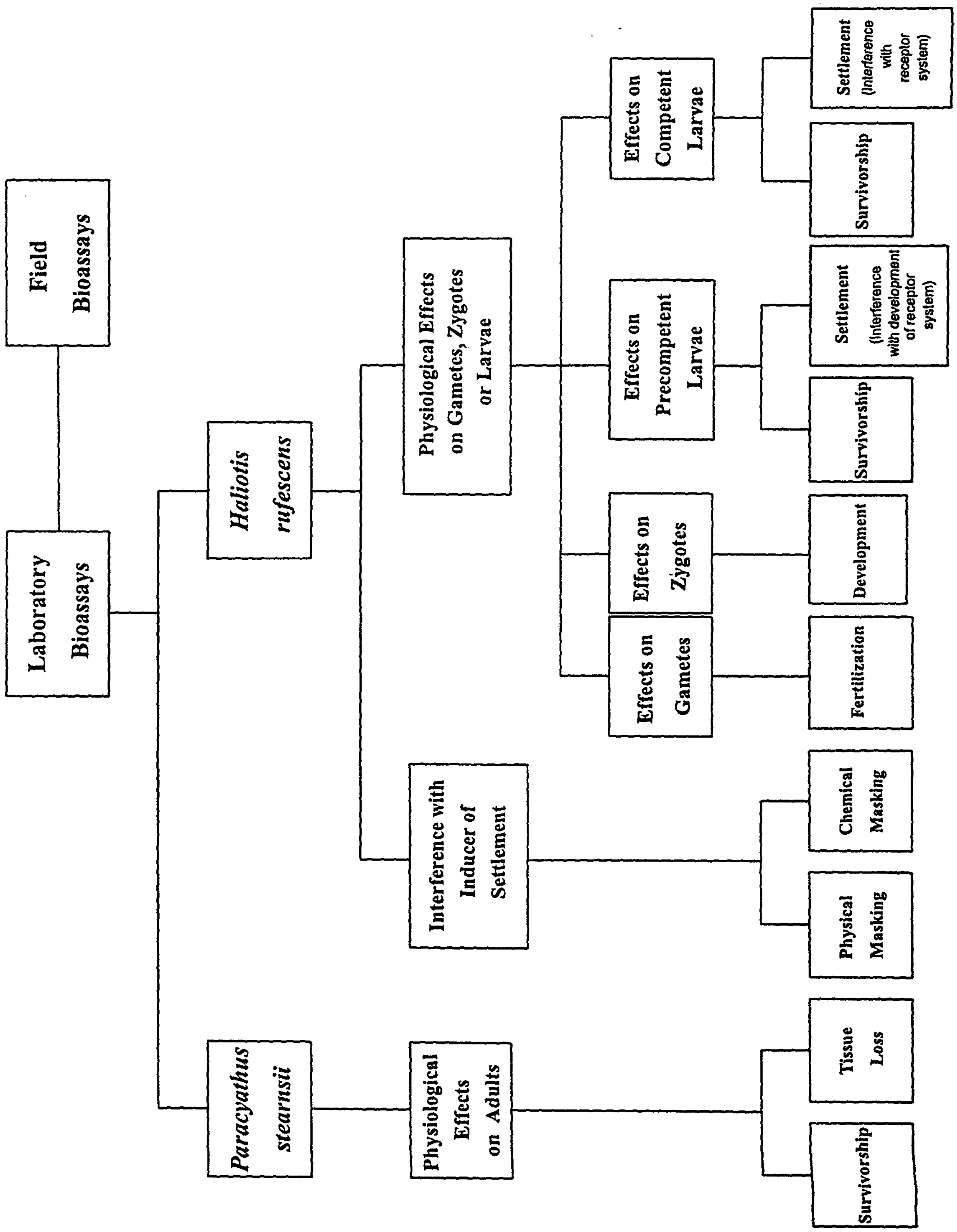
**Analysis of covariance - *Individuals Exhibiting Tissue Loss***

| **Source** | **df** | **SS** | **F** | **P** |
|---|---|---|---|---|
| Concentration of drilling muds | 3 | 0.010 | 0.24 | 0.867 |
| Day | 1 | 1.353 | 95.67 | *<0.001** |
| Interaction | 3 | 0.607 | 14.30 | *<0.001** |
| Residual | 16 | 0.226 | | |

**Analysis of covariance - *Viability***

| **Source** | **df** | **SS** | **F** | **P** |
|---|---|---|---|---|
| Concentration of drilling muds | 3 | 0.024 | 0.62 | 0.614 |
| Day | 1 | 0.804 | 62.16 | *<0.001** |
| Interaction | 3 | 0.341 | 8.79 | *0.001** |
| Residual | 16 | 0.207 | | |

Figure 1



Field Bioassays
Laboratory Bioassays
Haliotis rufescens
Paracyathus stearnsii
Physiological Effects on Gametes, Zygotes or Larvae
Interference with Inducer of Settlement
Physiological Effects on Adults
Effects on Competent Larvae
Effects on Precompetent Larvae
Effects on Zygotes
Effects on Gametes
Settlement (interference with receptor system)
Survivorship
Settlement (interference with development of receptor system)
Survivorship
Development
Fertilization
Chemical Masking
Physical Masking
Tissue Loss
Survivorship

# Physiological Effects on Red Abalone Larvae

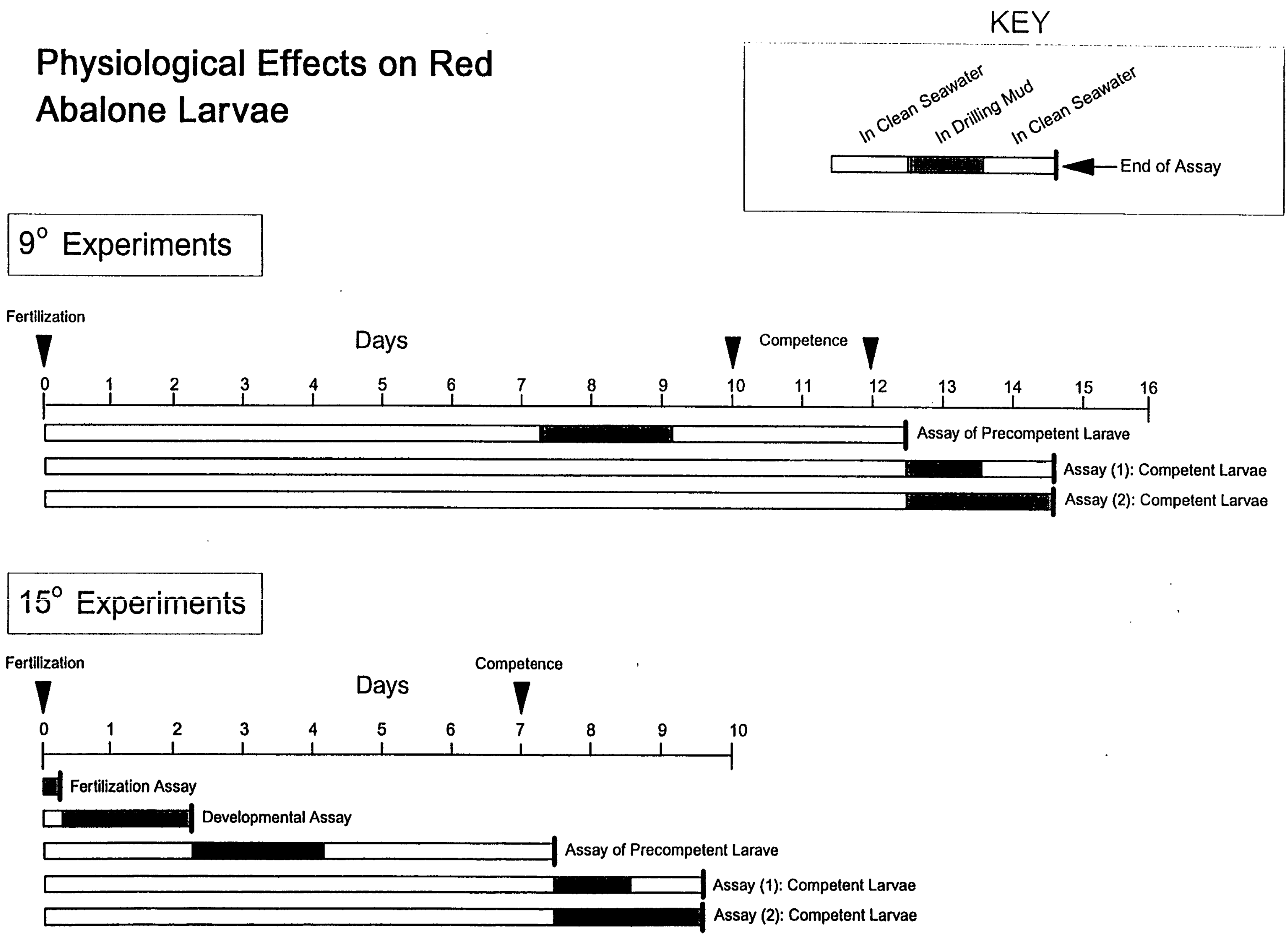
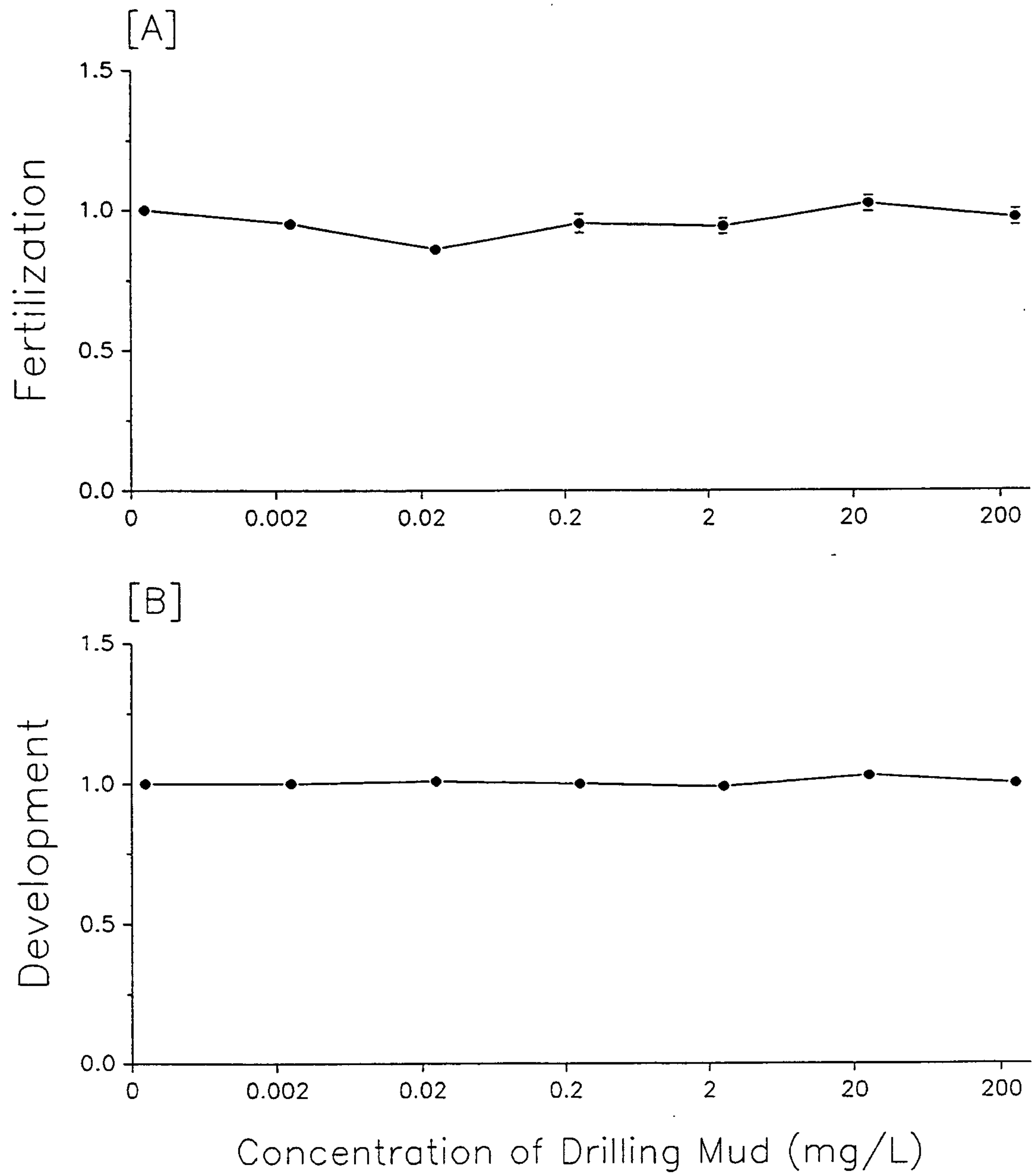



Figure 2

Figure 3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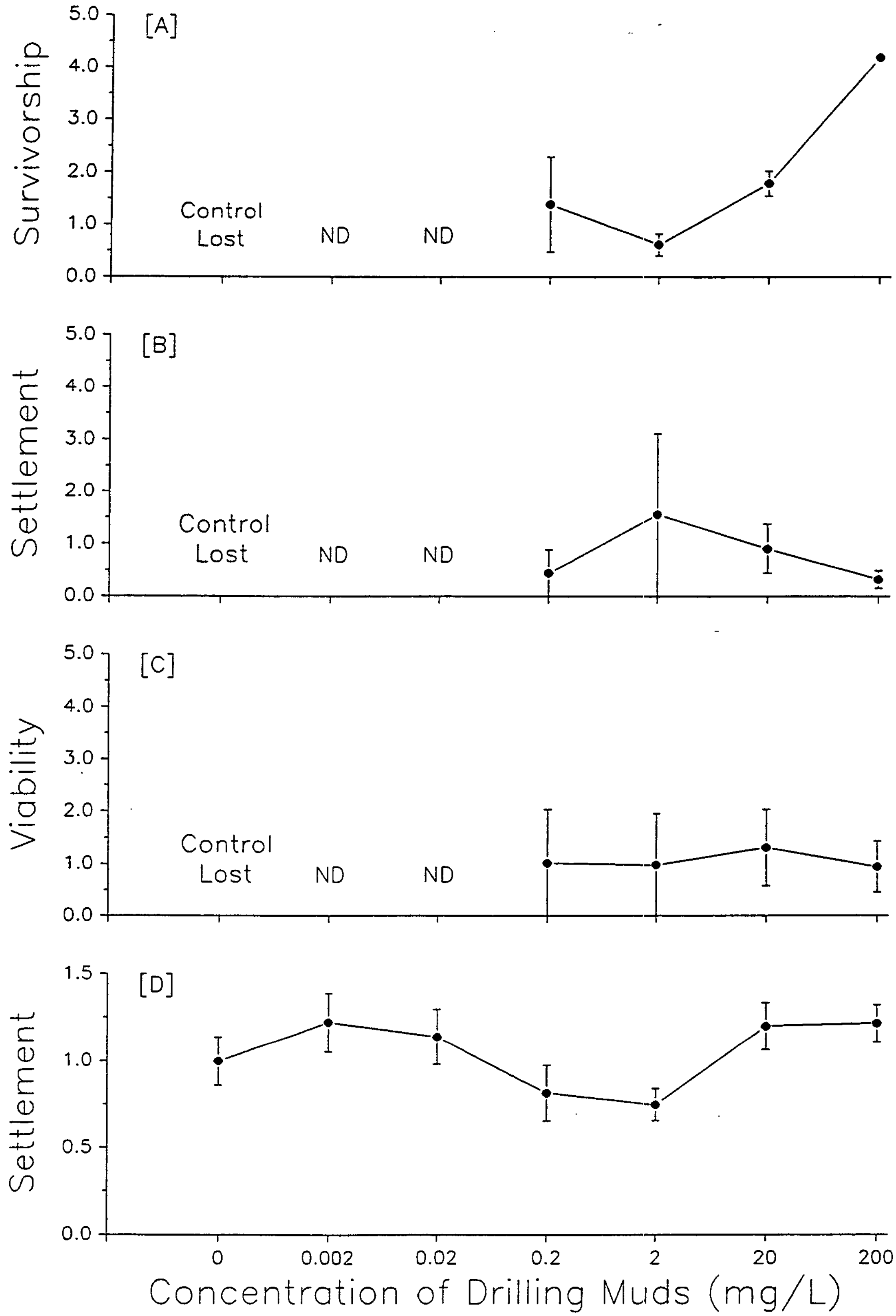
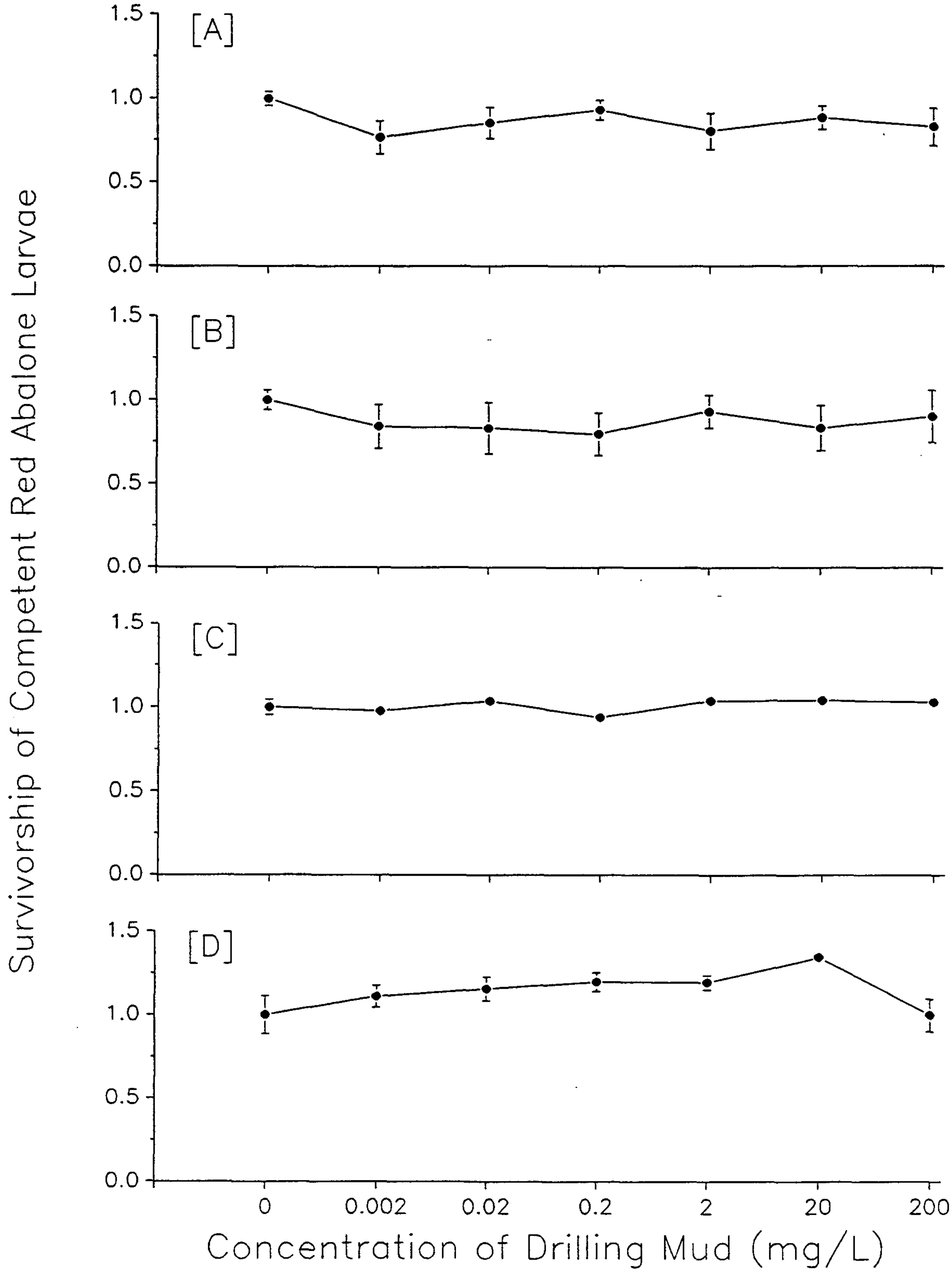
1.0
0.5
0.0
Fertilization
0
0.002
0.02
0.2
2
20
200
[B]
1.5
1.0
0.5
0.0
Development
0
0.002
0.02
0.2
2
20
200
Concentration of Drilling Mud (mg/L)

**Figure 4**



[A]
Survivorship
5.0
4.0
3.0
2.0
1.0
0.0
Control Lost
ND
ND
[B]
Settlement
5.0
4.0
3.0
2.0
1.0
0.0
Control Lost
ND
ND
[C]
Viability
5.0
4.0
3.0
2.0
1.0
0.0
Control Lost
ND
ND
[D]
Settlement
1.5
1.0
0.5
0.0
0
0.002
0.02
0.2
2
20
200
Concentration of Drilling Muds (mg/L)

**Figure 5**



Survivorship of Competent Red Abalone Larvae
[A]
[B]
[C]
[D]
1.5
1.0
0.5
0.0
0
0.002
0.02
0.2
2
20
200
Concentration of Drilling Mud (mg/L)

**Figure 6**

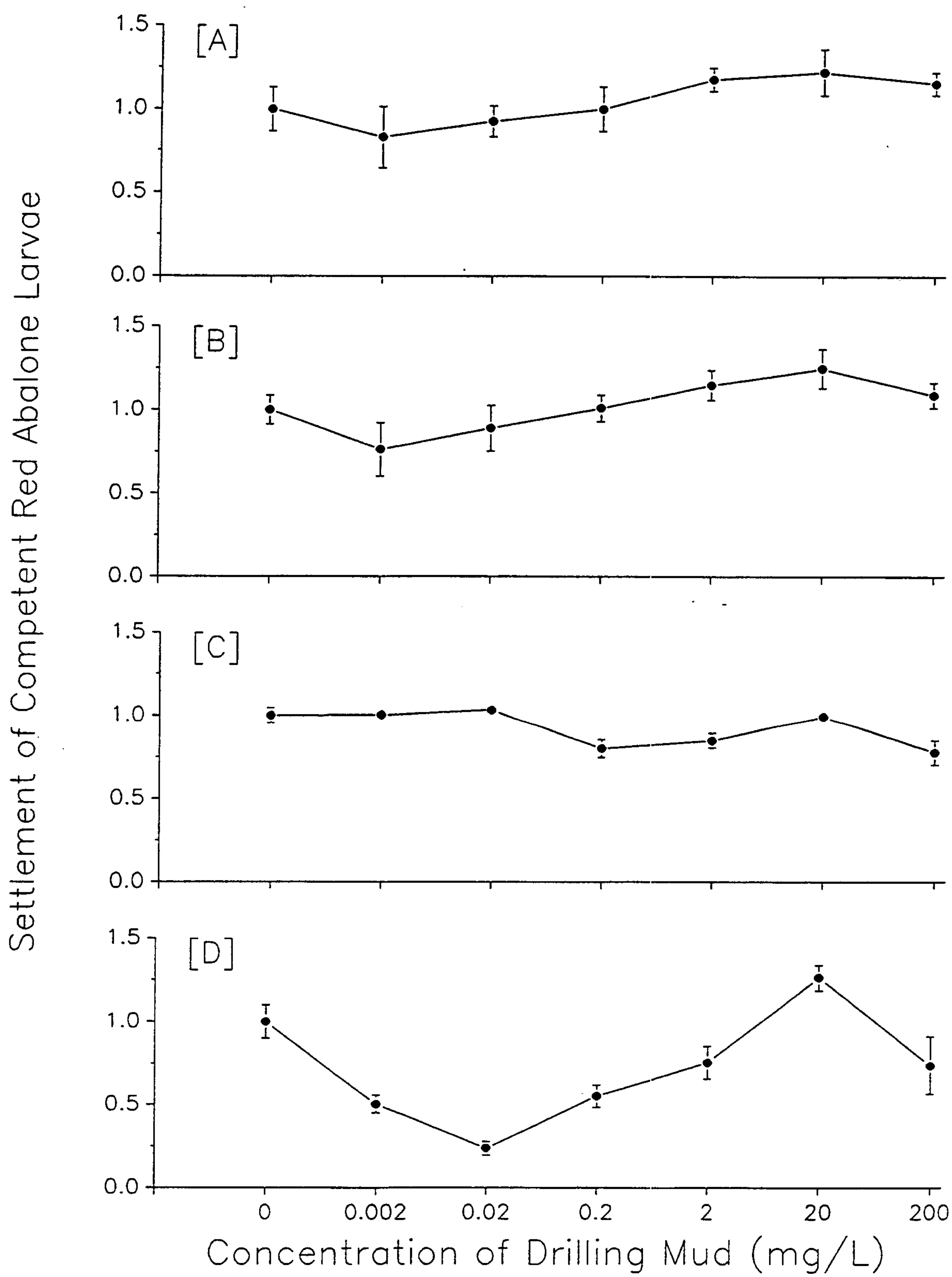

[A]
[B]
[C]
[D]
1.5
1.0
0.5
0.0
0
0.002
0.02
0.2
2
20
200
Settlement of Competent Red Abalone Larvae
Concentration of Drilling Mud (mg/L)

