SURFACE AND SUBSURFACE FAULTING IN NORTON SOUND AND CHIRIKOV BASIN, ALASKA

By

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SUMMARY

Seismic reflection data were obtained in July 1977 by the U. S. Geological Survey aboard R/V **SEA SOUNDER** along 2800 km of track in Norton Sound and northeaster Chirikov basin. These data and records from several previous surveys were analyzed in order to determine the location, extent, and possible age and activity potential of offshore faulting. Acoustic reflection records were obtained using sparkers (160 and 0.8 kilojoule), Uniboom (1200 joule), and 3.5 kHz subbottom profiler. Sidescan sonar measurements were made along some of the tracklines whenever the large sparker was not deployed.

Maps showing the distribution of surface, near-surface, and deeper subbottom faults show that faulting occurs most commonly within 50 km of the margins of Norton basin, the deep sedimentary trough which underlies Norton Sound and Chirikov basin. A smaller number of faults were detected in the central regions of the basin.

Surface fault scarps were seen in several places in northern Chirikov basin. These sea-floor offsets ranged in height from 5 to 15 m along several west-trending faults which may be associated with some of the major transcurrent faults in Alaska. The existence of these scarps

indicates possible disturbance of sedimentary deposits over the fault, although the scarps may have been maintained by non-deposition. Evidence from both onshore and offshore field studies indicate that movement along these faults may have occurred between 12,000-120,000 years ago.

Many northwest-trending faults were mapped around the margins and in the central regions of Norton basin; they appear to show increasing displacement with depth and a thickening of the strata as they dip basin-ward away from the fault. These characteristics indicate a more or less continual movement along the faults as Norton basin was subsiding. The lack of recorded earthquakes in Norton basin during historical time implies that either activity along the offshore faults has ceased, or that movement is taking place at a slow but steady rate, preventing a buildup of strain and consequent earthquake-producing ruptures.

The west-trending faults in northern Chirikov basin appear to offset, and therefore postdate, the northwest trending faults which parallel the Norton basin axis. These two intersecting trends may have resulted from a change in the direction of regional compression during late Tertiary or early Quarternary time.

Considerable sea-floor relief hampered identification of surface scarps associated with offshore faults near St. Lawrence Island; and horizontal (transcurrent) motions along these faults may have taken place during Quaternary time in conjunction with movements on the Kaltag Fault which displaced Pleistocene deposits in western Alaska.

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INTRODUCTION

Geological and geophysical studies were carried out by U. S. Geological Survey personnel aboard R/V SEA SOUNDER in Norton Sound and Chirikov basin during July 1977 (Fig. B1). Acoustic survey systems used included 160 and 0.8 kilojoule sparkers, a 1200 joule (four transducer) Uniboom, a 3.5 kHz bathymetric/subbottom profiling system, and sidescan sonar. This section of the annual report deals primarily with an interpretation of the extent and hazard potential of the surface and subsurface faults shown on the sparker and Uniboom records. Discussions of the 3.5 kHz and sidescan sonar data will be found in other sections.

The geophysical data obtained on this recent USGS cruise has been supplemented in places by seismic reflection information which was collected on previous expeditions by the USGS, NOAA, and the University of Washington (Fig. B1). In 1967 a joint USGS/University of Washington cruise obtained 4200 km of 1S0 joule sparker data (Grim and McManus, 1970), and 3200 km of 120 kilojoule sparker records (Scholl and Hopkins, 1969). High-resolution seismic reflection surveys were conducted in 1967 in the nearshore region south of Nome between Sledge Island and Cape Nome (Tagg and Greene, 1973). Walton et al. (1969) shot 3840 km of single channel 40 in^3 air gun records during a joint USGS/NOAA (then ESSA) survey in 1969, and that same year an additional 800 km of 150 joule sparker records were collected in Chirikov basin on a joint USGS/University of Washington cruise. Johnson and Holmes (1977) reported on preliminary results of a study of recent faulting in the northern Bering Sea, based primarily on examination of approximately 3000 km of seismic reflection data collected aboard R/V SEA SOUNDER in September and October 1976. Holmes et al. (1978) obtained an additional 675 km of single channel air gun reflection data and 13 refraction profiles in Norton Sound during a survey conducted by the USGS aboard R/V LEE in October 1977.