**Figure 7**

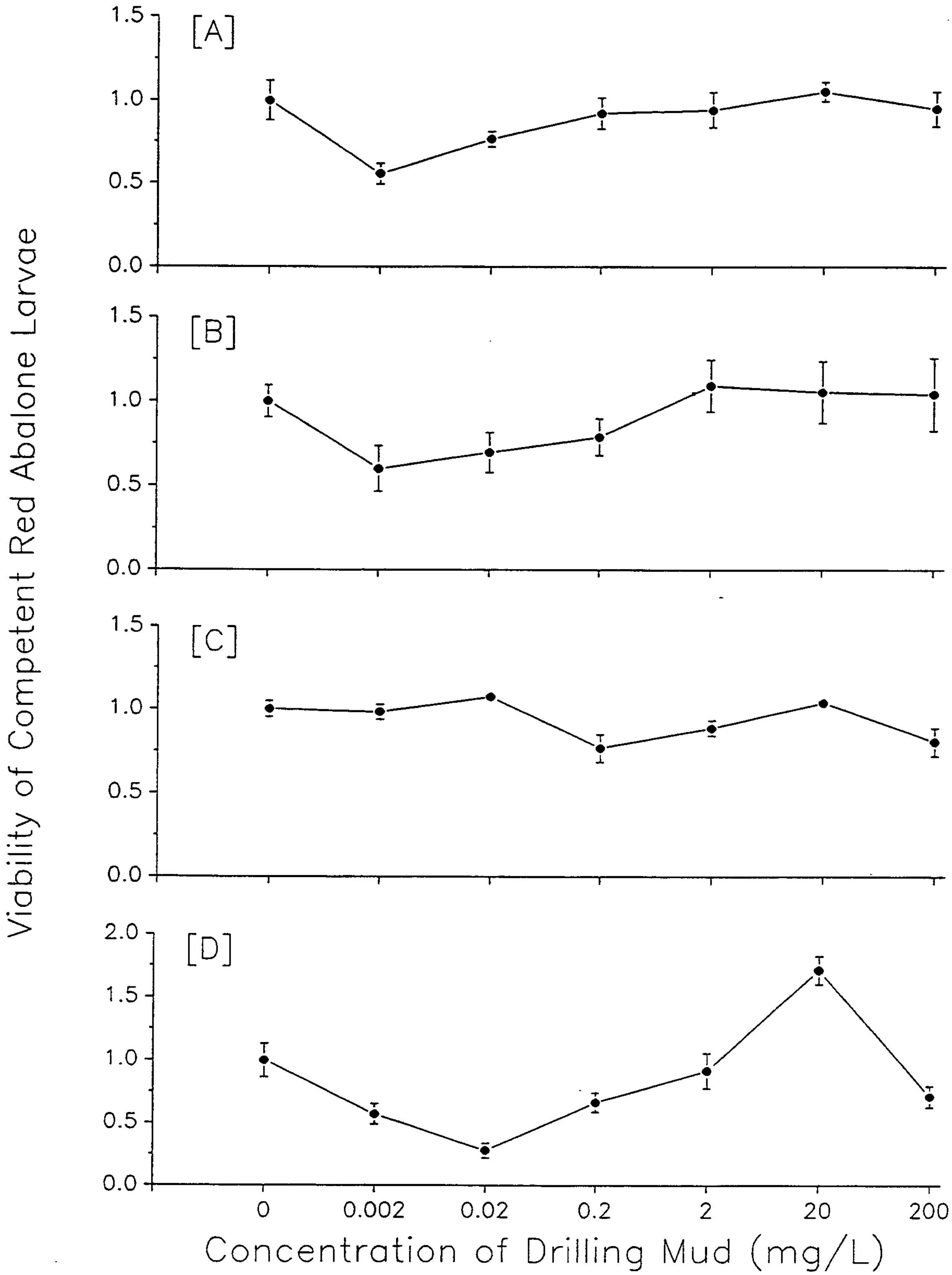
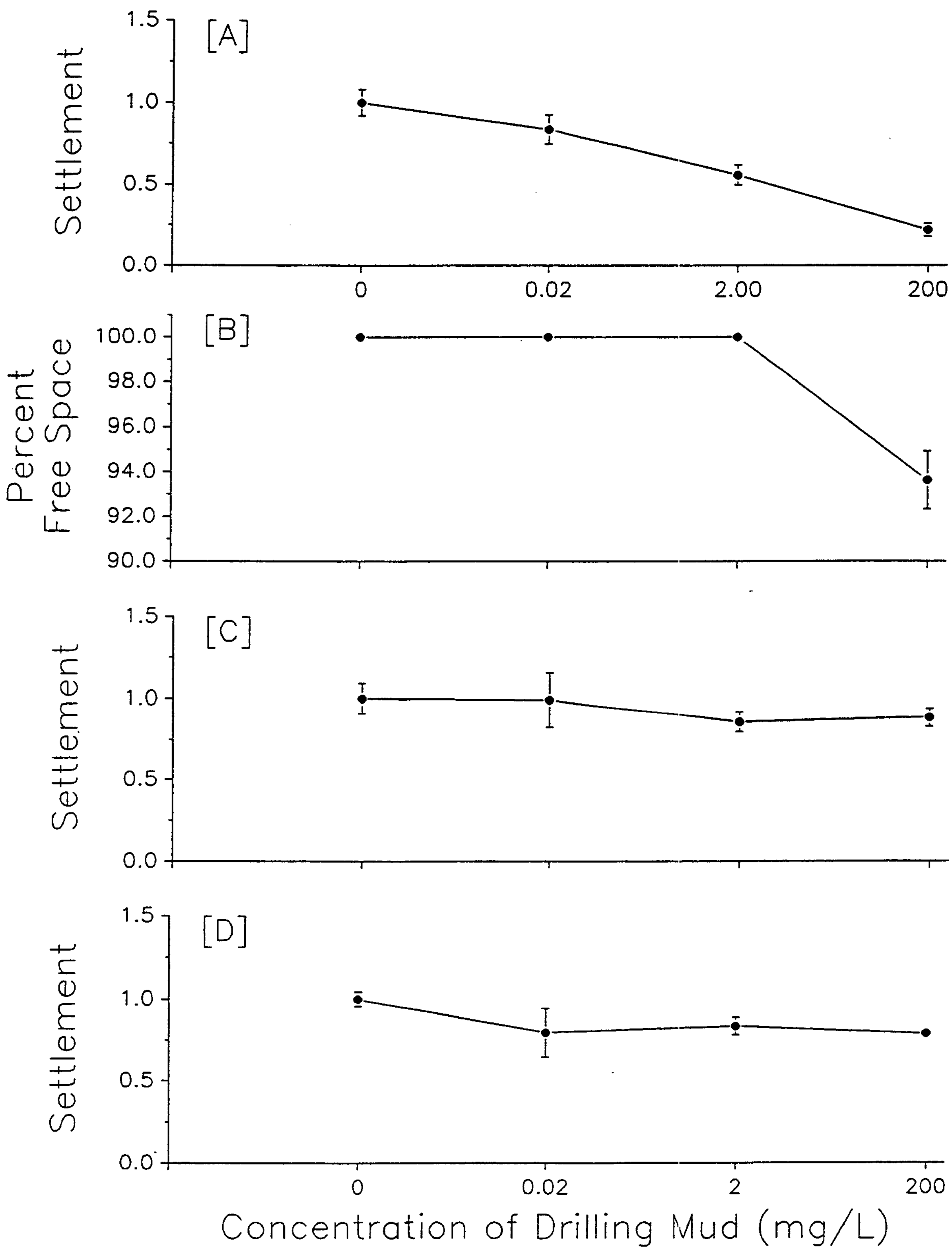
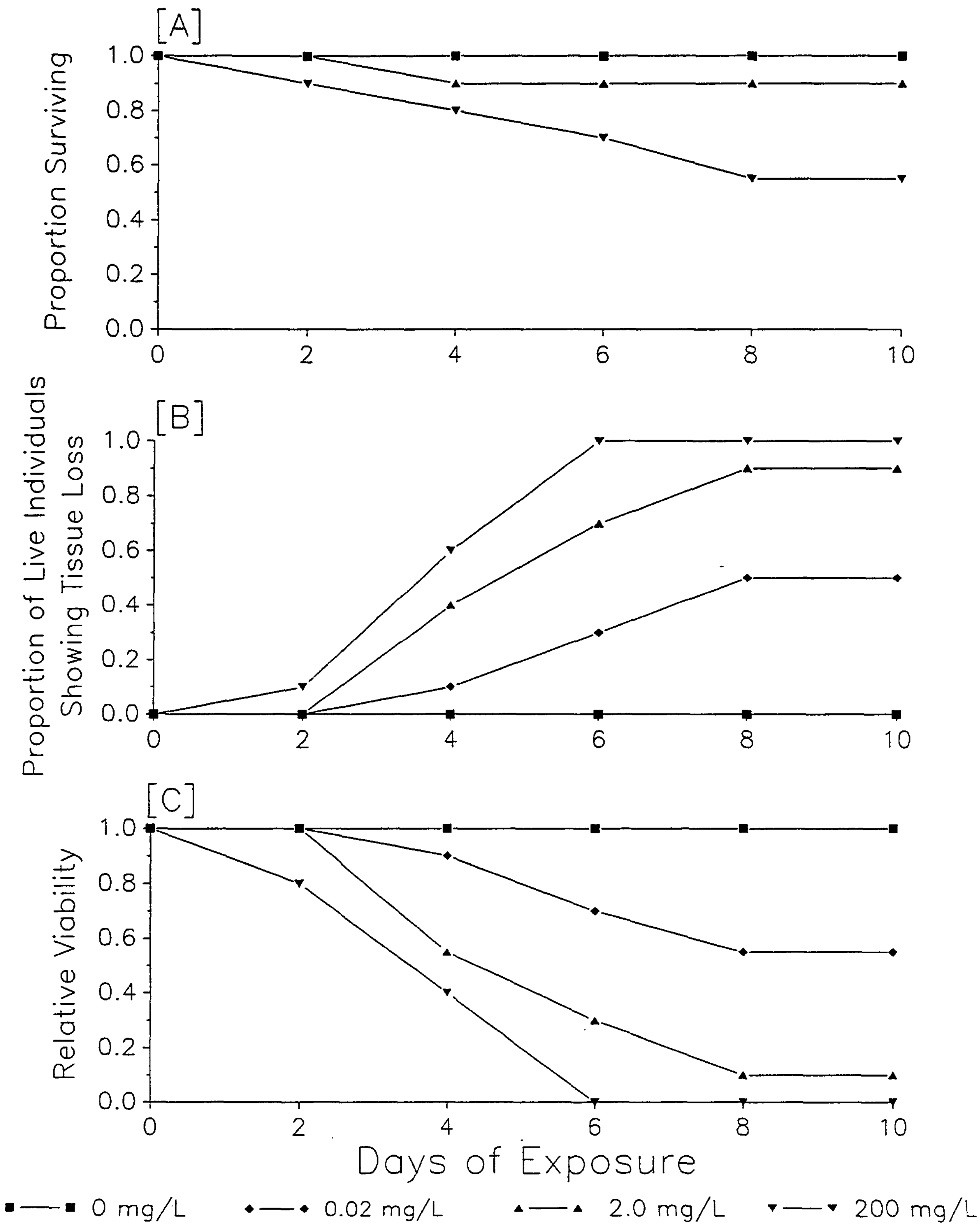

[A]
[B]
[C]
[D]
1.5
1.0
0.5
0.0
2.0
0
0.002
0.02
0.2
2
20
200
Viability of Competent Red Abalone Larvae
Concentration of Drilling Mud (mg/L)

Figure 8



[A]
Settlement
1.5
1.0
0.5
0.0
0
0.02
2.00
200
[B]
Percent Free Space
100.0
98.0
96.0
94.0
92.0
90.0
[C]
Settlement
1.5
1.0
0.5
0.0
[D]
Settlement
1.5
1.0
0.5
0.0
0
0.02
2
200
Concentration of Drilling Mud (mg/L)

Figure 9


[A]
Proportion Surviving
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
[B]
Proportion of Live Individuals Showing Tissue Loss
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
[C]
Relative Viability
1.0
0.8
0.6
0.4
0.2
0.0
0
2
4
6
8
10
Days of Exposure
0 mg/L
0.02 mg/L
2.0 mg/L
200 mg/L

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# Appendix D

# APPENDIX D

## BIOLOGICAL COMMUNITY MANUSCRIPT

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# LONG-TERM VARIABILITY OF HARD-BOTTOM EPIFAUNAL COMMUNITIES: EFFECTS FROM OFFSHORE OIL AND GAS PRODUCTION AND DEVELOPMENT

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[To be submitted to: Marine Environmental Research (Alternate, Deep-Sea Research)]

## ABSTRACT

Epifaunal communities occurring on nine deep-water reefs in the Santa Maria Basin, California were photographed over an eight year period (October 1986 to January 1994) to assess temporal and spatial variability and to determine the effects of platform discharges from offshore oil and gas production and development activities. The nine reefs varied in depth (105–212 m) and distance from Platform Hidalgo (0.5 to 6.4 km), thus representing potentially different exposures from platform discharges. The composition of these communities was strongly influenced by water depth and relief height. Over 200 taxa, dominated by cnidarian and echinoderm suspension feeders, were identified from the reefs. Hard-bottom reefs nearest Platform Hidalgo had fewer taxa with lower percentages of cover compared to the most distant reefs. However, temporal plots and linear regression of abundance (percent cover) for 24 dominant taxa provided little evidence for changes in community parameters associated with drilling periods. Thirty-five percent of the regressions showed significant (predominately negative) temporal trends for percent cover. However, an analysis of covariance (ANCOVA), which tested for changes with distance from the platform, found no consistent pattern of response for any one taxon. Further, Chi-square contingency analyses of the cumulative ANCOVA results indicated approximately equal numbers of positive and negative effects, thereby suggesting the trends could have been due to chance alone and not platform effects. Subtle or gradual long-term effects are consistent with drilling discharge impacts to some larvae and adults as indicated by companion results from in situ experiments and laboratory bioassays, respectively. Such impacts, particularly sublethal effects, may require years to be manifested and detected as changes in percent cover, especially using current, random photographic techniques alone. Long-term natural effects such as El Niño cycles and changes in biomass of macrozooplankton also may complicate these evaluations.

## INTRODUCTION

The United States Department of the Interior (DOI), Minerals Management Service/National Biological Service has been conducting multiyear environmental studies to assess the impacts of oil and gas development and production activities on the biological resources of the Pacific Outer Continental Shelf (OCS) (SAIC and MEC 1995). Biological resources at risk include soft-bottom infaunal communities, hard-bottom epifaunal reef communities, and associated fish and macroinvertebrates (Piltz 1986). This study focused on hard-bottom epifaunal reef communities, which are important because of their relative scarcity and generally unknown tolerance to platform discharges.

Recommendations for long-term studies of the Pacific OCS were first presented in MMS (1982), with site selection and reconnaissance studies (Phase I) conducted from 1983 to 1985 (SAIC 1986; Piltz 1986). Phase II and Phase III monitoring studies were performed from October 1986 to October 1990 (Brewer et al. 1991; Hardin et al. 1994; Hyland et al. 1994), and from October 1991 through January 1995 (SAIC and MEC 1993, 1995), respectively. The study sites, located in the Santa Maria Basin, off Point Arguello, California, were chosen because a mixture of soft- and hard-bottom habitats occur in the area. The sites are relatively isolated, with no major anthropogenic input sources (e.g., wastewater outfalls), and no oil or gas platform discharges prior to 1985. Development of the Point Arguello field included the installation of three production platforms, Harvest, Hermosa, and Hidalgo (Table 1). Phase II drilling operations (39 wells) began in November 1986 and continued until January 1989, and Phase III drilling operations (5 wells) occurred from September 1993 to May 1994 (Table 1). The Phase II drilling period discharged 46,084 cubic meters of drilling muds and cuttings, while substantially less material (5,547 cubic meters of muds and cuttings) was discharged during Phase III (Table 1). Because of the use of barite in drilling muds, barium concentrations provide a unique sediment and flux marker for assessing the spatial distribution, concentration, and persistence of the discharges onto nearby hard-bottom reef communities. Other metals and hydrocarbons are not present in high enough concentrations to be useful tracers (Hyland et al. 1994).

Three main types of impacts may result from oil and gas development and production activities: (1) physical alteration of the habitat; (2) discharge of potentially toxic materials; and (3) changes in flux and sedimentation rates that may affect biological processes (e.g., feeding and respiration) (Lissner et al. 1991). Physical alteration of the habitat has been documented for anchoring operations related to exploratory drilling operations (Texas A&M 1976, 1981; Ecomar 1978; Environmental Science and Engineering, Inc. 1987; Dustin et al. 1991; MEC 1995) and pipeline installations (Centaur Associates, Inc. 1984; MMS 1987; Marine Research Specialists 1992). Impacts from anchoring can include crushing and changes in the size of hard substrate, disruption and breakage of organisms and substrate, overall changes in the amount of hard substrate, and the creation of large furrows (Lissner et al. 1991; MEC 1995). These impacts differ from those caused by natural disturbances, although some fishing activities, such as trawling and dredging, may cause disturbances to soft-bottom (van der Veer et al. 1985; Butman et al. 1988; Van Dolah et al. 1991) and hard-bottom communities (Van Dolah et al. 1987; pers. obs.). Alteration of benthic habitats also can occur from the accumulation of drill cuttings and muds beneath the platform (Boesch and Robilliard 1987; SAIC and MEC 1993).

In contrast, impacts from sedimentation can occur naturally (e.g., from resuspension, slumping, and advective transport) or from anthropogenic inputs (e.g., discharge of drilling muds and cuttings, and dredge material disposal). In addition to direct effects of sedimentation (e.g., burial, smothering, and decreases in suspension feeding efficiency), which may be similar for both natural and anthropogenic inputs (Cimberg et al. 1981), there can be additional concerns associated with chronic toxicity from drilling muds and hydrocarbons. However, hard-bottom epifauna in the study area likely have some tolerance for sedimentation effects and exposure to hydrocarbons as these are natural features of the study area (e.g., natural oil seeps). Adequate knowledge of natural disturbances and the role they play in structuring communities is critical to distinguishing these natural impacts from man-induced disturbances (Lissner et al. 1991).

Hard-bottom reef communities and habitats are relatively rare in occurrence and spatial distribution along the Pacific OCS and, until recently, little was known about their natural history and ecology (SAIC 1986; SAIC and MEC 1989; Lissner et al. 1991; SAIC 1994; MEC 1995). Site specific, primarily qualitative surveys were associated with oil and gas exploration activities that occurred from the late 1970s through the mid-1980s. These studies resulted in the delineation of some hard-bottom habitats and generated preliminary data on species habitat preferences (Chambers, Consultants and Planners 1982; Dames & Moore 1982, 1983; Engineering Science 1984; Hooks McCloskey 1982; Nekton 1981; Nekton and Kinnetic Laboratories 1983; SAIC, 1986). However, most of these early efforts provided few insights into the ecology of the communities, particularly the environmental variables that affected them. Substantially more focused studies were initiated by DOI with the performance of long-term, monitoring studies of hard-bottom, epifaunal communities of the Santa Maria Basin (SAIC 1986; Steinhauer and Imamura 1990; Hardin et al. 1994; Hyland et al. 1994).

The Phase II program specifically targeted nine hard-bottom reef areas before, during, and after the production drilling phase of platform development (Steinhauer and Imamura 1990). General goals of the studies were to establish a quantitative baseline and expand the knowledge of the factors that regulate the spatial and temporal variability of these communities. Specific objectives included: (1) determine species composition and abundances of hard-bottom communities in the study area; (2) describe and determine the causes of temporal variation of these communities; and (3) determine the relationship between temporal variation in the communities and levels of contaminants associated with oil and gas development (Steinhauer and Imamura 1990).

Phase II studies included analysis of communities from high- and low-relief habitats at both shallow and deep locations within the vicinity of Platform Hidalgo (Figure 1 and Table 2). Results indicated that the distribution and abundance of hard-bottom epifauna were strongly related to water depth, vertical relief, and current orientation (Brewer et al. 1991; Hardin et al. 1994; Hyland et al. 1994). Similar results have been observed from other surveys in the study area and studies of similar communities off central and northern California (SAIC 1986; SAIC and MEC 1989; Lissner et al. 1991; MEC 1995). Four out of 22 common taxa showed significant ($p<0.05$) reductions in abundance during the drilling period (Hyland et al. 1994). These impacts were restricted to the deeper reefs (160–212 m) and were noted for three sessile suspension feeders (sabellid polychaetes, the cup coral *Caryophyllia* sp., and the tunicate *Halocynthia hilgendorfi igaboja*) and mobile, detrital-feeding galatheid crabs. There were no apparent effects to these or other species occurring on shallower reefs (105–119 m). Estimated concentrations of chemical contaminants from the drilling discharges were thought to be below toxic levels. Therefore, the observed biological changes were hypothesized to be influenced by physical effects associated with increased particle loading during the drilling phase (Parr et al. 1991; Hyland et al. 1994). These effects could be caused by disruption of suspension feeding, respiration, and/or decreased post-larval survivorship due to burial. However, no direct effects were evident from the Phase II data.

The objectives of the present study (Phase III) were to continue monitoring epifauna at the nine hard-bottom subtidal reefs surveyed for Phase II and evaluate community responses during post-Phase II drilling and Phase III drilling periods. Since the Phase III drilling period was much less than forecasted, analytical efforts focused on community responses in the post-drilling period that could be related to platform effects.

## MATERIALS AND METHODS

The study area consisted of nine, hard-bottom reefs in the vicinity of Platform Hidalgo (Figure 1). Sites were selected as part of initial Phase II studies to encompass various distances from the platform from nearfield to farfield (0.5–6.4 km), range of water depths from shallow (105–119 m), to deep (160–212 m), and low (0–1.0 m) and high (> 1.0 m) relief heights. Table 2 lists the key factors for each site and illustrates the similarities and differences between Phase II and Phase III surveys.

Sampling for Phase III was conducted in November 1991, October 1992, and January 1994. Sampling methods generally followed those of Phase II studies, and included a Remotely Operated Vehicle (ROV) equipped with a color video camera, a 70 or 35 mm still camera and strobe, two split-beam lasers for optimizing focus and standardizing the area of photoquadrats to 1 $m^2$, and a color sidescan sonar (SAIC and MEC 1995; Hardin et al. 1994). Survey navigation utilized a satellite differential Global Positioning System (GPS) interfaced with an acoustic navigational system on the ROV, thus providing positioning accuracy for the ROV of less than 3 meters. Photographs were taken with the camera angle pointed downwards in suitable, low-relief habitat. In high-relief habitat, the camera angle was oriented in a more forward (horizontal) direction. Photographs were taken randomly at approximately 30 second intervals or more, depending on substrate occurrence, thereby preventing any overlap of photographic data. Color video data, with the camera angled at approximately 45° from the bottom, were collected incidentally to the photoquadrats to document larger-scale community characteristics.

In addition to the photographic information, monitoring included documentation of sediment contaminants (Hyland et al. 1994; Phillips et al., in preparation; see Appendix B in SAIC and

MEC 1995), sediment and contaminant deposition and flux (sediment traps) (Coats 1994; Hyland et al. 1994; SAIC and MEC 1995; Phillips et al., in preparation), ocean currents (Steinhauer and Imamura 1990; Coats 1994; SAIC and MEC 1995), drilling mud toxicity (Raimondi et al., in preparation; see Appendix C-3 in SAIC and MEC 1995), and in situ bioassays and settling experiments (Raimondi et al. and Barnett et al., in preparation; see Appendices C-1 and C-2, respectively, in SAIC and MEC 1995). These studies provided data for estimating the exposure potential of the nine reefs to platform discharges.

Epifaunal photographs were analyzed by a random point-contact method using grid patterns that contained 50 points. Each photograph was projected at life size (1:1) onto a grid pattern, and the species or substrate type under each point, as well as counts of individual or solitary species, were recorded. In addition, counts of all taxa that occurred in the photograph, regardless of whether they fell under a contact point, were recorded. Because many taxa have not been previously described or were not identifiable to species, a descriptor name (e.g., "white encruster") was given in these cases. For data calculations, these latter taxa were assigned a default percent cover of 0.5 % as described for Phase II methods (Hardin et al. 1994). Percent cover estimates also were adjusted for dots that fell on shadows or soft sediments, and counts of individual organisms were normalized to the visible hard substrate in each photograph. To produce a continuous baseline and maintain consistency between studies, the Phase II epifaunal databases were acquired from DOI to demonstrate reproducibility of the Phase II results. This intensive effort was largely successful, although some taxonomic issues remain unresolved. However, the results indicate that for the common taxa, the Phase II and Phase III results can be analyzed as a continuous database (SAIC and MEC 1995).

Multivariate classification analysis using the 50 most numerically dominant taxa was used to delineate the major features of the study area. The analysis utilized the mean percent cover for each taxon for the eight-year (i.e., combined Phase II and Phase III) study period. The data were square-root transformed and normalized to the standard deviation before calculation of Bray-Curtis distances (Bray and Curtis 1957) to keep the most abundant taxa from dominating the analysis. The Bray-Curtis dissimilarity coefficient and flexible sorting strategy (ß= -0.25) was used to cluster the data (Smith 1976, Tetra Tech 1985). Both normal (sites) and inverse (species) analyses were conducted and plotted as dendrograms. A two-way coincidence table with dendograms was produced to aid in interpretation of the cluster results and to provide insights on the defining, physical features of the communities. The analysis was run using SAS Version 6 (SAS 1990).

To evaluate potential relationships among biological parameters and physical measurements, correlation coefficients (Pearson product moment) were calculated for dominant taxa and physical and chemical measurements from sediment flux traps near each hard-bottom site. Sediment parameters consistently measured and/or detected included 11 metals; Ag, As, Ba, Cd, Cr, Cu, Hg, Ni, Pb, Va, and Zn; percent clay; percent fines (silt + clay sediment fraction); median size of flux particles; flux rate ($mg/m^2/day$); and total organic carbon.

Potential long-term (e.g., sublethal) effects were evaluated by plotting, visual analysis, and linear regression of temporal trends in percent cover for 24 dominant taxa. The regressions were performed for 3 habitats (deep high- and low-relief and shallow low-relief; see below) by taxon, representing 72 combinations of temporal patterns.

To test for differences in abundance trends as a function of distance from Platform Hidalgo, an analysis of covariance (ANCOVA) was performed on percent cover of dominant taxa by survey. The covariate in the analysis was distance from Platform Hidalgo (nearfield, midfield, and farfield) for the hard-bottom sites. This required three sets of analysis for each of the 20 dominant taxa at deep high-relief, deep low-relief, and shallow low-relief sites. Too few data were available for shallow high-relief sites for them to be tested. The null hypothesis for the ANCOVA was that changes in percent cover for dominant taxa by habitat type were independent of distance from Platform Hidalgo. Significant differences between sites nearest Platform Hidalgo (nearfield) compared to sites farthest away (farfield) would reject the null hypothesis and suggest a possible platform effect. Effects were indicated when the rate of change in percent cover for the nearfield site was significantly different from the farfield site. Effects were interpreted to be positive when the nearfield site had increasing percent cover or less rapid decreases compared to decreases at farfield site. Positive effects were also indicated if the percent cover at the nearfield site increased significantly faster than the increase at the farfield site. Platform effects were interpreted as negative when percent cover at the nearfield site decreased faster than decreases at the farfield site. Negative effects were also indicated when percent cover at the nearfield decreased or increased more slowly than increases at the farfield site. When there were no significant differences between the nearfield and farfield sites, the results were interpreted as being inconsistent with a platform gradient effect and were assigned a 0 value. When the survey x distance interaction was nonsignificant no further testing was appropriate.

Determination of the statistical power to detect changes in mean values is important for assessing the significance of the study results. Power analysis was based on Taylor's Power Law for comparison between two sample means of a given variable (Green 1989). An appropriate comparison might be between two sites at a given time or between two sampling periods. Comparisons between sites for the pre-drilling phase were conducted in Phase II (Hyland et al. 1994). For Phase III, comparisons of pre-drilling with post-drilling abundances provided an estimate of statistical power for the dominant taxa by comparing the mean percent cover for the first two surveys of Phase II (October 1986 and May 1987, considered a baseline or pre-drilling phase) and the mean of six post-drilling surveys (Phase II = May and October 1989, and October 1990, and Phase III = November 1991, October 1992, and January 1994). The analysis focused on the occurrence of significant decreases in percent cover for the post-drilling surveys since this would be representative of a negative platform effect. For those taxa having significant decreasing temporal trends in the post-drilling surveys, the data were detrended. This did not affect mean values but generally reduced the variance estimate for the post-drilling period. The results are presented in two forms: (1) the actual power ($1-\beta$, $\alpha=0.05$) in percent, and (2) as the size decrease in the mean that would be detectable with a power of 80% ($\beta=0.2$).

## RESULTS

### Biology of Hard-Bottom Reefs

A total of 4,438 photographs from eight surveys were analyzed for Phase II, and 2,032 photographs over three surveys were analyzed for Phase III. From these photographs, 216 and 220 taxa (including qualitative descriptions, e.g., "sponge, tan encrusting") were identified from Phase II and Phase III, respectively. The combined phases yielded 286 separate taxa. This estimate of diversity is conservative because most small encrusting taxa (e.g., sponges, tunicates, and ectoprocts) cannot be identified to species from the photographs. To overcome difficulties in identifying organisms from photographs, and to achieve consistency between the Phase II and III surveys, some taxa were consolidated into gross taxonomic groups (e.g., galatheid crabs).

Classification analysis showed that water depth was the most significant determinant of community structure. This finding is consistent with other studies of hard-bottom (e.g., Vinogradova 1962; Rowe and Menzies 1969) and soft-bottom communities (Thompson et al. 1993; Diener et al. 1995) (Figure 2). For example, Sites PH-K (160 m) and PH-N (166 m) were more similar to the other two deep sites [PH-R (212 m) and PH-W (195 m)] than to any of the five shallow sites. However, there also is an indication that distance from Platform Hidalgo was an important determinant of community organization. The arrangement of site clusters provides evidence for a gradient in reef communities relative to Platform Hidalgo (Figures 1 and 2). Thus, Sites PH-E, PH-I, and PH-J can be considered shallow nearfield sites, Site PH-F shallow midfield, Site PH-U shallow farfield, Sites PH-K and PH-N deep nearfield, Site PH-R deep midfield, and Site PH-W deep farfield (Figure 2). This classification is consistent with estimated exposures from drilling mud (high, medium, and low dosage) of the same sites from the Phase II drilling period (Table 2; Coats 1994; Hyland et al. 1994).

The depth preference (occurrence) of the 50 most dominant taxa was evident from the two-way table (Figure 2) and a rank of the taxa by mean percent cover (Table 3). Based on Figure 2, taxa with a preference for the shallow site depths are represented by the first 10 taxa (*Rathbunaster californicus* – a seastar – to *Paracyathus stearnsii* – a cup coral); taxa preferring the deeper sites encompass the next 11 taxa (*Lophelia pertusa* – a colonial coral – to *Swiftia kofoidi* – a small gorgonian); taxa found at all depths are considered ubiquitous, as represented by the next 14 taxa (*Pyura haustor* – a tunicate – to "sponge-tan encrusting"); and the remaining 14 taxa (*Laqueus californianus* – a brachiopod – to "sponge-shelf") generally had highest coverage at the two deepest sites (PH-R and PH-W). Within these species clusters additional patterns are related to depth and distance from Platform Hidalgo. For example, some shallow site taxa (e.g., the seastars *R. californicus* and *Mediaster aequalis*) have higher mean percent cover at nearfield sites, while other taxa (e.g., *Octopus* sp., the seastar *Stylasterias forreri*, and the cup coral *P. stearnsii*) have higher coverage at farfield sites. This gradient in cup coral distribution is intriguing since adults of this species have been shown to be sensitive to laboratory exposures of drilling muds from Platform Hidalgo (Raimondi et al., in preparation; see Appendix C-3 in SAIC and MEC 1995). Taxa associated primarily with the deeper sites also showed some trends consistent with a platform gradient (Figure 2). For example, the six taxa from *L. pertusa* to "anemone-white disc with purple tentacles" and the eleven taxa from "ascidian-blue grey encrusting" to "sponge-shelf" prefer the two deepest, farfield sites, PH-R (212 m) and PH-W (195 m). In contrast, the three taxa from *L. californianus* to "anemone-tan zoanthid" showed the opposite pattern with a preference for the two deep nearfield sites, PH-K (160 m) and PH-N (166 m).

A second cluster analysis included relief height for the nine hard-bottom sites (Figure 3). These results also indicate the important influence of relief height on community composition, especially at the shallow sites. Variation in relief height of as little as one meter can have a profound influence on community composition. The site dendrogram for the shallow sites shows that both relief height and distance from Platform Hidalgo affect community composition, with relief height being the more important factor. Shallow nearfield sites PH-E, PH-I, and PH-J tended to be more similar to each other than to the other sites farther from Platform Hidalgo. However, the two-way table indicates that these distinctions are subtle since most shallow reef taxa had their highest percent cover in the low-relief habitat, and no taxa showed a strong preference for shallow, high-relief habitat.

Most of the 50 dominant taxa showed a preference for a particular water depth and/or relief height (Figure 3 and Table 4). In addition to the 10 taxa discussed above (Figure 2), inclusion of relief height adds three more taxa, *Phidolopora pacifica* and *Cellaria* sp. (ectoprocts or bryozoans), and the cup coral *Caryophyllia* spp., that prefer shallow reefs. Most of the shallow water taxa preferred low relief, although this may be a partial artifact of sampling since the shallow reef sites had little high relief. Three ahermatypic cup corals (*Balanophyllia elegans*, *P. stearnsii*, and *Caryophyllia* spp.) clearly preferred shallow reefs with low-relief habitats (Tables 3 and 4). *Balanophyllia* and *Paracyathus* were rare at the deeper reefs, while *Caryophyllia* spp. was fairly common at the deeper depths and high-relief habitat. This habitat preference is somewhat surprising since sediment fluxes were almost twice as high at shallow (30-80 g/m$^2$/day) compared to deep sites (24-40 g/m$^2$/day) and fluxes for high relief (18 g/m$^2$/day) were a little more than half that for low-relief habitat (30 g/m$^2$/day) (Parr et al. 1991, SAIC and MEC 1993; Phillips et al., in preparation; see Appendix B in SAIC and MEC 1995). This suggests that these cup corals may be naturally adapted to high amounts of sediment resuspension and suspended particle flux.

The ubiquitous taxa were dominated by echinoderms, including total ophiuroids, the ophiuroids *Ophionereis* sp. and *Ophiacantha diplasia*, and the crinoid *F. serratissima* (Figure 3). Of the seven taxa in this cluster, only one is sessile (gorgonian) suggesting that large, relatively mobile taxa may have broader habitat tolerances than attached taxa. Seven taxa showed a preference for high-relief habitat, with six of these characterized by patterns that were independent of water depth. *Desmophyllum dianthus* (formerly known as *D. crista-galli*), an ahermatypic cup coral, was found most commonly at deep high relief sites. Other taxa preferring high-relief habitat included the colonial ahermatypic coral (*Lophelia pertusa*; formerly known as *L. californica*), an anemone (*Metridium giganteum*; formerly called *M. senile*), white encrusting organisms, sponge-tan encrusting, and a seastar (*Peridontaster crassus*). The remaining 23 taxa preferred the deeper sites with eight of these taxa primarily occurring at the deepest sites (PH-R and PH-W). Thirteen of these taxa are exclusively hard-bottom epifauna, including two tunicates (*Pyura haustor* and "blue-gray ascidian"), total Polychaeta, a brachiopod (*Laqueus*), basket star (*Gorgonocephalus eucnemis*), three sponge taxa, five anthozoans, including four anemones (*Amphianthus californicus*, anemone "tan zoanthid", anemone "white disc purple tentacles", and *Stomphia didemon*), and a small gorgonian (*Swiftia kofoidi*).

Overall patterns from Figure 3 indicate that shallow, low-relief nearfield sites (PH-E, PH-I, PH-J) were more similar to each other than to the midfield (PH-F) or farfield sites (PH-U). For the deep sites, midfield and farfield sites PH-R and PH-W were most similar to each other based on relief height (high relief). Nearfield sites PH-K (high relief) and PH-N (low relief) showed strong similarities independent of relief height. Site PH-K (low relief) was different from other deep, low-relief sites. This relationship also is influenced by the lack of low-relief data from PH-K during Phase II, and the observation that most of the deep-water taxa at this site have lower abundances than for other comparable sites (Figure 3).

The mean number (listed in parentheses) of taxa per photograph was higher for deep (20.7) compared to shallow (15.6) sites, and was also higher for high-relief (22.0) compared to low-relief (16.8) habitats (Table 5). Thus, deep, high-relief habitats are characterized by more diverse and abundant biota than shallow, low-relief habitats. Similar trends were observed for percent cover of the 20 most dominant organisms by depth and relief height categories (Tables 3 and 4). The range in mean number of taxa (16.0 to 16.3) per photograph for shallow sites was almost identical for far-, mid-, and nearfield sites (Table 5). Deep, nearfield sites had somewhat fewer taxa (18.4) compared to midfield (20.8) and farfield (23.0) sites. This gradient for deeper sites was evident for both low- and high-relief habitats.

Mean percent cover for all taxa at the shallow low-relief sites was intermediate at the farfield site (29.4%), lowest at the midfield site (26.1%), and highest at the nearfield sites (30.7%) (Table 6). For the deep sites, total percent cover was lowest for the nearfield sites (37.9%), intermediate for the midfield site (43.7%), and highest at the farfield site (45.1%). These differences were not statistically significant; however, the results indicate that the deep reefs nearest to Platform Hidalgo have a lower density of taxa with less percent cover than observed for reefs farther away. These gradients and possible effects from Platform Hidalgo are discussed below.

The 20 most abundant taxa are listed by depth category (shallow versus deep) and by relief height (low versus high) in Tables 3 and 4, respectively. Different taxa dominate all four categories, including total ophiuroids, total white encrusters, *F. serratissima*, *O. diplasia*, galatheid crabs, *M. giganteum*, sponge-tan encrusting, *H. hilgendorfi*, *P. haustor*, and gorgonian-red or pink. The dominant phyla are cnidarians (44%), echinoderms (16%), and Porifera (12%) with the remaining five phyla combined accounting for 28% (Urochordata-8%, Arthropoda-8%, Brachiopoda-4%, Ectoprocta-4%, and annelid polychaetes-4%). Table 7 lists the overall rankings of the dominant taxa by habitat type.

Correlations of percent cover of dominant taxa with sediment flux trap parameters were examined to help define possible mechanisms for observed trends. Significant correlations were found for 13 of the 16 parameters measured, the most important of which included percent clay (43% of the dominant taxa correlated with this parameter), cadmium (38%), size of flux particles (33.3%), copper (28.6%), flux rate and total organic carbon (23.8%), and percent fines, mercury, and nickel concentration (19% each). No significant correlations were found for silver, lead, and vanadium. The remaining parameters (arsenic, barium, chromium, and zinc) were correlated less than 14% of the time with dominant taxa. Generally, correlations were negative with percent clay, percent fines, and flux rate, but usually were positive with the other parameters. These results suggest that fine particles and high sediment fluxes may be detrimental for filter and suspension feeding organisms. This would be consistent with reduced feeding efficiency and/or clogging of filtering structures for these biota. The generally positive correlations with metals suggest that toxicity (as often associated with metal contaminants) is not a significant factor for the dominant taxa.

## Trends in Dominant Biota

The relative dominance (rank order) of the most common epifauna has remained generally consistent over the eight year study period. Temporal plots and linear regression of mean percent cover by phylum and dominant taxa were used to illustrate the range of changes observed during the study and aid in visualizing the relationships to drilling periods (Figures 4-11). Further, ANCOVA results were applied to statistically evaluate survey x distance (from the platform) trends.

### Cnidaria

Cnidarians (anemones, corals, and gorgonians) were the most conspicuous biota observed during both phases, exhibiting a preference for deep (11.8%) versus shallow (8.0%) sites and high-relief (15.8%) versus low-relief habitat (6.8%). Decreasing temporal trends in percent cover were observed for deep, high- ($p=0.07$, $r^2=0.26$) and low-relief habitats ($p=0.06$, $r^2=0.28$). In contrast, no significant trends were evident for shallow low-relief habitats (Figure 4). To determine if the decreases coincided with the Phase II drilling period, the temporal plots were evaluated for nearfield and farfield, deep sites (Figure 5). ANCOVA results for all cnidaria combined indicated positive (enhancement) effects for deep high- and low-relief habitats, based on increasing percent cover for nearfield sites and decreasing trends for the farfield site. The opposite pattern was indicated for the shallow low-relief habitat suggesting a negative platform effect.

Of the 21 dominant taxa (based on percent cover), ten were cnidarians including five cup corals, four anemones, and a gorgonian (Table 7). All the cup corals showed specific habitat preferences, with *B. elegans, Caryophyllia*, and *P. stearnsii* preferring shallow low-relief habitats, and *D. dianthus* and *L. pertusa* preferring deep high-relief habitats. No significant temporal trends or correlations were found between *B. elegans* and the 16 sediment flux parameters. ANCOVA results indicated that for deep high-relief habitats, percent cover at the nearfield site (PH-K) decreased significantly faster than at farfield (PH-W) and midfield (PH-R), suggesting a negative platform effect (Table 8). In contrast, a positive effect was indicated for shallow low-relief habitat where percent cover at the farfield site (PH-U) decreased significantly faster than at nearfield sites (PH-J, PH-I, and PH-E). For deep low-relief habitats there was no significant survey x distance interaction. *Caryophyllia* spp. had significant decreasing temporal trends for deep high-relief ($r^2$=0.42) and deep low-relief habitats ($r^2$=0.73) (Figure 6). For low-relief habitats, *Caryophyllia* had significant correlations with four sediment flux measurements (Cu $r^2$=0.37, Ni $r^2$=0.43, % clay $r^2$= -0.34, flux rate $r^2$=0.40). ANCOVA results for *Caryophyllia* showed a negative platform effect for deep high- and low-relief habitats (i.e., percent cover for nearfield sites decreased significantly faster than the farfield site and there was no significant survey x distance interaction for shallow low-relief habitat) (Table 8 and Figure 6). *Caryophyllia* generally was not found on low-relief habitats near Platform Hidalgo. *P. stearnsii* exhibited a significant decreasing temporal trend for all habitats (deep high-relief $r^2$=0.63, deep low-relief $r^2$=0.75, and shallow low-relief $r^2$=0.46) and was significantly correlated with two sediment flux parameters (Ni $r^2$=0.37 and % clay $r^2$= -0.32). ANCOVA results indicated no significant difference between near- and farfield sites for deep high-relief habitat, possible negative platform effect for deep low-relief habitats, and no significant survey x distance interaction for shallow low-relief habitat.

No significant temporal trends were noted for the two deep high-relief corals. Percent cover for *D. dianthus* was significantly correlated with four flux parameters (As $r^2$= -0.50, Cr $r^2$= -0.55, Zn $r^2$= -0.51, and flux rate $r^2$= -0.53), while *L. pertusa* correlated only with As ($r^2$= -0.46). For *D. dianthus*, there was a positive platform effect for deep high-relief habitats (Table 8). For *L. pertusa*, a negative platform effect was indicated for shallow low-relief habitats. In summary, for the five cup corals, ANCOVA results showed two positive effects, one with no significant difference between near- and farfield, five negative effects, and seven non-significant survey x distance interactions (Table 8). In the preferred habitat of these species, based on percent cover, there were two positive and three non-significant survey x distance interactions. In contrast, in less preferred habitats there was one non-significant difference between near- and farfield, five negative effects, and four non-significant survey x distance interactions. These results suggest that proximity to the platform may be beneficial for a species in its preferred habitat but detrimental in less preferred habitats.

For anemones, decreasing temporal trends at deep low-relief habitats were observed for two of the four species, *Amphianthus californicus* ($r^2$=0.25) and *Stomphia didemon* ($r^2$=0.41). These anemones prefer high-relief habitat and, except for *Metridium*, prefer deeper habitat. *Metridium giganteum*, the tallest (e.g., to 1 m) West Coast anemone, was the second most dominant species over all depths and relief heights. *M. giganteum* preferred shallow (2.11%) versus deep (1.39%), and high (2.36%) versus low (1.23%) sites. The preference for high-relief habitat was more evident for shallow sites (high, 5.48%; low, 1.29%) than for deep sites (high, 1.68%; low, 1.16%). Nearfield sites had higher percent cover (2.74%) than midfield (0.62%) or farfield (0.72%). The percent cover variance estimates for this species was high (Tables 3 and 4), probably reflecting its patchy distribution and ability (at least by a congener) to detach and drift to new areas (Wahl 1985). *M. giganteum* was not significantly correlated with sediment flux parameters. ANCOVA results indicated no significant difference between near- and farfield sites for deep high-relief habitats (Figure 7) and a negative effect for shallow low-relief habitats (Table 8). *A. californicus* was significantly correlated with three sediment flux parameters (Zn $r^2$= -0.48,

% fines $r^2$= -0.50, and TOC $r^2$=0.75). ANCOVA analysis showed positive platform effects for deep high- (Figure 7) and low-relief habitats. Anemone "tan zoanthid" was not significantly correlated with sediment flux parameters. ANCOVA analysis indicated positive platform effects for deep high-relief and shallow low-relief habitats. *S. didemon* was significantly correlated with five sediment flux parameters (Cd $r^2$=0.56, % clay $r^2$= -0.80, flux rate $r^2$= -0.52, median flux size $r^2$=0.60, and TOC $r^2$=0.75). ANCOVA found no significant difference between near- and farfield sites for deep high- and low-relief habitats. In summary, based on ANCOVA, four positive platform effects, three results indicating no difference between near- and farfield sites, three non-significant survey x distance interactions, and only one negative effect were observed for the four anemone taxa (Table 8). These results suggest that these anemones may generally benefit from closer proximity to the platform.

The small unidentified pink gorgonian, possibly a species of *Lophogorgia*, also showed positive platform effects for deep high- and low-relief habitat. In summary, for the ten cnidaria, ANCOVA results indicated eight positive and seven negative effects. In preferred habitats there were five positive and no negative effects, while in less preferred habitats there were three positive and seven negative effects.

Echinodermata

Echinoderms were the second most abundant taxonomic group, representing the dominant biota at some sites. Many seastars were easily identifiable from photographs, while speciating the ophiuroids was more difficult. To ensure that taxonomic limitations did not influence the analysis, the ophiuroids were combined into an "all ophiuroids" group; this was the dominant taxon for all habitats (Table 7). Ophiuroids had a significant decreasing temporal trend for percent cover only at shallow low-relief habitats ($r^2$=0.55). Significant correlations were found between percent cover of ophiuroids and six sediment flux parameters (Cd $r^2$=0.47, Cu $r^2$=0.44, Hg $r^2$=0.40, % clay $r^2$= -0.45, % fines $r^2$= -0.48, and median flux size $r^2$=0.47). ANCOVA analysis indicated a positive platform effect for deep high-relief habitats and a negative effect for shallow low-relief habitats (Table 8).