All seismic records, sidescan records, and navigational data from the 1976 and 1977 R/V SEA SOUNDER cruises are on microfilm. Copies can be obtained from the National Geophysical and Solar-Terrestrial Data Center, EDS/NOAA, Boulder, Colorado 80302, or from the Alaska Technical Data Unit, USGS, 345 Middlefield Road, Menlo Park, California 94025.

METHODS

This section discusses the instrumentation and procedures used in collecting navigation and acoustic survey data on the R/V SEA SOUNDER cruise in July 1977.

Navigation

Navigational information was obtained by two independent systems. A Magnavox satellite navigator with integrated Teledyne Loran C received inputs from the ship's speed log and gyro. This system computed dead reckoning positions every two seconds and the data were stored on magnetic tape and a teleprinter. Performance of the system was degraded somewhat by proximity to the Loran C master station at Port Clarence and the high elevation of many of the satellites during transit.

A Motorola mini-Ranger system was used to obtain fixes every seven and one-half minutes which were recorded on paper tape in digital form, This system measures the range to two or more shore-based transponders which were maintained by survey personnel on land. On a few occasions the included angle between the transponders was too small to permit obtaining reliable fix information.

Fixes were plotted at least every fifteen minutes on the navigational charts with appropriate notations made at the time of major course and speed changes. Radar and line-of-sight bearings were sometimes used to augment the other navigational information, and navigational accuracy probably averaged ± 1S0 m.

Acoustic Survey Techniques

Figure B1 shows the tracklines for the 1977 R/V SEA SOUNDER cruise, as well as those of previous expeditions on which seismic reflection data were collected. The figure also notes which acoustic systems were used during the various cruises. The bathymetry-subbottom profiler and sidescan sonar systems used aboard R/V SEA SOUNDER will be briefly discussed, although interpretation of these data will be, as previously mentioned, found in other sections of the report.

Seismic profiling operations aboard R/V SEA SOUNDER were carried out at speeds ranging from 4-6 knots. It was found that speeds greater or less than this range resulted in generation of "ship noise" by the propulsion machinery which produced a significant amount of interference on the records.

Sparker. A Teledyne SSP (Seismic Section Profiler) was used to obtain 325 km of single channel seismic reflection records in Norton Sound and northeastern Chirikov basin. Power output was normally 160 kilojoules, but was reduced to 120 kilojoules at times because of equipment casualties. The signals were received by a Teledyne 100-element Hydrostreamer and processed through a Teledyne seismic amplifier before being printed off a modified Raytheon PFR (Precision Fathometer Recorder). Frequency pass band was normally set at 20-98 Hz, and sweep and fire rate was 4 seconds. The records were annotated at 30 minute intervals with date, time (GMT'), line number, water depth, and appropriate instrument settings. Changes in course, speed, or instrumentation were noted when they occurred.

Maximum penetration achieved by the sparker was approximately 2.1 km. The quality of the records was affected adversely by the shallow water and the generally flat nature of the bottom and subbottom reflectors. The shallow depth caused the water bottom multiple to appear at small distances below the initial sea-floor reflection, thus partially obscuring signals from deeper reflectors. The flat subbottom layering produced intra-nonnational or "peg-leg" multiples which also obscured or interfered with the primary reflections. In only a few places was an acoustic basement detected; more commonly the reflection amplitudes slowly decreased as the signal was attenuated in the sedimentary section.

Uniboom. Approximately 2800 km of high-resolution records were obtained using a hull-mounted EG & G Uniboom system consisting of four transducer plates. Total power level for this array was 1200 joules. An EG & G model 265 hydrophore streamer (lO-element) was used as a receiver. Records were printed on an EPC 4100 recorder after passing through a Krohn-Hite filter. Sweep and fire rate was normally 1/4 second, although a 1/2 second sweep was used on occasion. The filter pass band was typically set from 400-4000 Hz. Time marks were made at 5 minute intervals and record annotations similar to those for the sparker were made at 15 minute intervals.

The quality of the Uniboom records was most affected by sea state, surficial bottom sediment type, and machinery generated ship noise. The hydrophore streamer was towed alongside the ship and only 20-30 cm below the surface. Consistently choppy seas were responsible for a significant amount of noise on the record which sometimes totally obscured subbottom reflectors. Maximum penetration achieved was approximately 100 m, but was typically less than 7S m. Whenever coarse-grained and hard sediments were encountered penetration was severely reduced, and in some instances, such as near the Yukon Delta, the records are very poor.

Bathymetry/Subbottom Profiler. These data were collected along 2800 km of track using a Raytheon 3.5 kHz CESP II system. A hull-mounted transducer array consisting of 12 TR-109A units was used to send and receive the signals. Pulse generation and correlation functions were done by a CESP II (Correlator Echo Sounder Processor) and a PTR-105B (Precision Transmitter Receiver) was used as a tone burst amplifier during pulse transmission. Sweep and fire rates were normally 1/2 second. Time marks were made every 5 minutes and the records were annotated and depth measurements taken at 15-minute intervals.

Clarity of the records and amount of penetration varied considerably over the survey area. This system seemed less sensitive to ship-generated noise than the Uniboom, but the 3.5 kHz records were more adversely affected by hard bottom sediment. The long (50 msec) pulse generated during transmission also created an internal "ringing" in the transducer array which masked not only the weak subbottom reflections but sometimes the bottom echo as well in shallow water. Penetration ranged from 0-20 m.

Sidescan Sonar. An EG & G sidescan sonar system was used to record 1000 km of good to high quality data. Scales (sweeps) of SO m and 100 m were used, and the "fish" altitude above the sea-floor was maintained at approximately 10 percent of the scale being used. The sidescan system was used in shallow water areas of known or suspected sand waves and ice-gouge features, and at such times the sparker system was shut down and its associated arc cables and hydrostreamer were brought aboard to prevent their fouling the sidescan cable.

GEOLOGIC SETTING

Tectonic Framework

The structural features and evolution of the Bering Sea continental shelf have been discussed by Scholl and Hopkins, 1969; Scholl et al., 1968; Pratt et al., 1972; Churkin, 1972; Lathram, 1973; Nelson et al., 1974; and Marlow et al., 1976. Figure B2 shows the major Cenozoic structures of western Alaska and eastern Siberia.

The general tectonic framework is characterized by large scale oroclinal bending forming two distinct flexures in central Alaska and eastern Siberia concave toward the Pacific Ocean. The Bering and Chukchi continental shelves are part of the broad intervening structural arc which is concave toward the Arctic Ocean.

This large scale oroclinal folding appears to have been completed before Oligocene time (Nelson et al., 1974), but continued activity along the major Alaskan transcurrent faults has displaced upper Tertiary and Quaternary sediment in several places on land and beneath the shelf areas (Patton and Hoare, 1968; Scholl et al., 1970; Grim and McManus, 1970). Total horizontal (right-lateral) movement along some of these large transcurrent faults has been approximately 130 km since the beginning of the Tertiary (Grantz, 1966; Patton and Hoare, 1968).

Regional Geology

Norton Basin. The geology of Norton basin has been discussed by Moore, 1964; Scholl and Hopkins, 1969; Grim and McManus, 1970; Tagg and Greene, 1973; Nelson et al., 1974; and Holmes et al., 1978. A submarine seepage of natural gas 40 km south of Nome has been described by Cline and Holmes (1977). Seismic reflection data suggest that the basin area is about 130,000 km^2; maximum basin depth has recently been estimated to be approximately S.5 km (Anon., 1976). The basin probably contains as much as 180,000 km^3 of sediment.

The basin fill consists of three major stratified units (Homes et al., 1978), which are in turn covered by a thin mantle of Quaternary sediment (Grim and McManus, 1970; Tagg and Greene, 1973; Nelson and Creager, 1977). The lowermost unit in the basin, with a velocity of 4.9 km/see (Holmes et al., 1978), may consist of Cretaceus nonmarine sandstones similar to those mapped onshore in the Koyukuk geosyncline (Patton and Hoare, 1968; Cobb, 1974). A velocity discontinuity at the top of this unit indicates that this interface may be an erosional unconformity.