The dominant echinoderm species (based on percent cover) was the crinoid, *Florometra serratissima*. This species was almost equally abundant at the two depth categories (shallow, 2.48%; deep, 2.59%), but preferred low relief (low, 2.85%; high, 1.73%), and showed an increasing temporal trend for deep high-relief habitat ($r^2$=0.42) (Figure 8). For shallow low-relief sites percent cover was highest in the nearfield (3.92%), intermediate at midfield (1.15%), and lowest at farfield (0.50%) locations. For deep sites, no consistent gradient was evident. High-relief habitat had the highest percent cover (3.19%) at nearfield sites and lowest values (0.61%) at midfield. For low-relief habitat, the highest percent cover (4.75%) was at midfield and the lowest (2.24%) was at nearfield sites. There were no significant correlations with sediment flux parameters. ANCOVA results showed a negative platform effect for deep high-relief habitat (Figure 8 and Table 8).

Porifera

Sponges are another important component of the hard-bottom epifaunal community but, similar to many of the smaller taxa, are difficult to identify from photographs. Percent cover for all sponges combined was highest for deep high-relief habitats. A significant decreasing temporal trend was observed only for deep low-relief habitats ($r^2$=0.23). Sponges had significant correlations with seven flux parameters (Cd $r^2$=0.56, Cu $r^2$=0.50, Hg $r^2$=0.31, % clay $r^2$= -0.48, flux rate $r^2$= -0.38, median flux size $r^2$=0.42, and TOC $r^2$=0.63). ANCOVA analysis indicated positive platform effects for all three habitat types. For "total white encrusters" (a conglomerate grouping of all small, encrusting organisms including sponges, tunicates, and ectoprocts that were white in color), there was a preference for deep high-relief habitat but only the shallow low-relief habitat had a significant decreasing temporal trend for percent cover ($r^2$=0.55). Total white encrusters were significantly correlated with seven sediment flux parameters (Cd $r^2$=0.67, Cu $r^2$=0.62, Hg $r^2$=0.35, Ni $r^2$=0.40, % clay $r^2$= -0.47, median flux size $r^2$=0.46, and TOC $r^2$=0.56). ANCOVA analysis showed a positive effect for all three habitats; Figure 9 depicts the trends for deep high-relief habitats. "Tan encrusting sponge" showed a significant decreasing temporal trend for the shallow low-relief habitat ($r^2$=0.42) and significant (predominantly negative) correlations with eight sediment flux parameters (Ag $r^2$= -0.54, Ba $r^2$= -0.58, Cd $r^2$= -0.63, Cu $r^2$= -0.73, Ni $r^2$= -0.55, Zn $r^2$= -0.53, % clay $r^2$=0.63, and median flux size $r^2$=0.68). ANCOVA analysis indicated a negative platform effect for shallow low-relief habitat and a positive effect for deep high-relief habitats. "Shelf" sponges had a significant decreasing temporal trend only for deep low-relief habitats ($r^2$=0.49) and two significant correlations with flux parameters (% clay $r^2$= -0.34 and median flux size $r^2$=0.38). ANCOVA analysis identified a positive platform effect for deep high-and shallow low-relief habitats. In summary, for the three taxa there were six positive and one negative effect suggesting that sponges may benefit from close proximity to the platform.

Brachiopoda

The brachiopod, *L. californianus*, was relatively common in all habitats in the study area and is easily identified from photographs, thus representing a good species for assessing temporal trends and patterns relative to Platform Hidalgo. This species had significant decreasing temporal trends in percent cover for all habitats (deep high-relief $r^2$=0.45, deep low-relief $r^2$=0.92, and shallow low-relief $r^2$=0.68) (Figure 9) but was significantly correlated with only three flux parameters (Ba $r^2$=0.54, Cd $r^2$=0.59, and % fines $r^2$= -0.69). ANCOVA showed a negative platform effect for deep and shallow low-relief habitats (Table 8).

Urochordata

Tunicate species are common on hard substrate but most are difficult to identify from photographs. Tunicates had a slight preference for deep high-relief habitat and ANCOVA results indicated a positive effect for deep high-relief and a negative effect for deep low-relief habitat (Table 8). The solitary tunicate *Pyura* sp. had significant negative temporal trends for all three habitats ($r^2$=0.40–0.45). ANCOVA results indicated a positive effect for deep high-relief habitat and negative effects for deep and shallow low-relief habitats. *Halocynthia*, a large colonial tunicate had one significant negative temporal trend for deep low-relief habitat ($r^2$=0.40). ANCOVA results indicated negative effects for deep high- and low-relief habitats (Table 8). Tunicates, unlike the sponges, had more negative than positive effects.

**Four Taxa Characterized by Phase II Drilling Period Effects**

The Phase II study identified four dominant taxa, *Caryophyllia*, galatheid crabs, the tunicate *H. hilgendorfi*, and sabellid polychaetes, that displayed significant, negative responses to drilling mud discharges (Hyland et al. 1994). Except for *Caryophyllia*, which also had a significant survey x dose interaction for deep high-relief habitats, these effects were restricted to deep water, low-relief sites. No other potential negative effects on reef epifauna related to drilling phases were suggested from the Phase II studies. Temporal plots of these taxa by distance from Platform Hidalgo (as related to drilling mud dose; Table 2) are presented to evaluate the potential relationship to Phase II and Phase III drilling phases (Figures 6, 10, and 11; note that "Sabellidae" are included in the "Polychaeta" data in Figure 11). The cup coral *Caryophyllia* spp., had the lowest percent cover at deep nearfield (0.51%), was intermediate at midfield (0.64%), and highest at farfield sites (0.80%) for Phase II and III. As noted above, and consistent with the Phase II findings, the ANCOVA analysis indicated a negative effect near Platform Hidalgo for deep high- and low-relief habitats (Figure 6; Table 8). However, a concurrent decrease in percent cover did not occur at shallow nearfield sites. This suggests that the Phase II results for *Caryophyllia* spp. (Hyland et al. 1994) may have been due to either (1) natural variability or (2) variability in the sampling methods. However, the ANCOVA analysis may indicate potential long-term negative platform effects.

At the deep, low-relief nearfield sites, galatheid crabs (Figure 10) and the tunicate *H. hilgendorfi* showed decreases in percent cover during the Phase II drilling period. These decreases were not evident for shallow sites or deep, high-relief sites. Galatheid crabs were more abundant (percent cover) at deep (1.42%) as compared to shallow sites (0.52%). For deep sites, percent cover was lowest at nearfield sites (0.99%), highest at midfield (1.86%), and intermediate at farfield (1.44%). Percent cover decreased at the deep low-relief nearfield site, while it increased at the deep high-relief nearfield site. Since galatheid crabs are mobile, it is feasible that some movement occurred from low-relief to high-relief habitat, perhaps in response to drilling muds discharges during Phase II. This may be reasonable since galatheid crabs were associated with significant negative correlations with sediment fluxes ($r^2$= -0.58). However, the lack of a negative response at the high-relief sites suggests that if vertical migration occurred in response to drilling effects, the impact on this taxon appears to have been of minor significance. The rapid return to higher percentage cover following the drilling period suggests that any effects were of short duration. Galatheid crabs showed a significant decreasing temporal trend only for deep low-relief habitats (Figure 10) and had significant correlations with two sediment flux parameters (flux rate and TOC $r^2$=0.64). ANCOVA analysis found no significant difference between near- and farfield sites for deep high- and low-relief habitats (Table 8). This suggests that the Phase II findings of potential negative effects were either of short duration and/or resulted from natural or method variability and not drilling effects.

*H. hilgendorfi* had a slightly higher occurrence at deep (0.58%) compared to shallow sites (0.43%) and a slightly higher occurrence in low- compared to high-relief habitat. Percent cover was highest at the deep nearfield sites for both relief heights (low, 0.80%; high, 1.09%), lowest at midfield (low, 0.39%; high, 0.16%), and intermediate at farfield sites (low, 0.64%; high, 0.37%). Figure 10 shows the decrease in percent cover at the deep low-relief farfield and nearfield sites. However, the decrease at the nearfield sites appears to be influenced more by high values observed in May and October 1987 than to drilling activities, since the mean percent cover has been comparable or higher since the Phase II drilling period than for the initial survey. Overall, this species had significant decreasing temporal trends for deep high- ($r^2$=0.31) and low-relief habitats ($r^2$=0.40) and significant correlations with three flux parameters (Ba $r^2$=0.57, Cd $r^2$=0.56, and % fines $r^2$= -0.58. ANCOVA results indicated negative effects for changes in percent cover with distance from the platform for deep high- and low-relief habitats, thereby supporting the Phase II results for this species.

The Phase II analysis indicated that Sabellidae was a common taxon that showed a drilling-related effect Hyland et al. (1994). However, this taxon was poorly represented in Phase III photodocumentation, although other polychaete families (e.g., Serpulidae and Terebellidae) were identified. This suggests some problems in consistently identifying polychaetes to family during the photographic analyses. To overcome this taxonomic difference, the present study combined all polychaete data into a common group, "Polychaeta". As defined, Polychaeta occurred most commonly at deep (3.91%) compared to shallow sites (0.96%) and percent cover at deep sites was lowest for the nearfield sites (2.02%), intermediate at midfield (3.95%), and highest at farfield (5.92%). A distance gradient from Platform Hidalgo was not evident for the shallow sites but was consistent for both high- and low-relief at the deep sites. This suggests that the deep reefs nearest the platform had substantially fewer Polychaetes (Figure 11). The temporal plots of Polychaetes for deep nearfield and farfield sites showed no obvious effects of drilling-related impacts (Figure 11), although there was a significant decreasing temporal trend for deep high- ($r^2$=0.52) and low-relief habitats ($r^2$=0.70) (Figure 11). The most significant trend for this group has been the dramatic, unexplained decline in percent cover at the deep mid- and farfield site following the Phase II drilling period. Comparable trends were not observed for the nearfield sites. Polychaetes were significantly correlated with five flux parameters (Cd $r^2$=0.70, Cu $r^2$=0.72, Ni $r^2$=0.69, % clay $r^2$= -0.80, and median flux size $r^2$=0.67). Even though percent cover decreased at nearfield sites, the ANCOVA analysis showed a positive platform effect for deep high- and low-relief habitats, mainly due to the rapid decrease in percent cover at mid- and farfield sites (Table 8, Figure 11).

In summary, the temporal patterns for the four potentially sensitive taxa identified in Phase II and the results of the ANCOVA analysis in the present study provide support for significant drilling-related changes in percent cover for *Caryophyllia* at deep high- and low-relief habitats and for *Halocynthia* at deep low-relief habitat. ANCOVA indicated a positive effect for Polychaeta and no significant effect for galatheids on deep low-relief habitat, although a negative effect did occur for galatheids in shallow low-relief. ANCOVA results for these four taxa found two positive platform effects, three no significant effects, five negative effects, and two non-significant survey x distance interactions. These results support in part the findings of the Phase II analysis;

however, these potential effects may be influenced by natural variation or may have persisted for only a short time.

## ANCOVA Results For Additional Dominant Taxa

Percent cover for individual hard-bottom taxa potentially could increase, decrease, and/or change little (if at all) over time with respect to the proximity to Platform Hidalgo. The ANCOVA tests for the 20 dominant taxa produced 18 positive effects, 17 negative effects, and 11 that were not significant (Table 9). There also were 14 tests with non-significant survey x distance interactions. The distribution of the observed results was tested for significance using Chi-square contingency analysis (Zar 1974). Results from this analysis indicated that the combined ANCOVA conclusions were not significant, suggesting that the observed pattern of potential effects may have been due to chance alone. Therefore, while positive and negative changes in percent cover were found to be significant for proximity to Platform Hidalgo, the cumulative distribution of these results appears unrelated to platform effects.

## Power Test

The power ($1-\beta$) to detect significant decreases ($\alpha=0.05$) in mean percent cover at a site for dominant taxa in the post-drilling phase (6 surveys) compared to the mean percent cover for the pre-drilling period (2 surveys) is presented in Table 10. The power test was structured to detect decreases in mean percent cover in the post-drilling phase that would be consistent with negative impacts. The 15 taxa tested for three habitats at two sites produced 90 possible combinations. Of these 90, not enough data were available or they showed an increase in percent cover in 33 tests for the post-drilling surveys. Fifty-seven responses indicated a decrease in percent cover for the post-drilling surveys. However, only five of these 57 had greater than 80% power and 14 responses (8 out of 29 nearfield and 6 out of 28 farfield) had a power of 50% or greater. By habitat type, 5 of 16 responses had a power of 50% or greater for deep high-relief habitats, 6 out of 20 for deep low-relief habitats, and 3 out of 21 for shallow low-relief habitats. This suggests that there would be low power to detect significant differences in percent cover in these habitats using the present, random photoquadrat study design.

## Discussion

Hard-substrate epifauna of the Santa Maria Basin are diverse and abundant with most taxa having preferences for particular depth ranges and substrate relief heights. Other important factors that help structure these communities include orientation to bottom current flows (Hardin et al. 1994) and substrate size and type (MEC 1995). In the present study, the deeper sites had more taxa and higher percent cover than the shallow sites, and more taxa favored high- compared to low-relief habitats. The extensive list of Santa Maria Basin biota is supplemented with many new species that have been described from the DOI Phase I through Phase III surveys. The Taxonomic Atlas of the Santa Maria Basin, a 14 volume series sponsored by MMS, describes many new species and provides additional natural history information (Blake and Lissner 1993).

Oil and gas production platforms have the potential to impact hard-bottom epifauna by physical disturbances related to platform installation and discharges of drilling muds and cuttings, which can bury epifauna and hard-bottom habitats. The physical effects of these discharges, when they are not excessive, share similarities with natural processes of resuspension and sediment transport (Lissner et al. 1991). The exception concerns the discharge of potentially toxic substances (e.g., drilling muds, oil spill products, and produced water) which typically do not have natural counterparts. However, reef epifauna in the study area are likely to have some tolerance to crude oil exposure, as there are numerous natural oil seeps in the area.

Toxicity associated with drilling muds has decreased substantially over time due to stricter environmental controls and reductions in the use of toxic additives (e.g., chromium). However, drilling mud samples from Platform Hidalgo exhibited toxicity in bioassay tests with adult brown cup coral, *Paracyathus stearnsii* (Raimondi et al., in preparation; see Appendix C-3 in SAIC and MEC 1995). Furthermore, in situ bioassays using larvae of the red abalone, *Haliotis rufescens*, during the Phase III drilling period found lower settlement rates near the platform (Raimondi et al., in preparation; see Appendix C-1 in SAIC and MEC 1995). In contrast, natural settlement experiments indicated a general enhancement of settlement during drilling activities (Barnett et al., in preparation; see Appendix C-2 in SAIC and MEC 1995). Particle tracking models performed during Phase II and Phase III (Coats 1994; SAIC and MEC 1995) and sediment trap data (Parr et al. 1991; Phillips et al., in preparation) indicate that the fine particulates of drilling muds are widely dispersed and concentrations at nearfield reefs, while low, could reach levels determined from the bioassays to reduce growth and viability in the brown cup coral *P. stearnsii* (18-25 ppm drilling mud). Thus, results of the *in situ* bioassays and laboratory bioassays suggest that platform discharges may affect some epifaunal organisms by causing sublethal effects on settlement, growth, and viability. Consequently, impacts from drilling discharges may not be immediately apparent and could require a longer time period before community changes are discernable.

Phase II ANOVA testing (based on time-dose interaction) of effects related to drilling discharges identified four possible taxa that were consistent with negative responses to the discharge (Hyland et al. 1994). Since only 11% of the volume of drilling muds and cuttings was discharged in Phase III compared to Phase II (Table 1), the finding of new effects was unlikely. However, as a result of classification analysis and ANCOVA testing (based on survey-distance from platform interaction), the Phase II and III data showed a decreasing trend for many taxa over the nine years, with some different trends near as compared to farther away from the platform. This suggests some distance effects that might be related to drilling periods or to the expression of more subtle platform-related impacts over a longer time period.

The Phase II drilling period results suggested negative effects to *Caryophyllia* at deep high- and low-relief habitats, and to galatheid crabs, *Halocynthia*, and polychaetes at deep low-relief habitats near Platform Hidalgo. However, the Phase III ANCOVA tests, considered as post-drilling analyses for the Phase II drilling period, only supported negative effects in the same habitats as Phase II for *Caryophyllia* at deep high- and low-relief and for *Halocynthia* at deep low-relief. ANCOVA analysis suggested positive platform effects for polychaetes (including

Sabellids) and no significant effect for galatheid crabs for deep low-relief habitat. Temporal plots suggested that decreases in percent cover during the Phase II drilling period were of limited duration. Thus, the combined Phase II and III trends for galatheids and polychaetes appeared to be due to short-term responses of the biota, natural variability, or variability inherent in the sampling methods. Furthermore, based on ANCOVA tests of survey x distance (from platform) effects and subsequent Chi-square contingency analysis for 20 dominant taxa, the cumulative positive and negative results could have been due to chance alone. While some taxa appear to benefit from proximity to Platform Hidalgo (e.g., cup corals in preferred habitats, anemones, and sponges) others may be negatively effected (e.g., cup corals in non-preferred habitats and tunicates). Additional studies would be necessary to conclusively demonstrate that platform effects have contributed to changes in percent cover for the dominant taxa. Clearly, the drilling operations to date have not produced large-scale catastrophic impacts to the majority of the dominant taxa. Small-scale changes for a few taxa are not separable from natural variability and the variability associated with the sampling methods. However, these trends may reflect longer-term effects from platform activities.

The cup coral *P. stearnsii* has been shown to be sensitive to Platform Hidalgo drilling muds in laboratory conditions (Raimondi et al., in preparation; see Appendix C-3 in SAIC and MEC 1995). Close examination of the data for *P. stearnsii* indicates that this species occurred most commonly (2.11%) at shallow compared to deep sites (0.27%), with a preference for low-relief (1.16%) as compared to high-relief habitats (0.37%). More importantly, for shallow, low-relief habitats percent cover was lowest (1.71%) at nearfield sites, intermediate (2.88%) at midfield, and highest (3.24%) at farfield. This gradient in percent cover with distance from Platform Hidalgo is consistent with possible exposure to drilling muds, but was not supported by the ANCOVA which found no significant survey x distance interactions. Because of the naturally low overall abundances for the deeper sites, ANCOVA results for deep low-relief habitat was more likely related to chance or to natural or methodological variability.

Independent of the ANCOVA results and the evaluations of trends in the temporal plots, all of which are based on data collected using commonly applied methods (photoquadrats taken randomly by an ROV), the power analyses suggest that only major changes in the community are likely to be detected. This limitation is strongly influenced by the lack of fixed sampling locations that could document, for example, complete loss of habitat, such as burial of a low-relief community by sediment encroachment (natural or anthropogenic). As an example, based on present methods that randomly sample exposed hard-substrate, a reef that was buried between surveys would not be resampled since it then would not represent target, hard substrate. A combination of fixed and random methods may be more appropriate for further studies. Furthermore, sublethal effects to slow growing, large organisms (e.g., sponges) may take long time periods (years) for changes in percent cover to be manifested and detected. The Phase II study showed that the power to detect changes between two reefs for any survey or two surveys at a hard-bottom site was high (primarily due to pseudoreplicates of 60 photographs for each habitat) (Hyland et al. 1994). In contrast, the Phase III power tests (pre- and post-drilling surveys at one site) generally indicated poor statistical power to detect differences in mean percent cover.

Thus, the sampling methods used for the Phase II and III studies represented poor power to detect long-term sublethal effects.

Results from the linear regression of temporal trends in percent cover for 24 dominant taxa x 3 habitats found two increasing trends, 25 negative trends, and 45 nonsignificant patterns. Thus, although most of the dominant taxa showed no significant temporal trends, 35% were characterized by a significant decrease in percent cover over the study region. It cannot be determined from the present data whether these broad-scale changes are due to natural variability or to long-term anthropogenic effects, including drilling discharges, since there are no comparable data from other regions. As noted above, drilling-related impacts may be less likely since the primary source of potential contaminants, produced water discharges, has only been occurring since 1992–1993 (during Phase III). Other, large scale natural changes could be influenced by El Niño cycles or the apparently large decreases in the biomass of macrozooplankton in the southern California and Point Conception areas since 1951 (Roemmich and McGowan 1995). These decreases could reduce the availability of larvae as well as the food supply for epifauna on hard-bottom habitats. The plankton decreases appear to be related to increases in oceanic temperatures, which also can directly affect the distribution of biota.

In summary, long-term data from photographic surveys of large epifauna on hard-bottom reefs suggests that oil and gas drilling operations and platform discharges have not caused major changes to nearby communities. Approximately equal numbers of positive and negative effects were indicated for dominant taxa, and there was no consistent pattern of response for a single taxon over the three habitats (deep high- and low-relief and shallow low-relief). Statistical tests concluded that the cumulative distribution of responses could have been due to chance alone. The Phase III results support the negative associations of two taxa (*Caryophyllia* and *Halocynthia*) in the same habitats identified in Phase II as affected by drilling discharges, but could not support the Phase II findings for the other two taxa (galatheid crabs and polychaetes). Subtle and/or long-term gradual changes in percent cover likely are not detectable due to relatively high natural variability, as well as the variability associated with present field methods. It is recommended that future studies incorporate fixed quadrats in addition to "random walk" photographic surveys to reduce the variance estimates associated with the small-scale heterogeneity of reef habitats and to better assess sublethal effects to selected organisms over time. Additional in situ bioassays and laboratory experiments also are needed to demonstrate cause and effect relationships.

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## LITERATURE CITED

Barnett, A.M., P.T. Raimondi, and P.R. Krause. In preparation. Effects of offshore oil and gas development on larval recruitment: Field experiments on the outer continental shelf off Point Arguello, California. Appendix C-2 In: Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III. Final Report for the U.S. Department of the Interior, Minerals Management Service/National Biological Service, under Contract No. 14-35-001-30584.

Blake, J.A. and A. Lissner. 1993. Taxonomic atlas of the benthic fauna of the Santa Maria Basin and Western Santa Barbara Channel. Vol. 1, Introduction, Benthic Ecology, Oceanography, Platyhelminthes, and Nemertea. Report MMS 92-0042 to the U.S. Department of the Interior, Minerals Management Service, 132 pp.

Boesch, D.F. and G.A. Robilliard. 1987. Physical alteration of marine and coastal habitats resulting from offshore oil and gas development activities. Pages 1-53, In: D.F. Boesch and N.N. Rabalais, eds. Long-term environmental effects of offshore oil and gas development. Elsevier Applied Science, London.

Bray, J.R. and J.T. Curtis. 1957. An ordination of the upland forest communities of southern Wisconsin. Ecol. Monogr. 27:325-349.

Brewer, G.D., J.L. Hyland, and D.D. Hardin. 1991. Effects of oil drilling on deepwater reefs offshore California. Am. Fish. Soc. Symp. 11:26-38.

Butman, C.A., C.M. Webb, B. Butman, J.P. Grassle, D.A. Cacchione, D.E. Drake, and R. Chapman. 1988. Companion studies on sediment transport and bioturbation. In: J. Hyland and J. Neff, eds. California OCS Phase II Monitoring Program, Year-One Annual Report. Report to U.S. Department of Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30262.

Centaur Associates, Inc. 1984. Mitigation of seafloor conflicts between oil and gas pipelines and commercial trawl fisheries on the California Outer Continental Shelf. Report to U.S. Department of the Interior, Minerals Management Service, under Contract No. 14-12-0001-30050.

Chambers Consultants and Planners. 1982. Supplementary data report for characterization of the marine biota between Point Arguello and Point Conception. Report submitted to California State Lands Commission, Sacramento, CA.

Cimberg, R.L., T. Gerrodette, and K. Muzik. 1981. Habitat requirements and expected distribution of Alaska coral. Report submitted to the U.S. Department of the Interior, Bureau of Land Management, Alaskan OCS Office.

Coats, D.A. 1994. Deposition of drilling particulates offshore Point Conception, California. Mar. Env. Res. 37:95-127.

Dames and Moore. 1982. Site-specific marine biological survey, Lease P-0446, P-0447, P-0450, P-0451, and P-0452, southern Santa Maria Basin area. Report to Chevron U.S.A., Inc.

Dames and Moore. 1983. Site-specific marine biological survey, Chevron Platform Hermosa Project, western Santa Barbara Channel. Report to Chevron U.S.A., Inc.

Diener, D.R., S.C. Fuller, A. Lissner, C.I. Haydock, D. Maurer, G. Robertson, and T. Gerlinger. 1995. Spatial and temporal patterns of the infaunal community near a major ocean outfall in Southern California. Mar. Poll. Bull. (in press).