Two other units of the basin fill can also be distinguished on the basis of compressional velocities (Holmes et al., 1978). A strong reflector on the reflection records corresponds to an apparent unconformity separating those units; the unconformity lies at a depth of about 1.2 km near the basin axis and approaches to within a few tens of meters of the sea floor near the basin margins. The compressional velocities above this unconformity are low, ranging from 1.6 to 2.1 km/see; this section is probably composed of recent marine and glaciomarine sediment and loosely cemented sandstones and shales. The higher velocities (?.3-3.7 km/sec) below the unconformity are more characteristic of compact or indurated sandstones and shales (Grant and West, 1965; Gardner et al., 1974). The unconformity was probably formed during the late Miocene marine transgression which inundated the northern Bering Sea continental shelf (Nelson et al., 1974). Strata of the unit below the unconformity form a broad synclinorium whose principal axis trends generally northwest; the beds of the upper unit are more nearly flat-lying,

Although younger Quaternary deposits everywhere cover the older Cenozoic and Mesozoic basin fill, some onshore outcrops and drill-hole data give clues as to the nature of the two upper units. Nonmarine coal-bearing strata of late Oligocene age are exposed on northwestern St. Lawrence Island (Patton and Csejtey, 1970), and several offshore holes drilled by the U.S. Bureau of Mines near Nome encountered marine sands and clayey silts of early Pliocene age at a subbottom depth of approximately 18 m (Scholl and Hopkins, 1969; Nelson et al., 1974). Late Miocene or early Pliocene marine limestone was recovered from a dredge haul 30 km south of St. Lawrence Island, just outside the basin.

These facts and the regional stratigraphic patterns indicate that the basin fill probably consists of late Cretaceus and lower to middle Tertiary sedimentary rock in the lower two units and upper Tertiary and Plio-Pleistocene sedimentary rocks and sediment in the upper unit. All direct evidence suggests that the lower units are nonmarine, but the size of the basin is such that unseen transitions to marine facies could occur within this sequence.

Acoustic Basement. The high compressional velocity contrast across the acoustic basement is indicative of a marked lithologic change at this interface (Holmes et al., 1978). Velocities of S.5 to 6.5 km/see are characteristic of igneous and metamorphic rocks (Grant and West, 1965), indicating that Norton basin is probably floored by a basement surface formed on strata which are analogous to the diverse older rocks which occur on land around the basin margins. Sedimentary, metamorphic, and igneous rocks of Precambrian through Mesozoic age are exposed on the Chukotka Peninsula (Nalivkin, 1960); and Seward Peninsula is formed primarily of Paleozoic sedimentary and metamorphic units with some Mesozoic and Cenozoic intrusive and extrusive rocks. Mesozoic sedimentary rocks (some slightly metamorphosed) and Cenozoic volcanics have been mapped onshore in the Yukon-Koyukuk basin east and southeast of Norton Sound (Miller et al., 1959; Patton and Hoare, 1968). At the southern margin of Norton basin, St. Lawrence Island is constructed mainly of Paleozoic, Mesozoic, and Cenozoic intrusive and extrusive rocks with some Cenozoic sedimentary deposits (Miller et al., 1959; Scholl and Hopkins, 1969; Patton and Csejtey, 1970). The acoustic basement probably represents an erosional surface which has been steepened by tectonic subsidence during development of Norton basin.

RESULTS AND DISCUSS1ON

Observed Faults and Structures

Locations of faults observed on seismic reflection profiles from Norton Sound and Chirikov basin are shown in Fig. B3. The majority of faults, especially those extending close to the sea floor, occur within 50 km of the basin margins. Most faults in Chirikov basin and western

Norton Sound trend northwest in alignment with the major axis of Norton basin. Synclinal and anticlinal axes mapped by Greene and Perry (unpub.), and shown in Johnson and Holmes (1977, Fig. B3), reflect this same trend. In eastern Norton Sound, the structural grain is nearly east-west.

Seismic records from the basin margins generally show sediments of the upper two units of basin fill, the Main Layered Sequence of Scholl and Hopkins (1969), resting with onlap unconformity against the eroded surface of the acoustic basement. The single channel seismic reflection systems were unable to resolve acoustic basement in the deeper basin areas where sediment thickness exceeded 2 km. Numerous faults offset the acoustic basement, often displacing overlying sediments. Many normal and antithetic faults displace the basin fill and extend to within 100 meters of the sediment surface. A few of these have topographic expression as fault scarps.

Faulting appears to be most complex, and the fault density is highest, in the area west of Port Clarence (Fig. B3). Several west-trending faults appear to intersect, and can be seen to offset, the dominant pattern of northwest-trending faults. These west-trending faults must therefore be younger than the others, and may be indicative of a change in the direction of regional compression during Quaternary time.

One of the major faults comprising this major east-west trend is the Bering Strait Fault (BSF) of Hopkins (unpub.). It forms the northern boundary of the Bering Strait Depression (BSD) named by Greene and Perry (unpub.) and appears to extend for over 90 km west from Port Clarence {Fig. B3). A south-facing scarp 5 meters high marks the fault near the Bering Strait Depression. The scarp decreases in height eastward; no trace of the fault has been found beneath Port Clarence. This fault appears to have been active as recently as 12,000 years ago (Hopkins, unpub.).

The Port Clarence Rift (PCR) (Hopkins, unpub.) is a narrow fault-bounded depression extending eastward from the Bering Strait Depression; the fault along the northern margin of the depression is probably equivalent to the Cape York Fault of Greene and Perry (unpub.). This northern fault has a scarp 9 meters high near the Bering Strait Depression, which decreases to the east. No trace of this fault has been observed beneath Port Clarence, but displacement of bedrock beneath Grantley Harbor has been suggested as evidence for extension of the Port Clarence Rift further to the east. The Rocks beneath Grantley Harbor have experienced 16 km of left-lateral movement (Hopkins, unpub.). Several other west-trending faults with scarps up to 15 m high have been observed in the area west of Port Clarence (Fig. B3).

The rough seafloor topography north of St. Lawrence Island made identification of fault scarps difficult, but a few have been tentatively mapped (Fig. B3). A large west-trending fault has been inferred by Hopkins (unpub.) to parallel the northern coast of St. Lawrence Island and bend northward before reaching the western end of the island (Fig. B3). Existence of the St. Lawrence Fault Zone (SLF) is based on swarms of volcanic vents which trend N80°W through the axis of the Kookooligit

Mountains, and on the extension of these volcanic rocks into offshore regions. Hopkins has suggested that movement along this fault has been left-lateral. Possibly it is related to movement along the Kaltag Fault (KF), a large transcurrent fault in western Alaska that has been known to displace Pleistocene sediments onshore.

Many deep-seated and near-surface normal faults occur in the central part of Norton basin, although no surface expressions of these have been identified. An increase in displacement with depth, and apparent thickening of beds on the downthrown side of these faults, indicates that they are probably growth faults along which movement has taken place more or less continuously during the major episodes of basin subsidence.

Several subbottom faults occur along the southern and eastern margins of Norton Sound (Fig. B3). Short line segments indicate faults have been observed on one crossing, and therefore, their exact orientation is unknown. However, several faults appear to parallel the trend of the Kaltag Fault; others may represent splays of the Kaltag Fault. No surface scarps were associated with the near-surface faults along the eastern margin of Norton Sound.

Fault Activity and Hazard Potential

Surface fault scarps in northern Chirikov basin are associated with the Bering Strait Fault, the Port Clarence Rift, and other nearby faults (Fig. B3) . The Bering Strait Fault and Port Clarence Rift may represent extensions or splays of the large transcurrent faults which have been mapped in western Alaska and Seward Peninsula (Fig.B2). The scarps may have been caused by recent vertical movement on these faults, and therefore would indicate a definite hazard to man-made structures placed over or near these fault zones. There is also the possibility, that the faults have been inactive for some time, and the scarps have been maintained by nondeposition or lack of erosion. Currents west of Port Clarence flow almost normal to the trend of these scarps, and carry almost one third of the Yukon River sediment load into the Chukchi Sea (Nelson and Creager, 1977). The persistence of the surface expression of the faults in spite of apparently vigorous erosional agents would argue for the fault scarps to be recently formed features.