Dustin, P., B.H. Lidz, and E.A. Shinn. 1991. Impact of exploratory wells, offshore Florida: A biological assessment. Bull. Mar. Sci. 48(1):94-124.

Ecomar. 1978. Tanner Bank mud and cuttings study. Final Report submitted to Shell Oil Company.

Engineering-Science. 1984. Marine biological survey for Platform Hidalgo site and corresponding pipeline route. Report to Chevron U.S.A., Inc.

Environmental Science and Engineering, Inc., LGL Ecological Research Associates, Inc., and Continental Shelf Associates, Inc. 1987. Southwest Florida shelf ecosystems study data synthesis report. Final Report to U.S. Department of Interior, Minerals Management Service, Gulf of Mexico OCS Region, New Orleans, LA, under Contract No. 14-12-0001-30276.

Green, R.H. 1989. Power analysis and practical strategies for environmental monitoring. Environ. Res. 50:195-205.

Hardin, D.D., J. Toal, T. Parr, P. Wilde, and K. Dorsey. 1994. Spatial variation in hard-bottom epifauna in the Santa Maria Basin, California: The importance of physical factors. Mar. Env. Res. 37:165-193.

Hooks McCloskey. 1982. Biological survey of megafaunal species in or near Leases OCS P-0450, P-0406, P-0410, and P-0411 in the Santa Maria Basin Offshore Lease Sale Area. Report to Exxon Co., U.S.A.

Hyland, J., D. Hardin, M. Steinhauer, D. Coats, R. Green, and J. Neff. 1994. Environmental impact of offshore oil development on the outer continental shelf and slope off Point Arguello, California. Mar. Env. Res. 37:195-229.

Lissner, A., G. Taghon, D. Diener, S. Schroeter, and J. Dixon. 1991. Colonization and recovery of hard-substrate communities: Potential impacts from oil and gas development. Ecolog. Appl. 1:258-267.

Marine Research Specialists. 1992. A survey of prominent anchor scars and the level of disturbance to hard substrate communities in the Pt. Arguello Region. Cruise Report to Chevron Corporation.

MEC (MEC Analytical Systems, Inc.). 1995. Disturbance of deep-water reef communities by exploratory oil and gas operations in the Santa Maria Basin and Santa Barbara Channel. Report submitted to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Camarillo, CA, under Contract No. 14-35-0001-30601.

MMS (Minerals Management Service). 1982. Recommendations for a Pacific Outer Continental Shelf monitoring program for OCS oil and gas development activities. Summary and recommendations of a conference. March 30 and March 31, 1982. U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Administrative Report, Los Angeles, CA.

MMS. 1987. Proposed 5-year Outer Continental Shelf oil and gas leasing program, mid-1987 to mid-1992, Final Environmental Impact Statement, Vol. 1. U.S. Department of the Interior, Minerals Management Service, OCS EIS-EA, Report No. MMS 86-0127.

Nekton. 1981. A biological survey of a hard-bottom feature, Santa Maria Basin, Califonria. Report to ARCO Oil and Gas Co.

Nekton and Kinnetic Laboratories. 1983. Site-specific faunal characterization survey for Platform Harvest, OCS Lease P-0315, Point Conception, California. Report to Texaco U.S.A.

Parr, T., F.C. Newton, D. Hardin, and P. Kinney. 1991. Spatial and temporal variation of bottom sediments near rock reefs exposed to drilling discharges off Point Arguello, California. Chapter 3, In: Battelle Ocean Sciences. California OCS Phase II Monitoring Program Final Report. U.S. Department of the Interior, Minerals Management Service, Los Angeles, CA, Report No. MMS 91-0083.

Phillips, C., J. Evans, W. Hom, and J. Clayton. In preparation. Temporal trends in sediment contaminant concentrations associated with drilling-related discharges in the Santa Maria Basin, California. Appendix B In: Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III. Final Report for the U.S. Department of the Interior, Minerals Management Service/National Biological Service, under Contract No. 14-35-001-30584.

Piltz, F. 1986. Monitoring long-term changes in biological communities near oil and gas production platforms. Pages 856-861, In: Oceans '86. Proceedings Volume 3. Monitoring Strategies Symposium. Institute of Electrical and Electronics Engineers, New York, and Marine Tech. Soc., Washington, D.C.

Raimondi, P.T., A.M. Barnett, and P.R. Krause. In preparation. Effects of offshore oil and gas development on marine larval settlement: In situ manipulated field experiments. Appendix C-1 In: Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III. Final Report for the U.S. Department of the Interior, Minerals Management Service/National Biological Service, under Contract No. 14-35-001-30584.

Raimondi, P.T., A.M. Barnett, and P.R. Krause. In preparation. The effects of drilling muds on marine invertebrate larvae and adults. Appendix C-3 In: Monitoring Assessment of Long-Term Changes in Biological Communities in the Santa Maria Basin: Phase III. Final Report for the U.S. Department of the Interior, Minerals Management Service/National Biological Service, under Contract No. 14-35-001-30584.

Roemmich, D. and J. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. Science 267:1324-1326.

Rowe, G.T. and R.J. Menziesi. 1969. Zonation of large benthic invertebrates in the deep-sea of the Carolinas. Deep Sea Res., 16:531-537.

SAIC (Science Applications International Corporation). 1986. Assessment of long-term changes in biological communities of the Santa Maria Basin and western Santa Barbara Channel: Phase I, Vol. II Synthesis of Findings. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30032.

SAIC and MEC. 1989. Benthic reconnaissance of central and northern California OCS areas. Final Report to the U.S. Department of the Interior, Minerals Management Service. Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30388.

SAIC and MEC. 1993. Monitoring and assessment of long-term changes in biological communities in the Santa Maria Basin: Phase III, Year One Report. Report to the U.S. Department of the Interior. Minerals Management Service/National Biological Service, under Contract No. 14-35-0001-30584.

SAIC and MEC. 1995. Monitoring and assessment of long-term changes in biological communities in the Santa Maria Basin: Phase III, Final Report. Report to the U.S. Department of the Interior, Minerals Management Service/National Biological Service, under Contract No. 14-35-0001-30584.

SAS. 1990. SAS/STAT User's Guide, Version 6, Fourth Edition, Volume 1. SAS Institute Inc., Cary, NC. 943 pp.

Smith, R.W. 1976. Numerical analysis of ecological survey data. Ph.D. Dissertation. University of Southern California, Los Angeles, CA. 401pp.

Steinhauer, M. and E. Imamura (eds). 1990. California OCS Phase II Monitoring Program: Year-three Annual Report. Report to the U.S. Department of the Interior, Minerals Management Service, Pacific OCS Region, Los Angeles, CA, under Contract No. 14-12-0001-30262.

Tetra Tech. 1985. Recommended Biological Indices for 301(h) Monitoring Programs. EPA Final Report TC-3953-03, 17pp.

Texas A&M University. 1981. Northern Gulf of Mexico topographic features study. Final Report to the U.S. Department of Interior, Bureau of Land Management, OCS Office, New Orleans, LA, under Contract No. AA551-CT8-35.

Texas A&M Research Foundation and Texas A&M Department of Oceanography. 1976. A biological and geological reconnaissance of selected topographic features on the Texas shelf. Report to the U.S. Department of Interior, Bureau of Land Management. OCS Office, New Orleans, LA, under Contract No. 98550-CT5-4.

Thompson, B., D. Tsukada, and J. Laughlin. 1993. Megabenthic assemblages of coastal shelves, slopes, and basins off Southern California. Bull. So. Cal. Acad. Sci. 92(1):35-42.

van der Veer, H.W., M.J.N. Bergman, and J.J. Beukema. 1985. Dredging activities in the Dutch Wadden Sea: Effects on macrobenthic infauna. Neth. J. Sea Res. 19: 183-190.

Van Dolah, R.F., P.H. Wendt, M.V. Livisen. 1991. A study of the effects of shrimp trawling on benthic communities in two South Carolina sounds. Fish. Res. 12:139-157.

Van Dolah, R.F., P.H. Wendt, N. Nicholson. 1987. Effects of a research trawl on a hard bottom assemblage of sponges and corals. Fish. Res. 5:39-54.

Vanogradova, N.G. 1962. Vertical zonation in the distribution of the deep-sea benthic fauna of the ocean. Deep Sea Res. 8:245-250.

Wahl, M. 1985. The recolonization potential of *Metridium senile* in an area previously depopulated by oxygen deficiency. Oecologia 67:255-259.

Zar, J. H. 1974. Biostastical Analysis. Prentice-Hall, Inc., Englewood Cliffs, NJ. 620pp.

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**Figure 10.** Temporal plot of mean percent cover of galatheid crabs for all habitats (upper) and of the tunicate *Halocynthia hilgendorfi igaboja* for deep low-relief sites (lower) with distance from Platform Hidalgo. Nearfield = PH-K and PH-N; Midfield = PH-R; and Farfield = PH-W. Shaded areas indicate drilling periods for Platform Hidalgo.

**Figure 11.** Temporal plot of mean percent cover of all Polychaeta for all habitats (upper) and for deep low-relief sites (lower) with distance from Platform Hildalgo. Nearfield = PH-K and PH-N; Midfield = PH-R; and Farfield = PH-W. Shaded areas indicate drilling periods for Platform Hidalgo.

**Table 1.** Summary of oil and gas drilling activities in the Point Arguello region for Phase II and Phase III.

| Platform | Date Platform Installed | DOI Study Phase | Drilling Period | Duration (months) | No. of Wells | Platform Discharges | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Muds ($m^3$) | Cuttings ($m^3$) | Produced Water (MGD) |
| Harvest | 6/12/85 | Phase II<br>Phase III | 11/86 - 05/88<br>n/a | 18<br>n/a | 19<br>0 | 16,340<br>0 | n/a<br>0 | n/a<br>0 |
| Hermosa | 10/5/85 | Phase II<br>Phase III | 01/87 - 09/88<br>09/93 - 11/93 | 20<br>2 | 13<br>1 | 16,373<br>822 | 3,114<br>136 | n/a<br>0.592 |
| Hidalgo | 7/2/86 | Phase II<br>Phase III | 11/87 - 01/89<br>11/93 - 05/94 | 14<br>6 | 7<br>4 | 7,963<br>3,850 | 2,294<br>739 | n/a<br>1.720 |

MGD = million gallons per day.
n/a = not available

**Table 2.** Site description and classification for hard-bottom epifauna for Phase II and Phase III studies (1986–1994).

| Site | Approximate Depth (m) | Depth [a] Category | Phase II Dose [b] Category | Gradient [c] Category | Distance from Platform Hidalgo (km) | Habitat [d] Category | Sampled in Phase II | Sampled in Phase III |
|---|---|---|---|---|---|---|---|---|
| PH-F | 105 | shallow | medium | midfield | 2.1 | low<br>high | yes<br>NA | yes<br>NA |
| PH-I | 109 | shallow | high | nearfield | 0.8 | low<br>high | yes<br>NA | yes<br>yes |
| PH-U | 113 | shallow | low | farfield | 3.8 | low<br>high | yes<br>NA | yes<br>NA |
| PH-J | 117 | shallow | high | nearfield | 0.5 | low<br>high | yes<br>NA | yes<br>yes |
| PH-E | 119 | shallow | high | nearfield | 1.2 | low<br>high | yes<br>NA | yes<br>yes |
| PH-K[e] | 160 | deep | high | nearfield | 0.6 | low<br>high | NA<br>yes | yes<br>yes |
| PH-N | 166 | deep | high | nearfield | 0.9 | low<br>high | yes<br>NA | yes<br>NA |
| PH-W | 195 | deep | low | farfield | 6.4 | low<br>high | yes<br>yes | yes<br>yes |
| PH-R | 212 | deep | medium | midfield | 1.1 | low<br>high | yes<br>yes | yes<br>yes |

a Shallow: 105–119 m; Deep: 160–212 m

b Represents potential chemical dose, based on barium concentrations from sediment traps, to which epifauna may be exposed (Hyland et al. 1994)

c Based on cluster analysis, Phases II and III combined

d Low-relief: 0.2–0.5 m; High-relief: >1.0 m

e Phase II noted abundant high-relief; Phase III noted abundant low-relief but little high-relief.

NA = No appropriate habitat type found

**Table 3.** Twenty most abundant hard-bottom taxa at deep- (n=3,348) and shallow-water (n=3,122) stations in the vicinity of Platform Hidalgo for Phase II and Phase III studies (1986–1994).

| Rank | Taxa | Taxa Group | Mean % Cover | Standard Deviation |
|---|---|---|---|---|
| | **Deep-Water Stations** | | | |
| 1 | Total Ophiuroidea | Echinodermata | 5.36 | 6.11 |
| 2 | Total Polychaeta | Polychaeta | 3.91 | 4.64 |
| 3 | Total white encrusters | Porifera, Urochordata, Ectoprocta | 3.06 | 2.71 |
| 4 | *Florometra serratissima* | Echinodermata | 2.59 | 6.82 |
| 5 | *Amphianthus californicus* | Anthozoa | 2.58 | 4.06 |
| 6 | *Ophiacantha diplasia* | Echinodermata | 1.48 | 2.80 |
| 7 | Galatheidae | Crustacea | 1.42 | 1.67 |
| 8 | *Metridium giganteum* | Anthozoa | 1.39 | 4.76 |
| 9 | *Desmophyllum dianthus* | Anthozoa | 1.18 | 2.74 |
| 10 | Sponge, tan encrusting | Porifera | 1.13 | 1.95 |
| 11 | *Stomphia didemon* | Anthozoa | 0.96 | 2.72 |
| 12 | *Pyura haustor* | Urochordata | 0.95 | 1.53 |
| 13 | Anemone, tan zoanthid | Anthozoa | 0.90 | 2.01 |
| 14 | *Laqueus californianus* | Brachiopoda | 0.84 | 1.56 |
| 15 | Anemone, white and purple | Anthozoa | 0.77 | 1.34 |
| 16 | *Lophelia pertusa* | Anthozoa | 0.77 | 4.22 |
| 17 | Sponge, shelf | Porifera | 0.75 | 2.68 |
| 18 | Gorgonian, red or pink | Anthozoa | 0.75 | 1.25 |
| 19 | *Caryophyllia* spp. | Anthozoa | 0.63 | 0.82 |
| 20 | *Halocynthia hilgendorfi* | Urochordata | 0.58 | 1.09 |
| | **TOTAL** | | **32.0** | |

**Table 3.** Continued.

| Rank | Taxa | Taxa Group | Mean % Cover | Standard Deviation |
|---|---|---|---|---|
| | **Shallow-Water Stations** | | | |
| 1 | Total Ophiuroidea | Echinodermata | 5.95 | 7.31 |
| 2 | *Florometra serratissima* | Echinodermata | 2.48 | 7.38 |
| 3 | *Paracyathus stearnsii* | Anthozoa | 2.11 | 2.48 |
| 4 | *Metridium giganteum* | Anthozoa | 2.11 | 2.48 |
| 5 | Total white encrusters | Porifera, Urochordata, Ectoprocta | 1.59 | 1.88 |
| 6 | *Caryophyllia* spp. | Anthozoa | 1.52 | 1.58 |
| 7 | *Ophiacantha diplasia* | Echinodermata | 1.46 | 3.14 |
| 8 | Total Polychaeta | Polychaeta | 0.96 | 1.61 |
| 9 | Sponge, tan encrusting | Porifera | 0.85 | 1.59 |
| 10 | *Cellaria* sp. | Ectoprocta | 0.75 | 1.07 |
| 11 | Gorgonian, red or pink | Anthozoa | 0.64 | 0.89 |
| 12 | *Pyura haustor* | Urochordata | 0.63 | 1.04 |
| 13 | *Balanophyllia elegans* | Anthozoa | 0.62 | 1.01 |
| 14 | Galatheidae | Crustacea | 0.52 | 0.77 |
| 15 | *Halocynthia hilgendorfi* | Urochordata | 0.43 | 0.86 |
| 16 | *Ophionereis* sp. | Echinodermata | 0.27 | 0.53 |
| 17 | Sponge, shelf | Porifera | 0.22 | 1.30 |
| 18 | Anemone, tan zoanthid | Anthozoa | 0.22 | 0.60 |
| 19 | *Laqueus californianus* | Brachiopoda | 0.20 | 0.46 |
| 20 | Paguridae | Crustacea | 0.17 | 0.45 |
| | **TOTAL** | | **23.7** | |

**Table 4.** Twenty most abundant hard-bottom taxa at low- (n=4,649) and high-relief (n=1,821) stations in the vicinity of Platform Hidalgo for Phase II and Phase III studies (1986–1994).

| Rank | Taxa | Taxa Group | Mean % Cover | Standard Deviation |
|---|---|---|---|---|
| | **High-Relief** | | | |
| 1 | Total Ophiuroidea | Echinodermata | 4.39 | 4.89 |
| 2 | Total white encrusters | Porifera, Urochordata, Ectoprocta | 4.15 | 3.04 |
| 3 | *Amphianthus californicus* | Anthozoa | 3.74 | 4.97 |
| 4 | Total Polychaeta | Polychaeta | 2.92 | |
| 5 | *Metridium giganteum* | Anthozoa | 2.36 | 6.89 |
| 6 | *Desmophyllum dianthus* | Anthozoa | 2.03 | 3.47 |
| 7 | *Florometra serratissima* | Echinodermata | 1.73 | 6.15 |
| 8 | Sponge, tan encrusting | Porifera | 1.70 | 2.82 |
| 9 | Galatheidae | Crustacea | 1.70 | 1.81 |
| 10 | *Lophelia pertusa* | Anthozoa | 1.49 | 5.79 |
| 11 | *Ophiacantha diplasia* | Echinodermata | 1.16 | 2.43 |
| 12 | Sponge, shelf | Porifera | 1.10 | 3.11 |
| 13 | *Stomphia didemon* | Anthozoa | 1.07 | 2.70 |
| 14 | Anemone, tan zoanthid | Anthozoa | 0.98 | 2.43 |
| 15 | *Pyura haustor* | Urochordata | 0.85 | 1.39 |
| 16 | Anemone, white and purple | Anthozoa | 0.80 | 1.49 |
| 17 | Gorgonian, red or pink | Anthozoa | 0.78 | 1.37 |
| 18 | *Laqueus californianus* | Brachiopoda | 0.73 | 1.42 |
| 19 | *Caryophyllia* spp. | Anthozoa | 0.70 | 0.87 |
| 20 | *Paguridae* | Crustacea | 0.48 | 0.67 |
| | **TOTAL** | | **34.9** | |

**Table 4.** Continued.

| Rank | Taxa | Taxa Group | Mean % Cover | Standard Deviation |
|---|---|---|---|---|
| | **Low-Relief** | | | |
| 1 | Total Ophiuroidea | Echinodermata | 6.50 | 7.22 |
| 2 | *Florometra serratissima* | Echinodermata | 2.85 | 7.41 |
| 3 | Total Polychaeta | Polychaeta | 2.33 | 3.93 |
| 4 | Total white encruster | Porifera, Urochordata, Ectoprocta | 1.65 | 1.73 |
| 5 | *Ophiacantha diplasia* | Echinodermata | 1.59 | 3.15 |
| 6 | *Paracyathus stearnsii* | Anthozoa | 1.46 | 2.23 |
| 7 | *Metridium giganteum* | Anthozoa | 1.23 | 5.09 |
| 8 | *Caryophyllia* spp. | Anthozoa | 1.20 | 1.43 |
| 9 | *Pyura haustor* | Urochordata | 0.77 | 1.30 |
| 10 | Sponge, tan encrusting | Porifera | 0.71 | 1.03 |
| 11 | Galatheidae | Crustacea | 0.71 | 1.05 |
| 12 | Gorgonian, red or pink | Anthozoa | 0.66 | 0.96 |
| 13 | *Halocynthia hilgendorfi* | Urochordata | 0.53 | 1.02 |
| 14 | *Laqueus californianus* | Brachiopoda | 0.45 | 1.10 |
| 15 | Anemone, tan zoanthid | Anthozoa | 0.41 | 0.96 |
| 16 | *Balanophyllia elegans* | Anthozoa | 0.41 | 0.88 |
| 17 | *Amphianthus californicus* | Anthozoa | 0.40 | 1.17 |
| 18 | *Paguridae* | Crustacea | 0.34 | 0.66 |
| 19 | *Ophionereis* sp. | Echinodermata | 0.31 | 0.60 |
| 20 | *Stomphia didemon* | Anthozoa | 0.30 | 1.66 |
| | **TOTAL** | | **24.8** | |

**Table 5.** Mean number of taxa per photograph (± 1 standard deviation) by depth, relief height, and gradient classification for Phase II and Phase III studies (1986–1994).

| | **Low Relief** | **High Relief** | **Total** |
|---|---|---|---|
| Shallow Station | 16.2 ± 6.48 | 10.3 ± 2.77 | 15.6 ± 6.46 |
| Deep Station | 17.6 ± 8.19 | 24.5 ± 7.84 | 20.7 ± 8.74 |
| Total | 16.8 ± 7.24 | 22.0 ± 9.05 | |
| | | | |
| | **Farfield** | **Midfield** | **Nearfield** |
| Shallow Low Relief | 16.3 ± 6.51 | 16.0 ± 6.42 | 16.3 ± 6.49 |
| Shallow High Relief | NA | NA | 10.3 ± 2.77 |
| Total | 16.3 ± 6.51 | 16.0 ± 6.42 | 15.3 ± 6.44 |
| | | | |
| Deep Low Relief | 19.3 ± 8.63 | 18.1 ± 7.22 | 15.8 ± 8.21 |
| Deep High Relief | 26.9 ± 8.89 | 23.8 ± 6.89 | 22.5 ± 6.78 |
| Total | 23.0 ± 9.54 | 20.8 ± 7.63 | 18.4 ± 8.35 |

**Table 6.** Mean percent cover for all taxa per photograph (± 1 standard deviation) by depth, relief height, and gradient classification for Phase II and Phase III studies (1986–1994).

| | **Low Relief** | **High Relief** | **Total** |
|---|---|---|---|
| Shallow Station | 29.5 + 16.0 | 22.1 ± 15.1 | 28.7 ± 16.1 |
| Deep Station | 34.7 ± 18.3 | 51.5 ± 18.7 | 42.1 ± 20.3 |
| Total | 31.5 ± 17.2 | 46.2 ± 21.4 | |
| | | | |
| | **Farfield** | **Midfield** | **Nearfield** |
| Shallow Low Relief | 29.4 ± 15.1 | 26.1 ± 14.4 | 30.7 ± 16.8 |
| Shallow High Relief | NA | NA | 22.1 ± 15.1 |
| Total | 29.4 ± 15.1 | 26.1 ± 14.4 | 29.2 ± 16.8 |
| | | | |
| Deep Low Relief | 38.4 ± 19.6 | 34.1 ± 17.7 | 32.1 ± 17.2 |
| Deep High Relief | 52.3 ± 20.3 | 54.5 ± 18.9 | 47.1 ± 15.5 |
| Total | 45.1 ± 21.1 | 43.7 ± 21.0 | 37.9 ± 18.1 |

**Table 7.** Overall mean ranking of dominant taxa by relief height and depth categories. * = rank greater than 20; note that "missing" numbers in the sequences from 1–20 by category correspond to taxa other than those listed.