The Bering Strait Fault must have formed between 12,000 and 120,000 years ago; evidence exists that a lake was formed during the Wisconsin glaciation when development of the fault scarp dammed a northward-flowing river west of present day Port Clarence. Marine terraces on Seward Peninsula may have been uplifted during the Illinoian glaciation as a result of movement along the fault 130,000 years ago. Although no specific age can be given to movements along these faults in northern Chirikov basin, the area should definitely be considered as potentially hazardous to placement of structures on the bottom in the vicinity of the fault scarps.

Only a few surface scarps have been noted in association with faults along the northern side of the St. Lawrence Island or in southern and eastern Norton Sound; the rough sea-floor topography in this area makes identification of fault scarps difficult. Movement may have occurred along these faults during Tertiary and Quaternary time in conjunction with known displacement in western Alaska along the large transcurrent Kaltag Fault. Further study is necessary to determine if this represents a hazard to resource development.

Earthquake records show an almost complete lack of epicenters beneath Norton basin. This lack of seismicity can be interpreted to indicate either inactivity or, conversely, that strain release is being accomplished by small but frequent adjustments along the faults. The growth nature of most of the northwest trending faults which parallel the Norton basin axis support the latter interpretation, although the rate of basin subsidence may have decreased since the end of Pleistocene time when rising sea-level opened Bering Strait and resulted in a significant change in deposition patterns in the northern Bering Sea.

CONCLUSIONS

Based on the foregoing discussion, the following conclusions may be made regarding the faulting observed in Norton Sound and Chirikov basin:

1. Faults are most numerous in a belt approximately 50 km wide around the margins of Norton basin. Near surface faults are more numerous in central Norton basin than previously reported, but are still less prevalent than around the periphery of the basin. Most of the faults trend generally northwest, with the basinward sides down-dropped; antithetic faults are also common, resulting in series of narrow horsts and grabens along the basin margins. These faults and the many associated anticlinal and synclinal folds involving the basin fill and acoustic basement are the result of tectonic activity which occurred during subsidence and filling of the 5.5-km deep Norton basin. Initial subsidence of the basin probably began during late Cretaceus time, and has continued to the present with two apparent major interruptions during early and late Tertiary time.

2. Surface scarps up to 15 m high are associated with some of the long west-trending faults in northern Chirikov basin. These scarps can indicate either recent activity or persistence due to lack of erosion or burial by sedimentation since the last movement. Scarps occur on the Bering Strait Fault and on the northern side of the Port Clarence Rift, and movement along these faults possibly occurred as recently as 12,000 years ago in conjunction with uplift of marine terraces on Seward Peninsula.

3. The west-trending faults in northern Chirikov basin intersect and appear to offset the northwest-trending faults and structures south of Bering Strait. This relationship implies that the west-trending features postdate the main Norton basin structures; the different trends could also be indicative of a shift in regional compressive axes.

4. None of the faults can definitely be classed as historically active, however the area of northern Chirikov basin west of Port Clarence should be considered potentially hazardous to any bottom mounted structures. The fault scarps in this region are still well defined in spite of the swift currents and bottom sediment transport which occur normal to the trend of the fault zones. Basin subsidence is probably still taking place, and the lack of recorded earthquakes beneath Norton basin may indicate that strain release is being accomplished by small but frequent movement along some of these faults.

5. West-trending subbottom faults without surface fault scarps occur along the southern margin of Norton basin. These may represent splays or displacements related to the Kaltag Fault, one of the major transcurrent faults in western Alaska. Movement along onshore portions of the Kaltag Fault have displaced Pleistocene deposits, but data regarding age of movements along the offshore portion are inconclusive.

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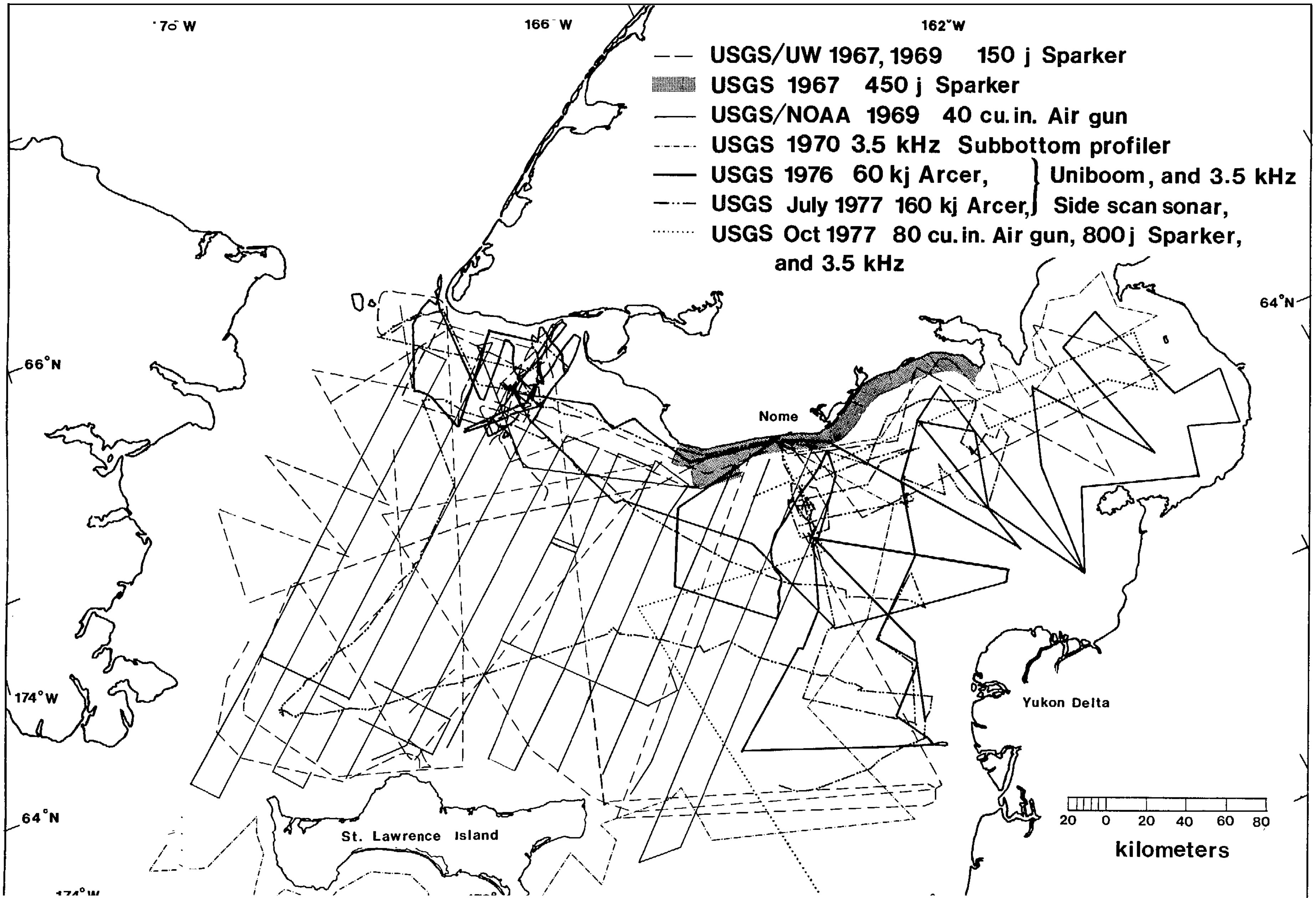