| | Taxa Group | Rank by Mean Percent Cover | | | | |
|---|---|---|---|---|---|---|
| | | All Habitats | Deep Water | Shallow Water | High Relief | Low Relief |
| Total Ophiuroidea | Echinodermata | 1 | 1 | 1 | 1 | 1 |
| Total white encrusters | Porifera<br>Urochordata<br>Ectoprocta | 2 | 3 | 5 | 2 | 4 |
| *Florometera serratissima* | Echinodermata | 3 | 4 | 2 | 7 | 2 |
| Total Polychaeta | Polychaeta | 4 | 2 | 8 | 4 | 3 |
| *Metridium giganteum* | Anthozoa | 5 | 8 | 4 | 5 | 7 |
| *Ophiacantha diplasia* | Echinodermata | 6 | 6 | 7 | 11 | 5 |
| Sponge, tan encrusting | Porifera | 7 | 10 | 9 | 8 | 10 |
| Galatheidae | Crustacea | 8 | 7 | 14 | 9 | 11 |
| *Amphianthus californicus* | Anthozoa | 9 | 5 | * | 3 | 17 |
| *Pyura hauster* | Urochordata | 10 | 12 | 12 | 15 | 9 |
| *Paracyathus stearnsii* | Anthozoa | 11 | * | 3 | * | 6 |
| *Caryophyllia* spp. | Anthozoa | 12 | 19 | 6 | 19 | 8 |
| *Desmophyllum dianthus* | Anthozoa | 13 | 9 | * | 6 | * |
| Gorgonian, red or pink | Anthozoa | 15 | 18 | 11 | 17 | 12 |
| Anemone, tan zoanthid | Anthozoa | 15 | 13 | 18 | 14 | 15 |
| *Laqueus californicus* | Brachiopoda | 16 | 14 | 19 | 18 | 14 |
| *Stomphia didemon* | Anthozoa | 17 | 11 | * | 13 | 20 |
| Sponge, shelf | Porifera | 18 | 17 | 17 | 12 | * |
| *Lophelia pertusa* | Anthozoa | 19 | 16 | * | 10 | * |
| *Halocynthia hilgendorfi* | Urochordata | 20 | 20 | 15 | * | 13 |
| *Balanophyllia elegans* | Anthozoa | * | * | 13 | * | 16 |

**Table 8.** Results of ANCOVA for taxonomic groupings and dominant taxa. Nearfield (near), midfield (mid), and farfield (far) represent distances from Platform Hidalgo (see Table 2). Distances connected by lines are not significantly different from the farfield site used as the reference ($p < 0.05$). Distances are ordered from left to right with reefs having the greatest rate of change (plus or minus) on the left. Arrows indicate temporal trends (increasing or decreasing percent cover). Effects are rated as + for enhancement of percent cover for taxa near the platform, — for decreasing percent cover, 0 for no significant difference between farfield reference and nearfield sites, and ns to indicate that the survey x distance interaction term was nonsignificant and no further testing could be done.

| Parameter and Habitat | Distance from Platform Hidalgo and Percent Cover Trend | Effects |
|---|---|---|
| All Ophiuroidea (brittlestars) | | |
| Deep high relief | near ↑ far ↓ mid ↓ | + |
| Deep low relief | | ns |
| Shallow low relief | mid ↑ near ↓ far ↑ | — |
| Total white encrusters (sponges, tunicates, bryozoans) | | |
| Deep high relief | far ↓ mid ↑ near ↑ | + |
| Deep low relief | far ↓ near ↓ mid ↑ | + |
| Shallow low relief | mid ↑ near ↑ far ↑ | + |
| *Florometra serratissima* (crinoid) | | |
| Deep high relief | far ↑ near ↑ mid ↑ | — |
| Deep low relief | mid ↓ far ↑ near ↑ | 0 |
| Shallow low relief | mid ↓ far ↑ near ↑ | 0 |
| All Polychaeta (worms) | | |
| Deep high relief | far ↓ mid ↓ near ↓ | + |
| Deep low relief | far ↓ mid ↓ near ↓ | + |
| Shallow low relief | | ns |
| *Metridium giganteum* (anemone) | | |
| Deep high relief | near ↑ far ↑ mid ↓ | 0 |
| Deep low relief | | ns |
| Shallow low relief | far ↑ mid ↓ near↓ | — |

**Table 8.** Continued.

| Parameter and Habitat | Distance from Platform Hidalgo and Percent Cover Trend | Effects |
|---|---|---|
| Sponge, tan encrusting | | |
| Deep high relief | mid ↑ near ↑ far ↑ | + |
| Deep low relief | far ↓ near ↓ mid ↓ | 0 |
| Shallow low relief | near ↓ mid ↓ far ↓ | — |
| Galatheidae (crabs) | | |
| Deep high relief | near ↓ far ↓ mid ↑ | 0 |
| Deep low relief | mid ↓ near ↓ far ↓ | 0 |
| Shallow low relief | far ↑ mid ↑ near ↓ | — |
| *Amphianthus californicus* (anemone) | | |
| Deep high relief | far ↓ mid ↓ near ↑ | + |
| Deep low relief | far ↓ mid ↓ near ↓ | + |
| Shallow low relief | | ns |
| *Pyura haustor* (tunicate) | | |
| Deep high relief | far ↓ mid ↓ near ↓ | + |
| Deep low relief | near ↓ far ↓ mid ↓ | — |
| Shallow low relief | near ↓ mid ↓ far ↓ | — |
| *Paracyathus stearnsii* (cup coral) | | |
| Deep high relief | near ↓ far ↓ mid ↓ | 0 |
| Deep low relief | near ↓ mid ↓ far ↓ | — |
| Shallow low relief | | ns |
| *Caryophyllia* spp. (cup coral) | | |
| Deep high relief | near ↓ far ↓ mid ↓ | — |
| Deep low relief | near ↓ mid ↓ far ↓ | — |
| Shallow low relief | | ns |

**Table 8.** Continued.

| Parameter and Habitat | Distance from Platform Hidalgo and Percent Cover Trend | Effects |
|---|---|---|
| *Desmophyllum dianthus* (cup coral) | | |
| Deep high relief | far ↓ near ↑ mid ↑ | + |
| Deep low relief | | ns |
| Shallow low relief | | ns |
| Gorgonian, red or pink | | |
| Deep high relief | far ↓ mid ↓ near ↓ | + |
| Deep low relief | far ↓ near ↓ mid ↓ | + |
| Shallow low relief | near ↓ far ↓ mid ↑ | 0 |
| Anemone, tan zoanthid | | |
| Deep high relief | far ↓ mid ↓ near ↑ | + |
| Deep low relief | near ↓ mid ↓ far ↓ | — |
| Shallow low relief | far ↓ near ↓ mid ↓ | + |
| *Laqueus californicus* (brachiopod) | | |
| Deep high relief | | ns |
| Deep low relief | near ↓ far ↓ mid ↓ | — |
| Shallow low relief | near ↓ far ↓ mid ↓ | — |
| *Stomphia didemon* (anemone) | | |
| Deep high relief | mid ↓ far ↓ near ↓ | 0 |
| Deep low relief | mid ↓ far ↓ near ↓ | 0 |
| Shallow low relief | | ns |
| Sponge, shelf | | |
| Deep high relief | far ↓ mid ↓ near ↓ | + |
| Deep low relief | | ns |
| Shallow low relief | far ↓ near ↓ mid ↑ | + |

**Table 8.** Continued.

| Parameter and Habitat | Distance from Platform Hidalgo and Percent Cover Trend | Effects |
|---|---|---|
| *Lophelia pertusa* (cup coral) | | |
| Deep high relief | | ns |
| Deep low relief | | ns |
| Shallow low relief | far ↑ mid ↑ near ↓ | — |
| *Halocynthia hilgendorfi* (tunicate) | | |
| Deep high relief | near ↓ far ↓ mid ↓ | — |
| Deep low relief | near ↓ far ↓ mid ↓ | — |
| Shallow low relief | mid ↓ far ↓ near ↓ | 0 |
| *Balanophyllia elegans* (cup coral) | | |
| Deep high relief | near ↓ mid ↓ far ↓ | — |
| Deep low relief | | ns |
| Shallow low relief | mid ↓ far ↓ near ↓ | + |

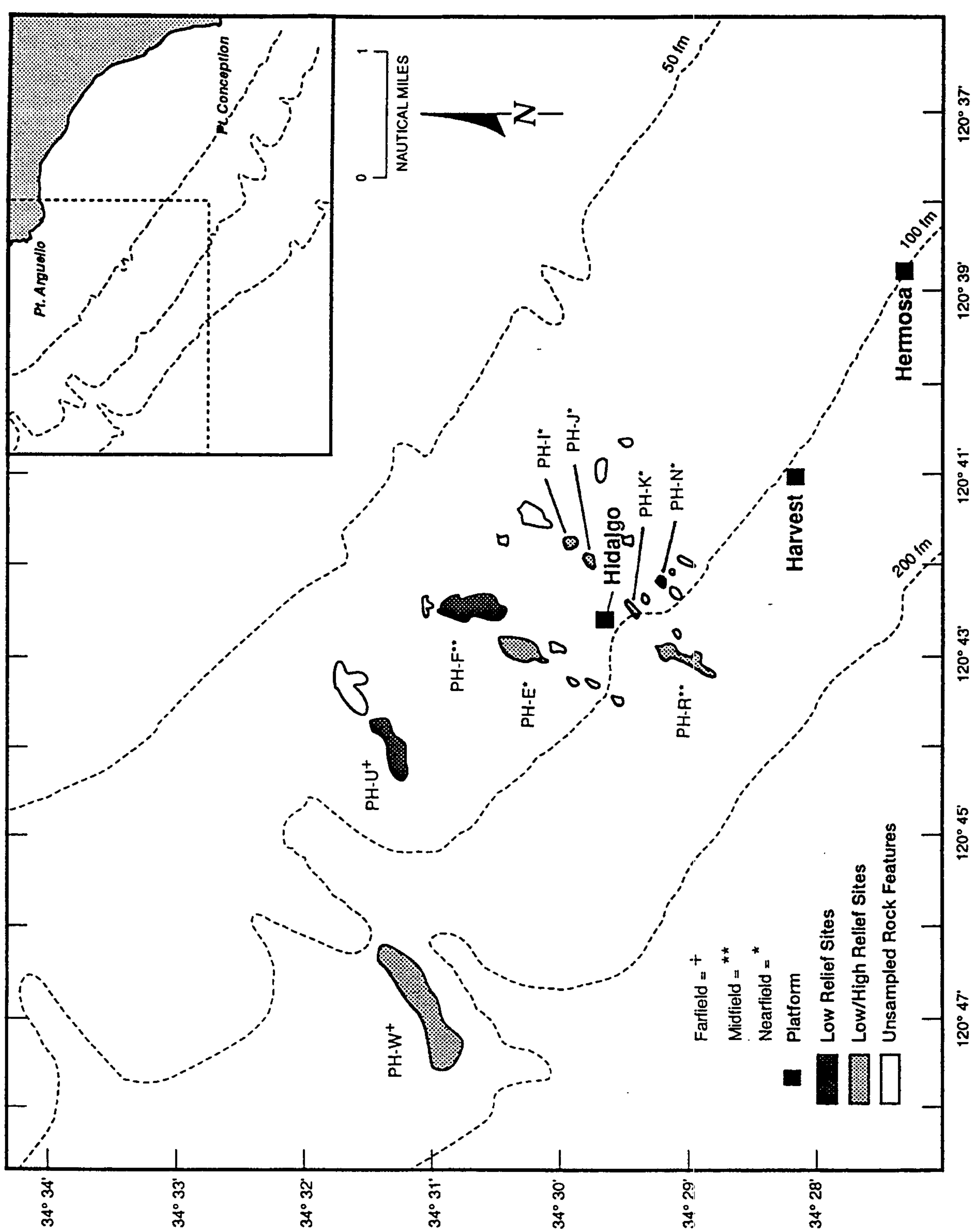
**Table 9.** Contingency table based on results of the ANCOVA analysis (see Table 8). Numbers represent a summation of potential platform effects for dominant taxa by habitat type (e.g., 10 taxa at deep, high-relief reefs showed increases or less rapid decreases in percent cover compared to the farfield site, indicating a possible enhancement effect near Platform Hidalgo). Numbers in parentheses are the frequency expected if $H_o$ is true. $H_o$: changes in percent cover of dominant taxa by habitat type is independent of proximity to Platform Hidalgo. $H_o$ not rejected, $\chi^2_{4df} = 4.07$, $p > 0.25$.

| **Platform Effects** | **Habitat** | | | **Total** |
|---|---|---|---|---|
| | **Deep High Relief** | **Deep Low Relief** | **Shallow Low Relief** | |
| + | 10 (7) | 4 (5) | 4 (5) | 18 |
| 0 | 4 (4) | 4 (3) | 3 (3) | 11 |
| — | 4 (5) | 6 (5) | 7 (5) | 17 |
| Total | 18 | 14 | 14 | 46 |

**Table 10.** Power test for dominant taxa by habitat type. Power is based on a decrease in mean percent cover for the six post-drilling surveys compared to the mean percent cover of the two predrilling surveys. Percent cover was arcsin transformed and significant temporal trends for the post-drilling survey were detrended. Numbers are the power ($1-\beta$, $\alpha=0.05$) in percent probability (e.g., 0.64=64% for *Amphianthus*) of detecting a significant decrease in mean percent cover for in the post-drilling phase. Numbers in parentheses represent the percentage of the observed decrease in mean percent cover that would be needed to be detectable with a power of 80% ($\beta=0.2$). For example, 0.19 for *Metridium* would indicate that the observed decrease in percent cover was only 19% of the change needed to detect a significant decrease with 80% power.

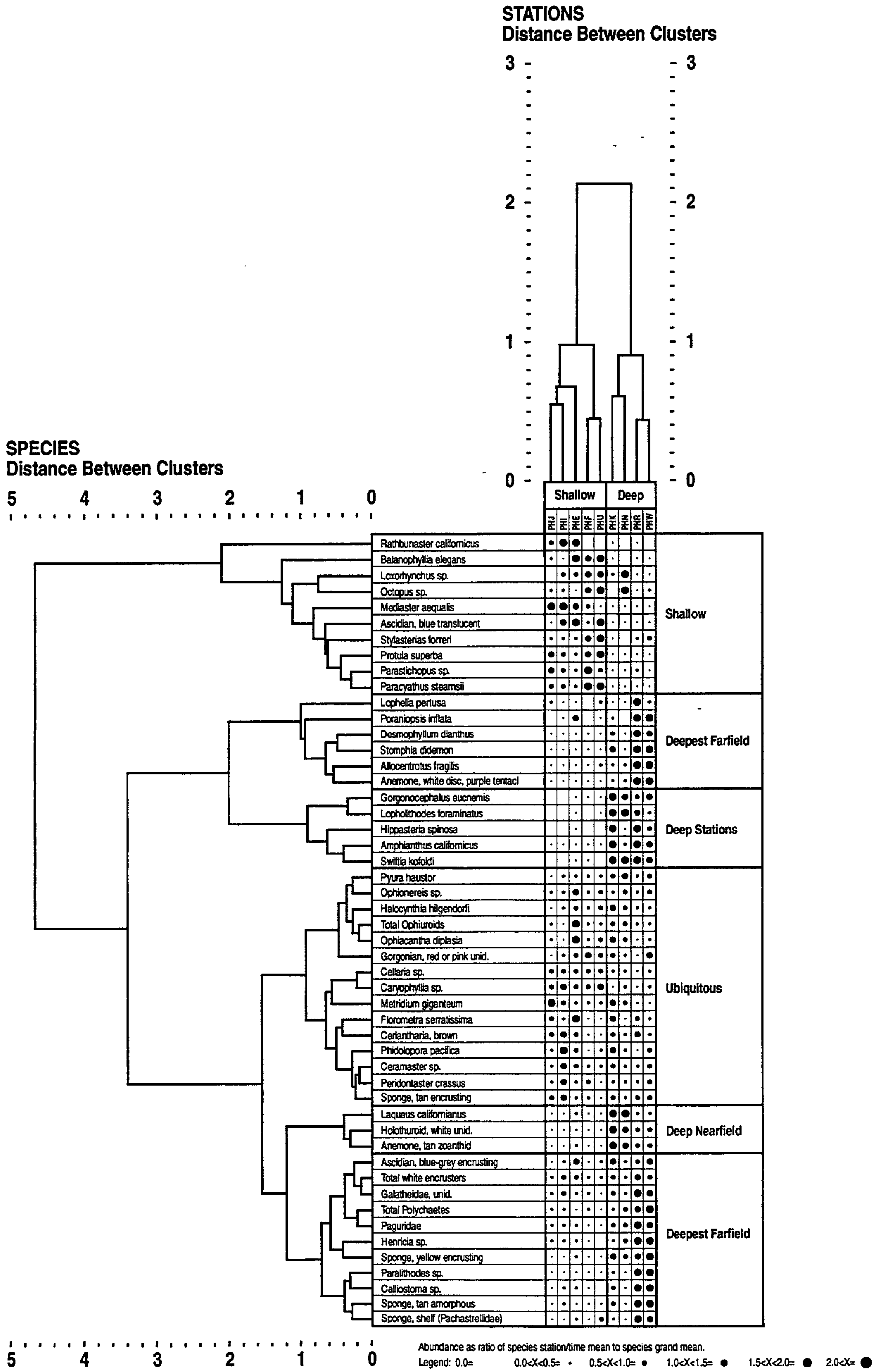
| Taxa | Deep Reefs High Relief | | Deep Reefs Low Relief | | Shallow Reefs Low Relief | |
|---|---|---|---|---|---|---|
| | Farfield | Nearfield | Farfield | Nearfield | Farfield | Nearfield |
| Cnidaria | | | | | | |
| *Amphianthus californicus* | 1.00 (2.4) | | 0.64 (.80) | | | 0.11 (.16) |
| Anemone, tan zoanthid | 0.26 (.40) | | 0.09 (.12) | | 0.07 (.08) | 0.05 (.06) |
| *Metridium giganteum* | | | 0.13 (.20) | | | 0.16 (.19) |
| *Stomphia didemon* | | | | | 0.07 (.06) | 0.10 (.13) |
| Cnidaria (cupcorals) | | | | | | |
| *Balanophyllia elegans* | | 0.09 (0.08) | | | | 0.12 (.21) |
| *Caryophyllia* spp. | 0.12 (.18) | 0.98 (1.50) | 0.24 (.38) | 0.44 (.60) | | 0.08 (.09) |
| *Desmophyllum dianthus* | 0.77 (.96) | | 0.09 (.14) | 0.05 (.07) | | 0.08 (.10) |
| *Lophelia pertusa* | 0.51 (.67) | | 0.10 (.14) | | | 0.10 (.15) |
| *Paracyathus stearnsii* | 0.16 (.26) | 0.15 (.24) | 0.16 (.28) | 0.51 (.67) | | 0.52 (.68) |
| Cnidaria gorgonian | | | | | | |
| Gorgonian, red or pink | 0.34 (.50) | | 0.82 (1.04) | 0.08 (.10) | 0.16 (.26) | 0.07 (.08) |
| Brachiopoda | | | | | | |
| *Laqueus californianus* | 0.06 (.04) | 0.23 (.36) | | 1.00 (1.47) | 0.09 (.15) | 0.70 (.88) |
| Crustacea (crabs) | | | | | | |
| Galatheidae | | | 0.12 (.19) | 0.72 (.89) | | 0.06 (.05) |
| Echinodermata | | | | | | |
| *Florometra serratissima* | | | 0.17 (.28) | | | 0.37 (.52) |
| Urochordata | | | | | | |
| *Halocynthia hilgendorfi* | 0.07 (.05) | 0.09 (.10) | 0.25 (.40) | 0.42 (.58) | 0.10 (.10) | 0.12 (.17) |
| *Pyura haustor* | 0.74 (.92) | 0.06 (.02) | 0.29 (.43) | 0.95 (1.30) | 0.12 (.18) | 0.52 (.69) |

Figure 1



Pt. Arguello
Pt. Conception
0
1
NAUTICAL MILES
N
50 fm
100 fm
200 fm
Hermosa
Harvest
Hidalgo
PH-I*
PH-J*
PH-K*
PH-N*
PH-F**
PH-E*
PH-R**
PH-U+
PH-W+
Farfield = +
Midfield = **
Nearfield = *
Platform
Low Relief Sites
Low/High Relief Sites
Unsampled Rock Features
120° 37'
120° 39'
120° 41'
120° 43'
120° 45'
120° 47'
34° 34'
34° 33'
34° 32'
34° 31'
34° 30'
34° 29'
34° 28'

Figure 2



STATIONS
Distance Between Clusters
3
2
1
0
Shallow
Deep
PHJ
PHI
PHE
PHF
PHU
PHK
PHN
PHR
PHW
SPECIES
Distance Between Clusters
5
4
3
2
1
0
Rathbunaster californicus
Balanophyllia elegans
Loxorhynchus sp.
Octopus sp.
Mediaster aequalis
Ascidian, blue translucent
Stylasterias forreri
Protula superba
Parastichopus sp.
Paracyathus stearnsii
Lophelia pertusa
Poraniopsis inflata
Desmophyllum dianthus
Stomphia didemon
Allocentrotus fragilis
Anemone, white disc, purple tentacl
Gorgonocephalus eucnemis
Lopholithodes foraminatus
Hippasteria spinosa
Amphianthus californicus
Swiftia kofoidi
Pyura haustor
Ophionereis sp.
Halocynthia hilgendorfi
Total Ophiuroids
Ophiacantha diplasia
Gorgonian, red or pink unid.
Cellaria sp.
Caryophyllia sp.
Metridium giganteum
Florometra serratissima
Ceriantharia, brown
Phidolopora pacifica
Ceramaster sp.
Peridontaster crassus
Sponge, tan encrusting
Laqueus californianus
Holothuroid, white unid.
Anemone, tan zoanthid
Ascidian, blue-grey encrusting
Total white encrusters
Galatheidae, unid.
Total Polychaetes
Paguridae
Henricia sp.
Sponge, yellow encrusting
Paralithodes sp.
Calliostoma sp.
Sponge, tan amorphous
Sponge, shelf (Pachastrellidae)
Shallow
Deepest Farfield
Deep Stations
Ubiquitous
Deep Nearfield
Deepest Farfield
Abundance as ratio of species station/time mean to species grand mean.
Legend: 0.0=  0.0<X<0.5=  0.5<X<1.0=  1.0<X<1.5=  1.5<X<2.0=  2.0<X=

**Figure 3**

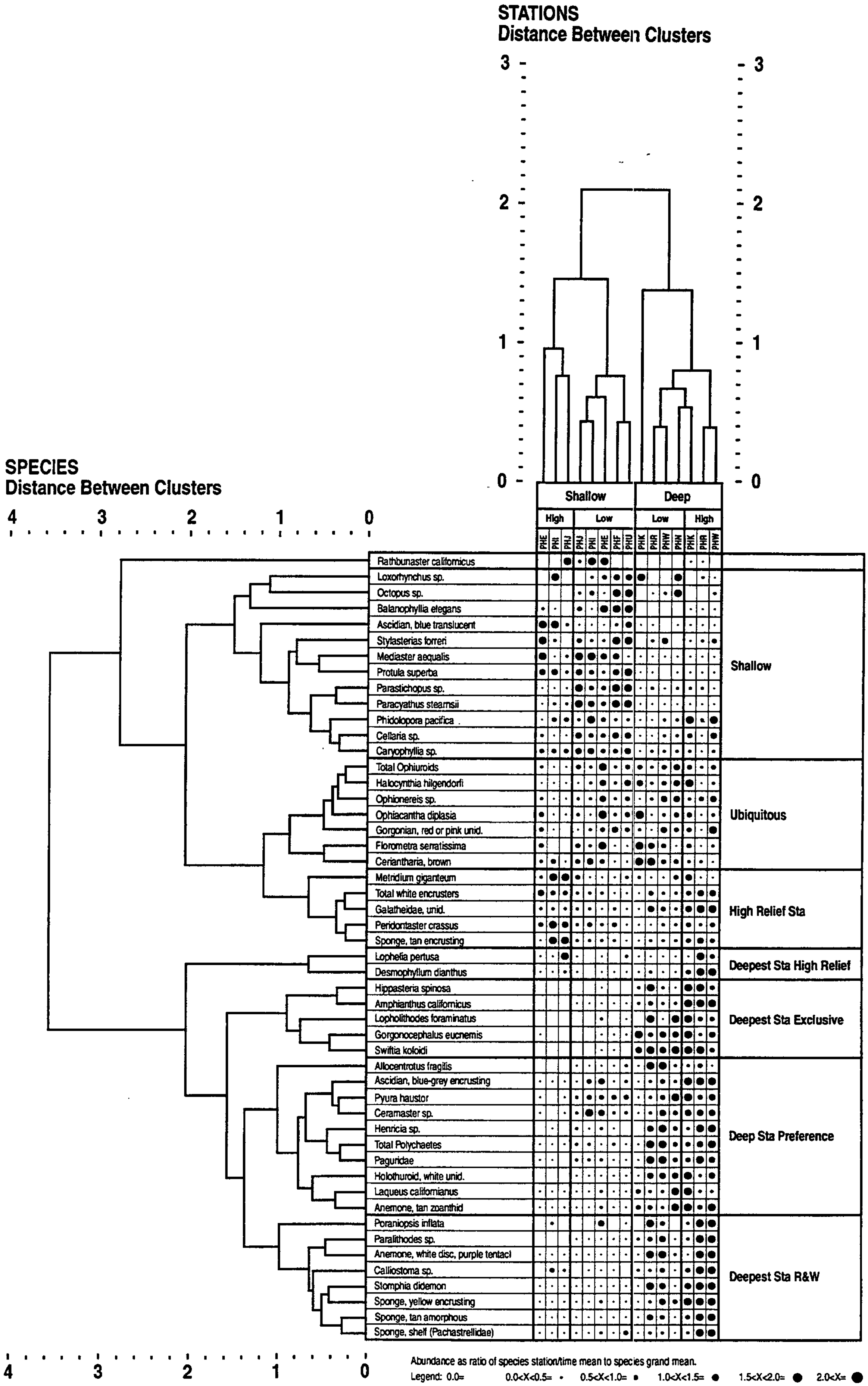
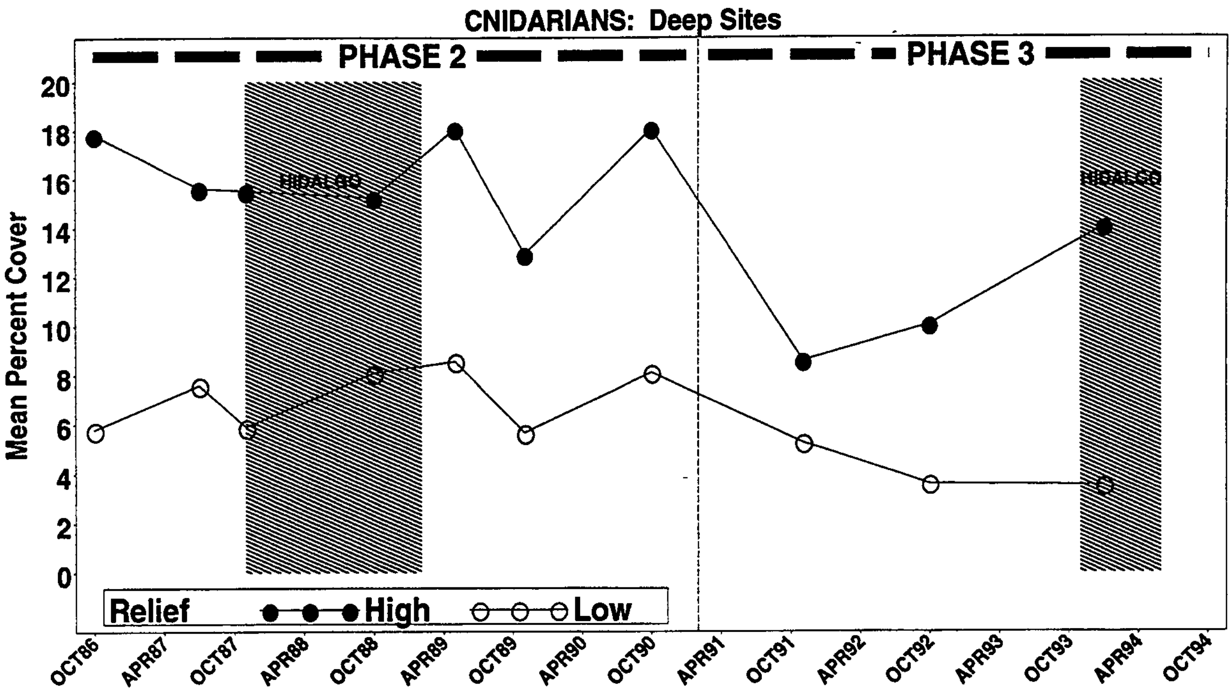

STATIONS
Distance Between Clusters
3
2
1
0
Shallow
Deep
High
Low
Low
High
PHE
PHI
PHJ
PHJ
PHI
PHE
PHF
PHU
PHK
PHR
PHW
PHN
PHK
PHR
PHW
SPECIES
Distance Between Clusters
4
3
2
1
0
Rathbunaster californicus
Loxorhynchus sp.
Octopus sp.
Balanophyllia elegans
Ascidian, blue translucent
Stylasterias forreri
Mediaster aequalis
Protula superba
Parastichopus sp.
Paracyathus stearnsii
Phidolopora pacifica
Cellaria sp.
Caryophyllia sp.
Total Ophiuroids
Halocynthia hilgendorfi
Ophionereis sp.
Ophiacantha diplasia
Gorgonian, red or pink unid.
Florometra serratissima
Ceriantharia, brown
Metridium giganteum
Total white encrusters
Galatheidae, unid.
Peridontaster crassus
Sponge, tan encrusting
Lophelia pertusa
Desmophyllum dianthus
Hippasteria spinosa
Amphianthus californicus
Lopholithodes foraminatus
Gorgonocephalus eucnemis
Swiftia kofoidi
Allocentrotus fragilis
Ascidian, blue-grey encrusting
Pyura haustor
Ceramaster sp.
Henricia sp.
Total Polychaetes
Paguridae
Holothuroid, white unid.
Laqueus californianus
Anemone, tan zoanthid
Poraniopsis inflata
Paralithodes sp.
Anemone, white disc, purple tentacl
Calliostoma sp.
Stomphia didemon
Sponge, yellow encrusting
Sponge, tan amorphous
Sponge, shelf (Pachastrellidae)
Shallow
Ubiquitous
High Relief Sta
Deepest Sta High Relief
Deepest Sta Exclusive
Deep Sta Preference
Deepest Sta R&W
Abundance as ratio of species station/time mean to species grand mean.
Legend: 0.0= 0.0<X<0.5= • 0.5<X<1.0= • 1.0<X<1.5= ● 1.5<X<2.0= ● 2.0<X= ●

**Figure 4**


CNIDARIANS: Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
0
2
4
6
8
10
12
14
16
18
20
Relief
High
Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

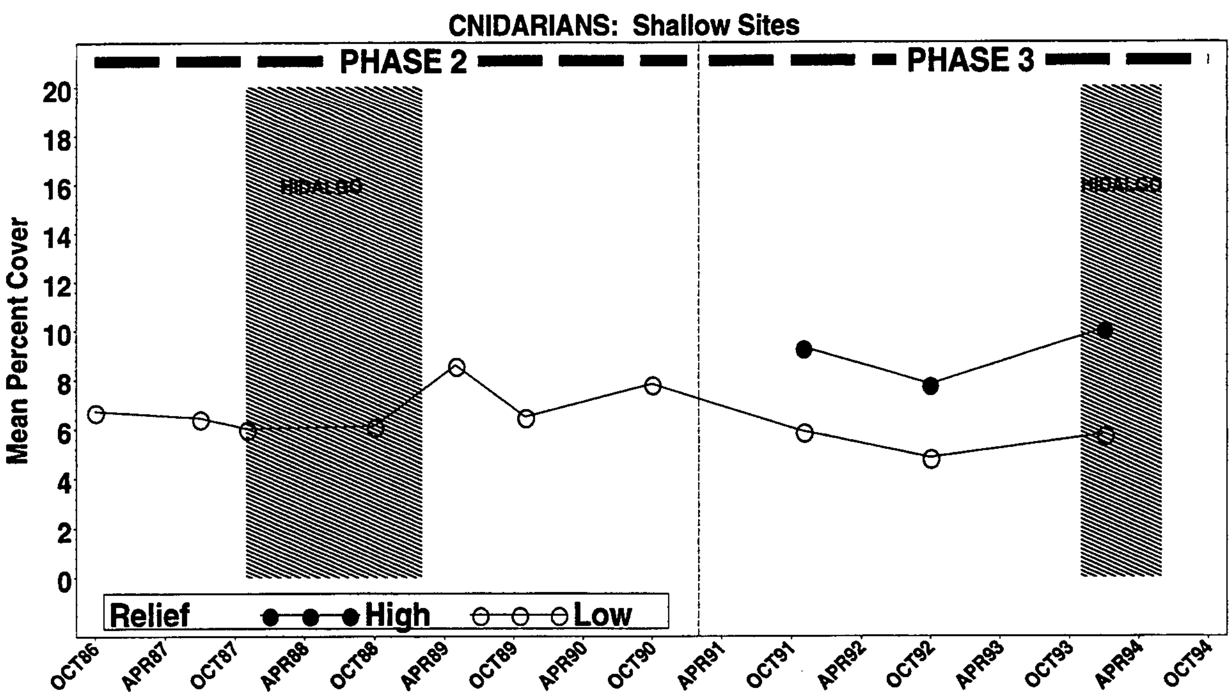
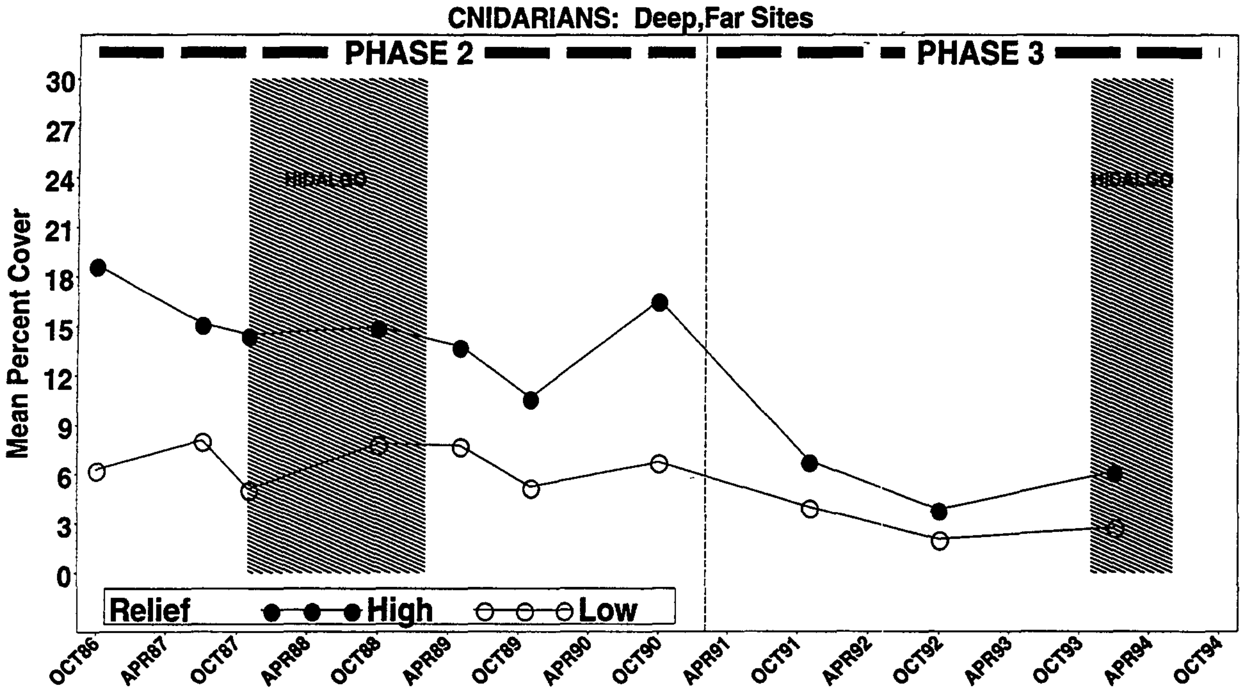
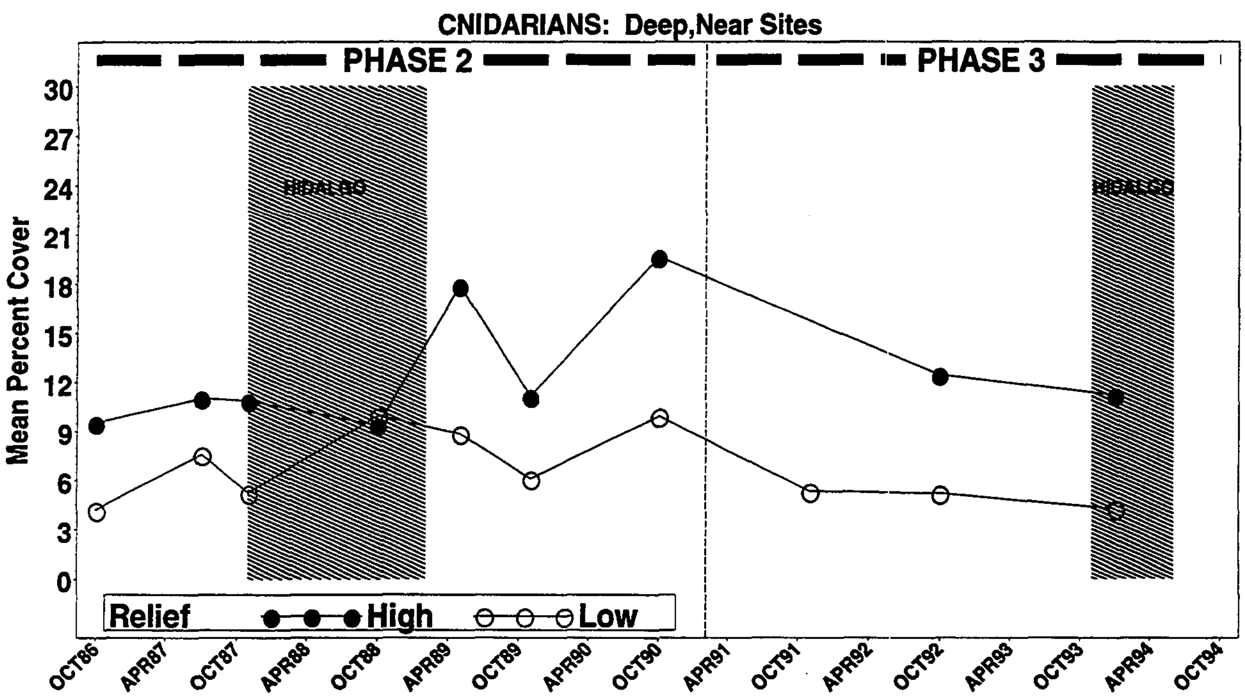

CNIDARIANS: Shallow Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
0
2
4
6
8
10
12
14
16
18
20
Relief
High
Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

Figure 5

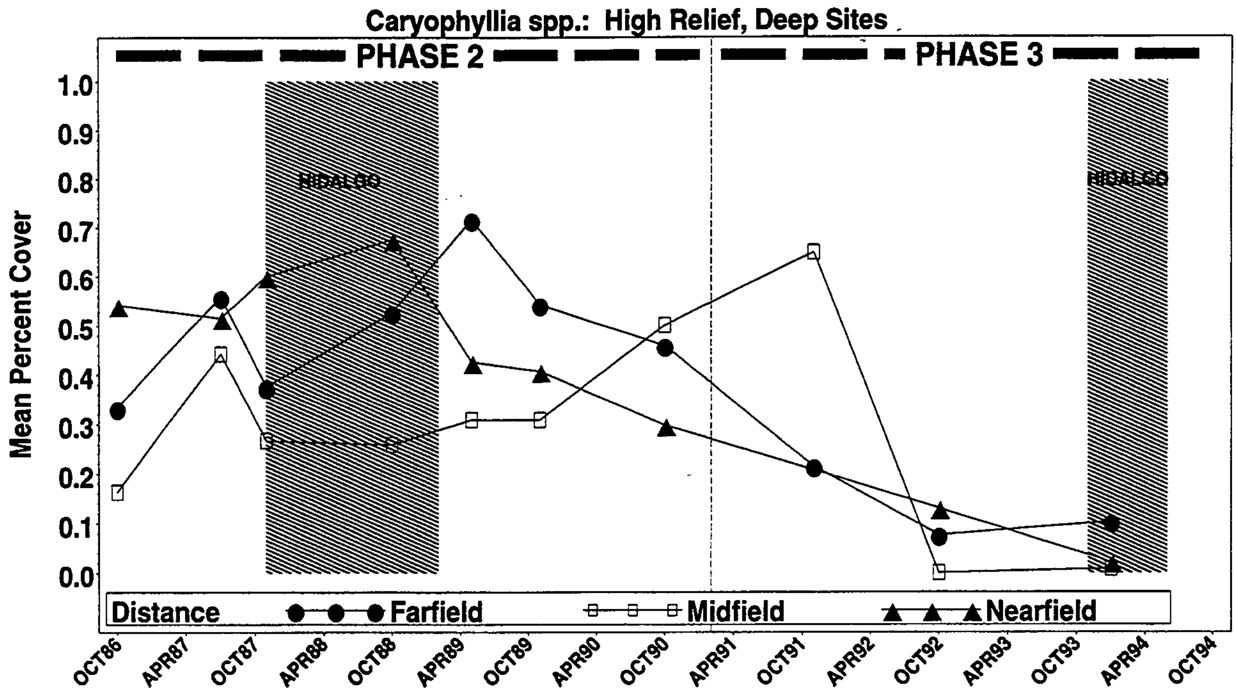


CNIDARIANS: Deep,Far Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
30
27
24
21
18
15
12
9
6
3
0
Relief
High
Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

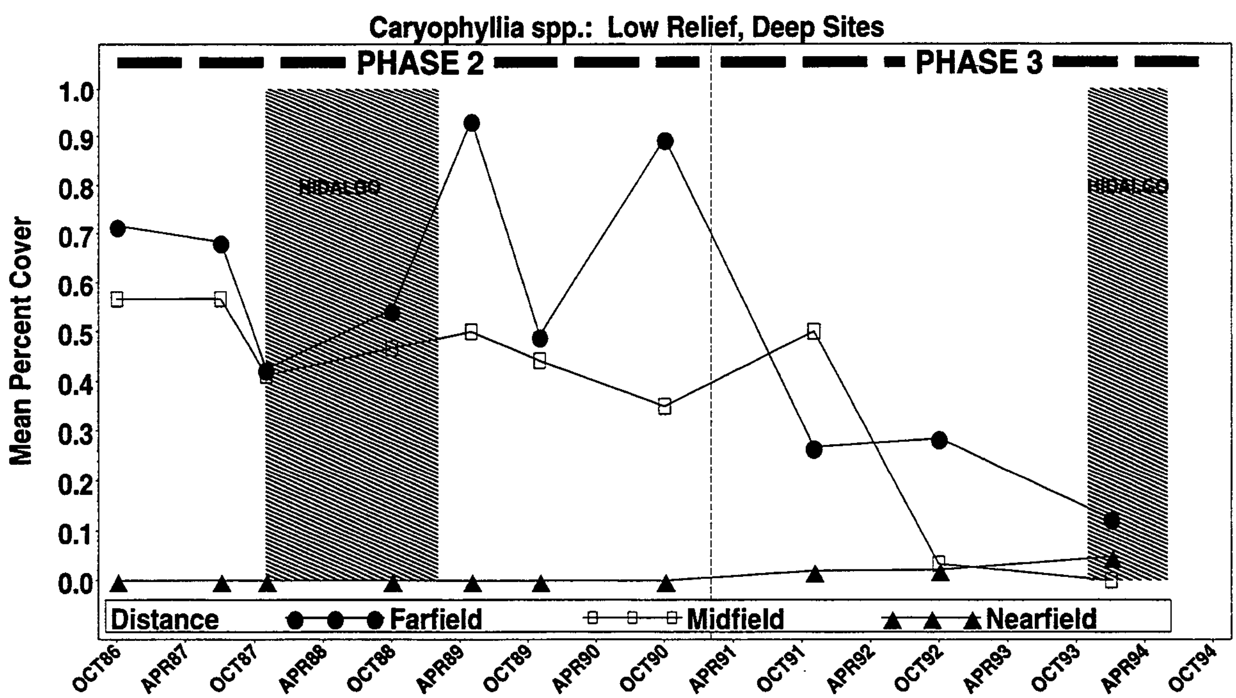



CNIDARIANS: Deep,Near Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
30
27
24
21
18
15
12
9
6
3
0
Relief
High
Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

Figure 6

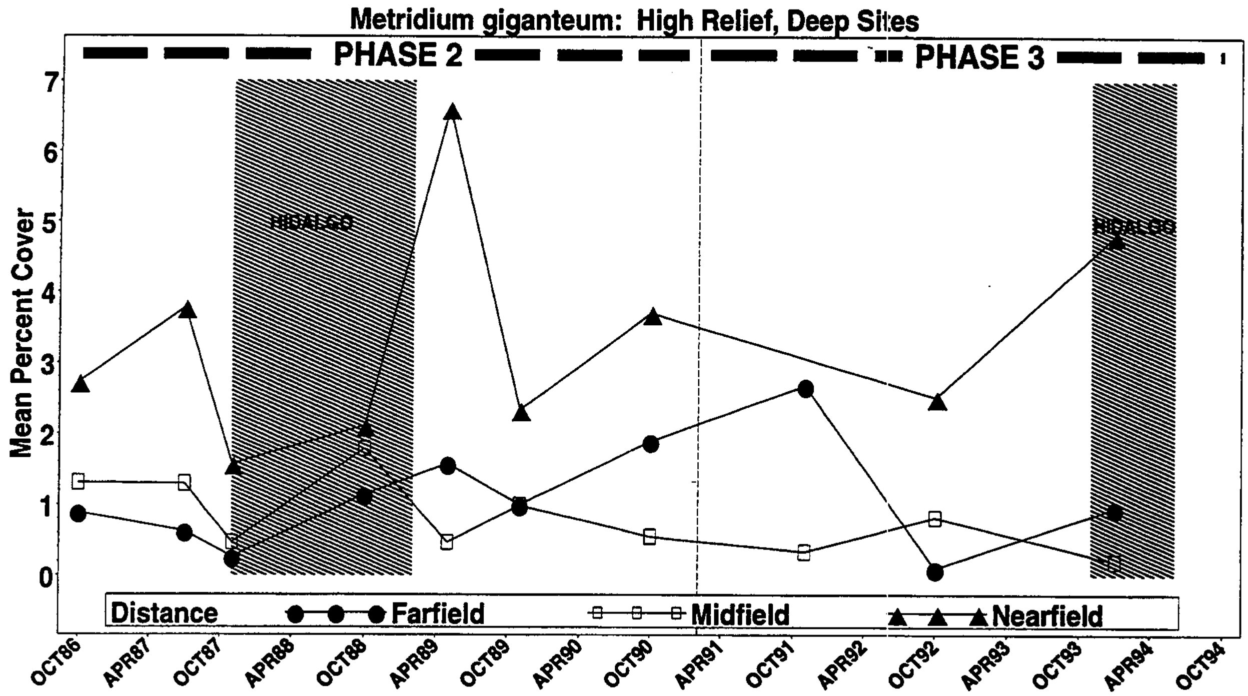


Caryophyllia spp.: High Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

Caryophyllia spp.: Low Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

Figure 7


Metridium giganteum: High Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
7
6
5
4
3
2
1
0
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

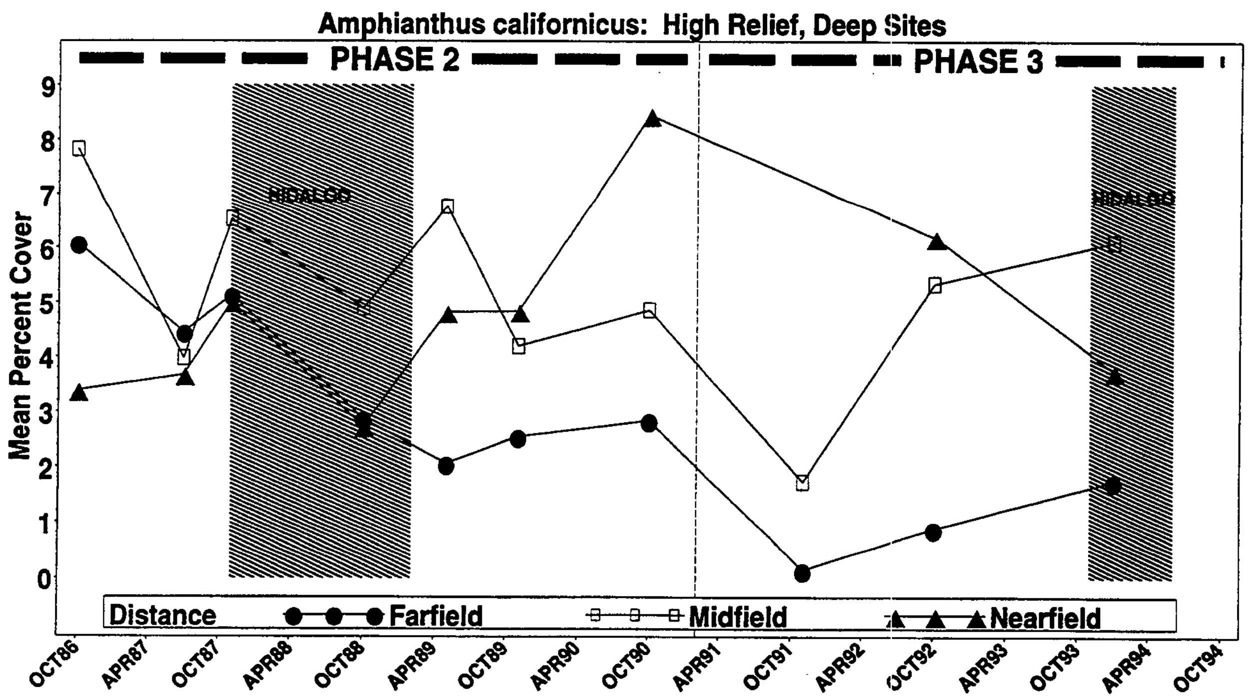
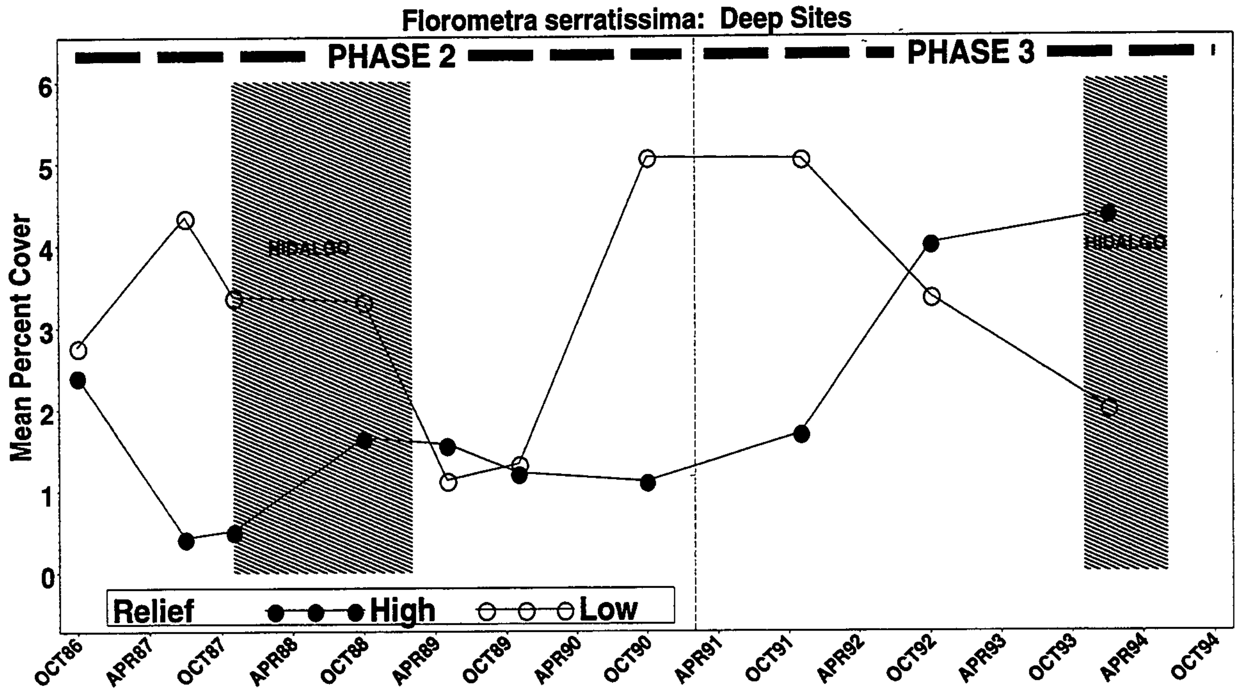
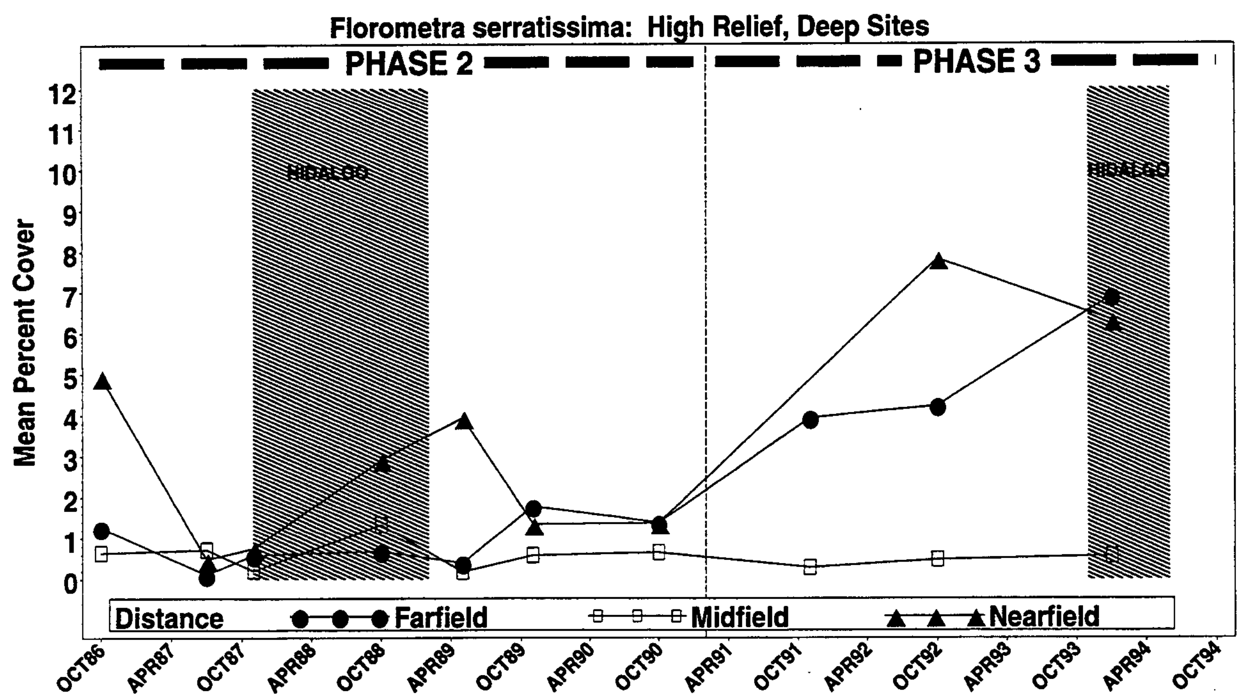
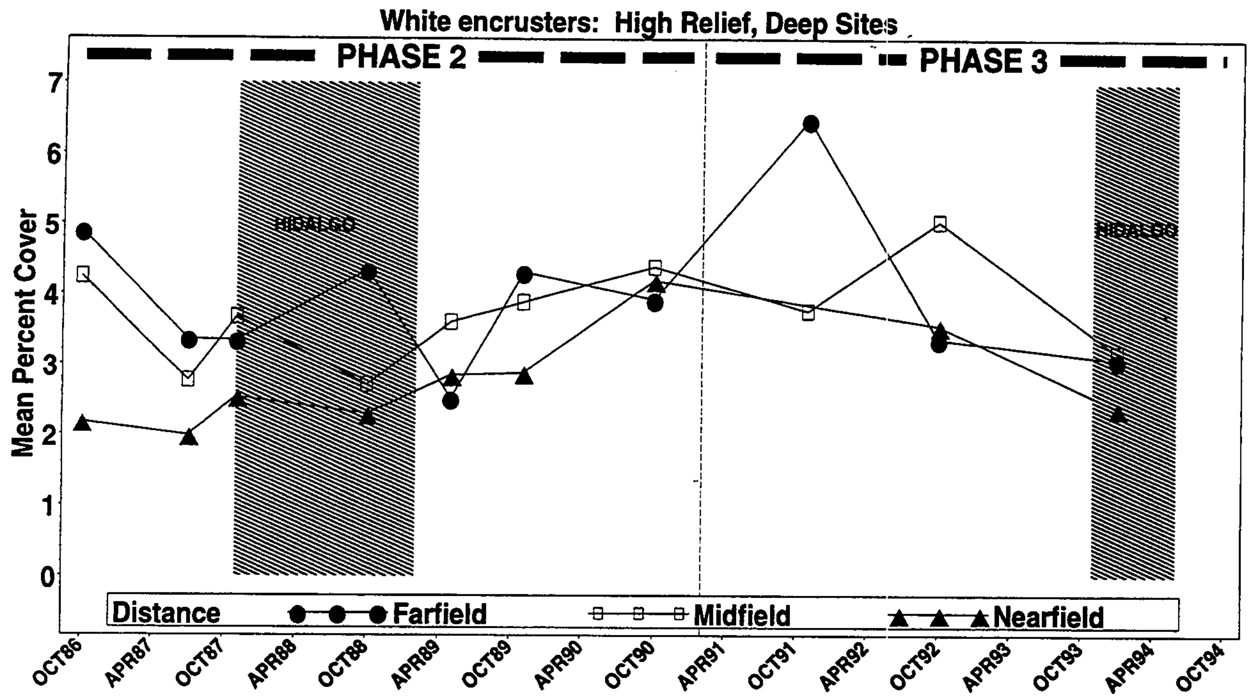
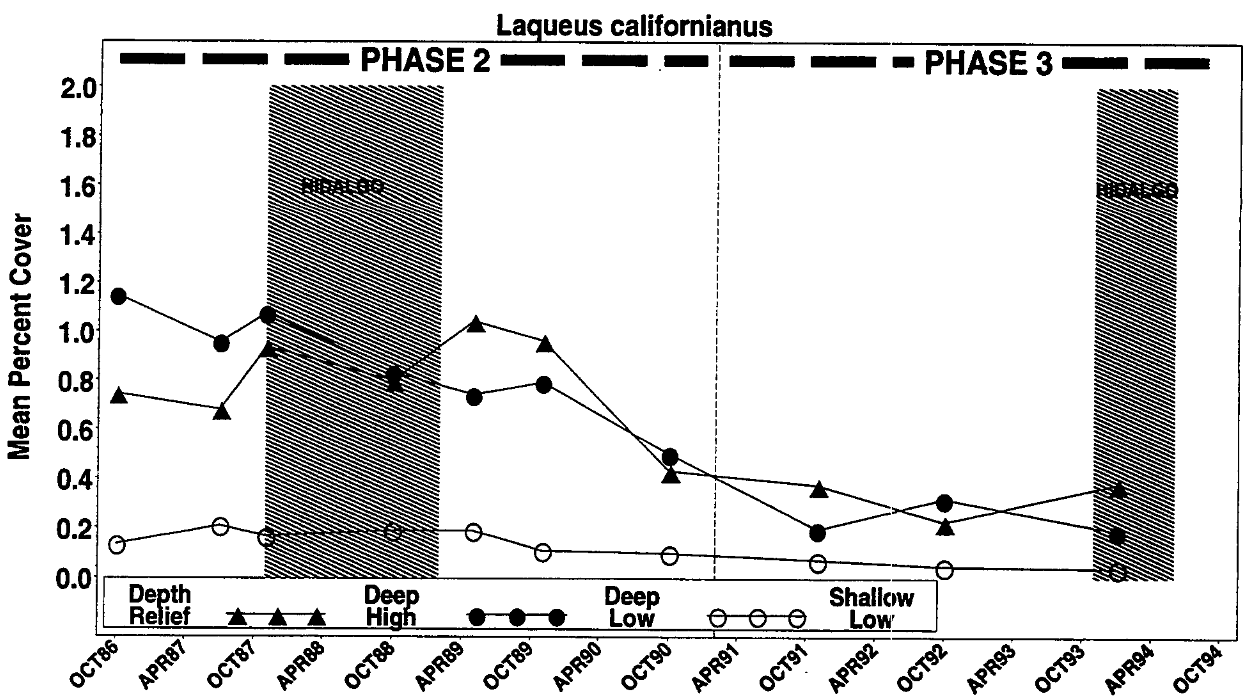

Amphianthus californicus: High Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
9
8
7
6
5
4
3
2
1
0
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

Figure 8

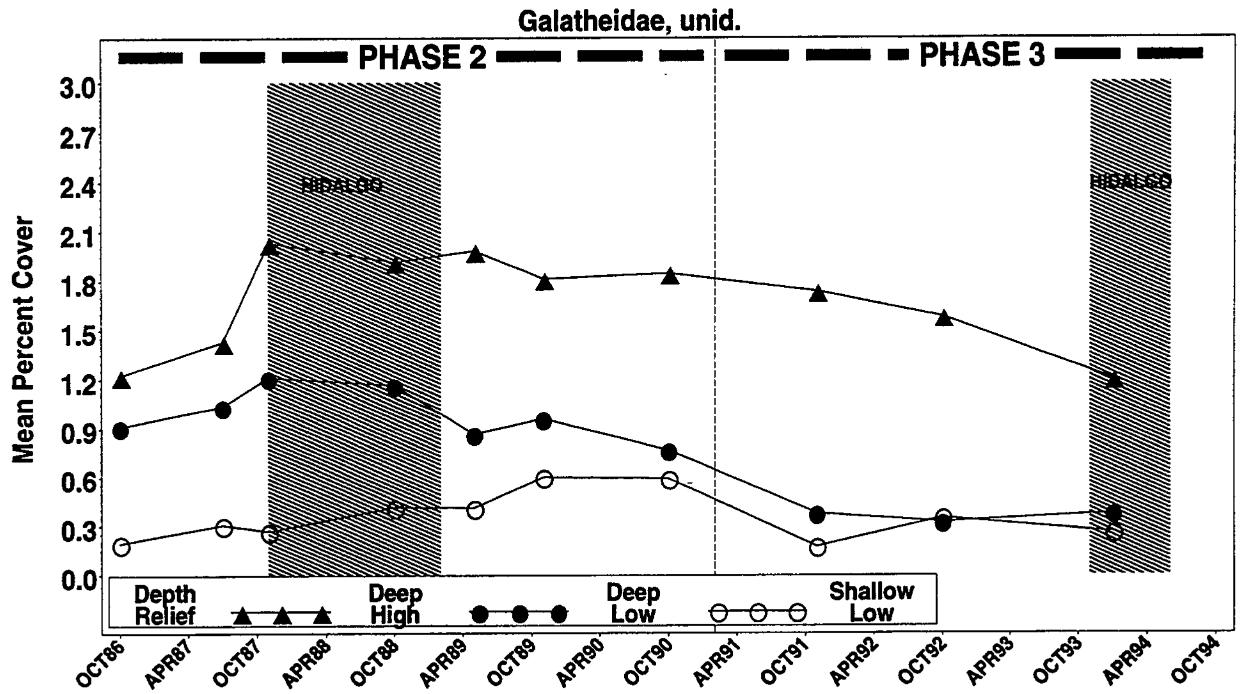

Florometra serratissima: Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
0
1
2
3
4
5
6
Relief
High
Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94


Florometra serratissima: High Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
0
1
2
3
4
5
6
7
8
9
10
11
12
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

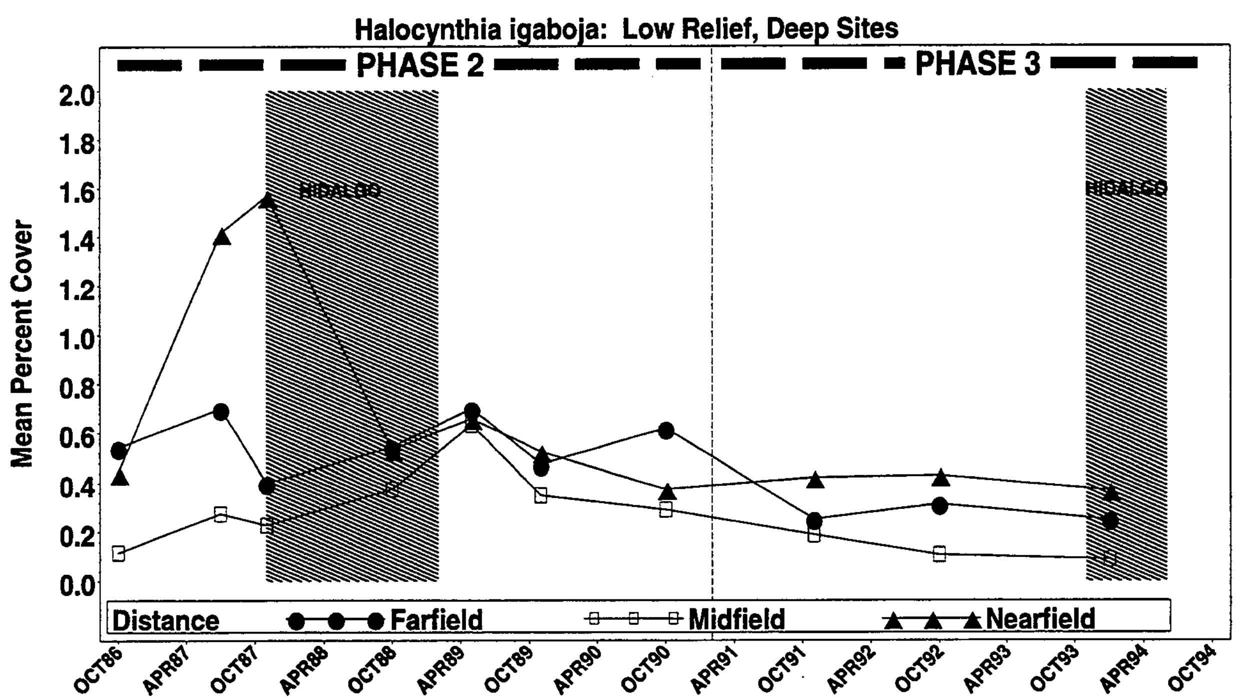

White encrusters: High Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
0
1
2
3
4
5
6
7
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94


Laqueus californianus
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
Depth Relief
Deep High
Deep Low
Shallow Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

# Figure 10

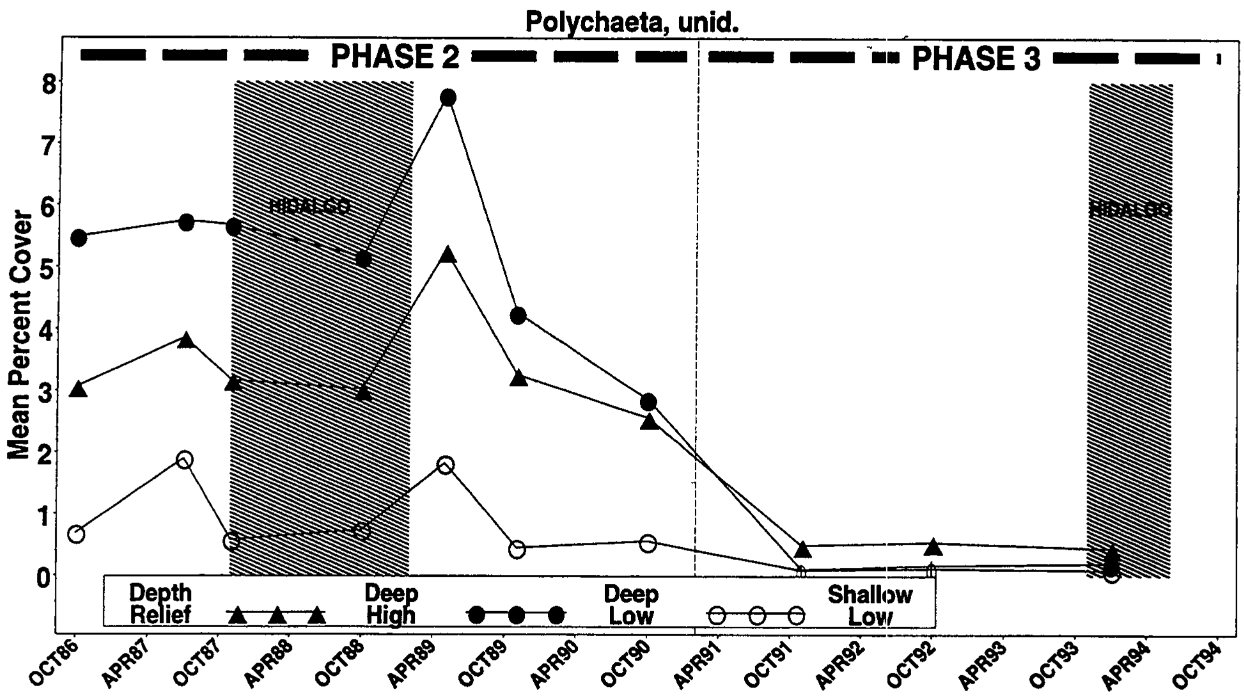


Galatheidae, unid.
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
3.0
2.7
2.4
2.1
1.8
1.5
1.2
0.9
0.6
0.3
0.0
Depth Relief
Deep High
Deep Low
Shallow Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

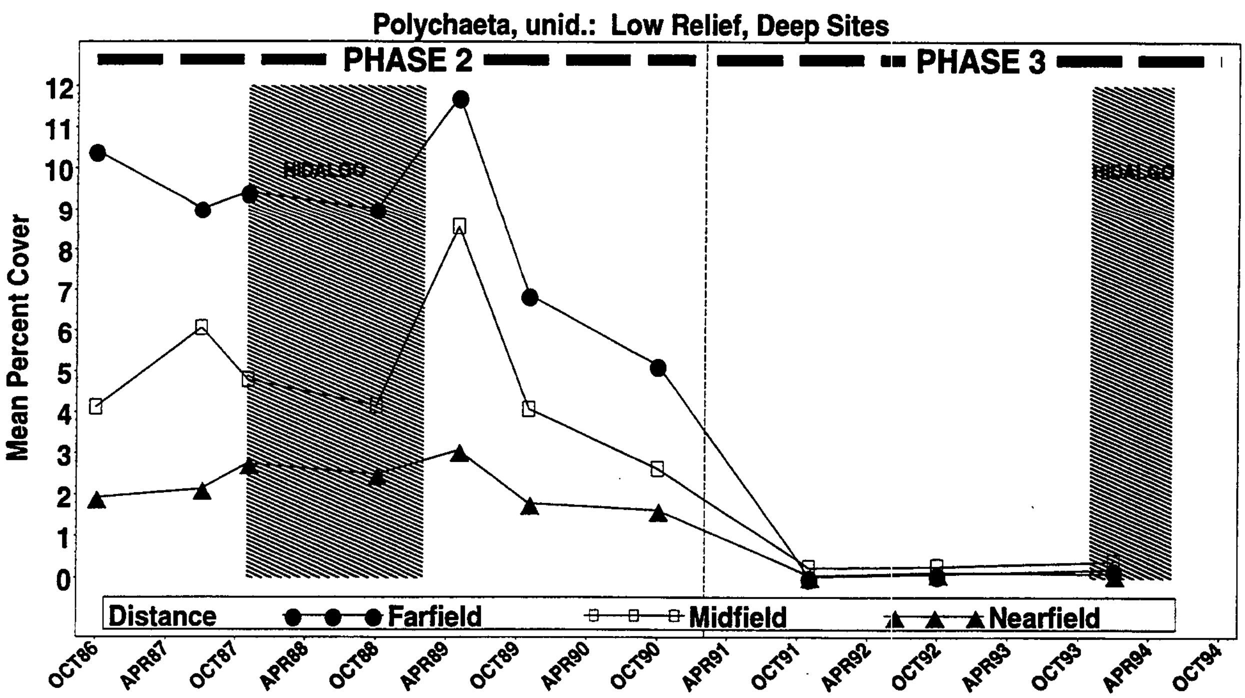



Halocynthia igaboja: Low Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

Figure 1



Polychaeta, unid.
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
8
7
6
5
4
3
2
1
0
Depth Relief
Deep High
Deep Low
Shallow Low
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

Polychaeta, unid.: Low Relief, Deep Sites
PHASE 2
PHASE 3
HIDALGO
HIDALGO
Mean Percent Cover
12
11
10
9
8
7
6
5
4
3
2
1
0
Distance
Farfield
Midfield
Nearfield
OCT86
APR87
OCT87
APR88
OCT88
APR89
OCT89
APR90
OCT90
APR91
OCT91
APR92
OCT92
APR93
OCT93
APR94
OCT94

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.