170° W
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USGS/UW 1967, 1969 150 j Sparker
USGS 1967 450 j Sparker
USGS/NOAA 1969 40 cu. in. Air gun
USGS 1970 3.5 kHz Subbottom profiler
USGS 1976 60 kj Arcer,
USGS July 1977 160 kj Arcer,
Uniboom, and 3.5 kHz
Side scan sonar,
USGS Oct 1977 80 cu. in. Air gun, 800 j Sparker, and 3.5 kHz
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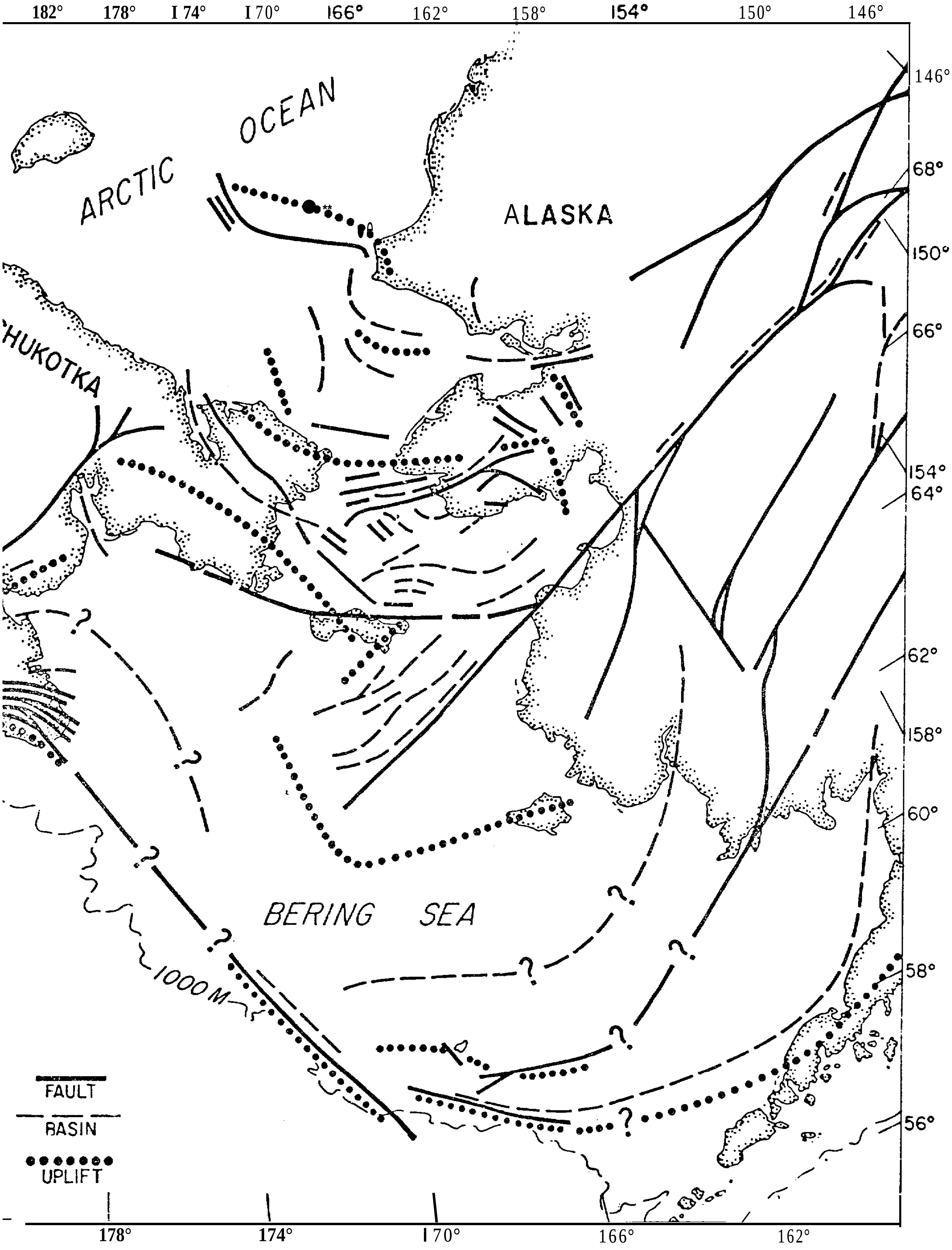
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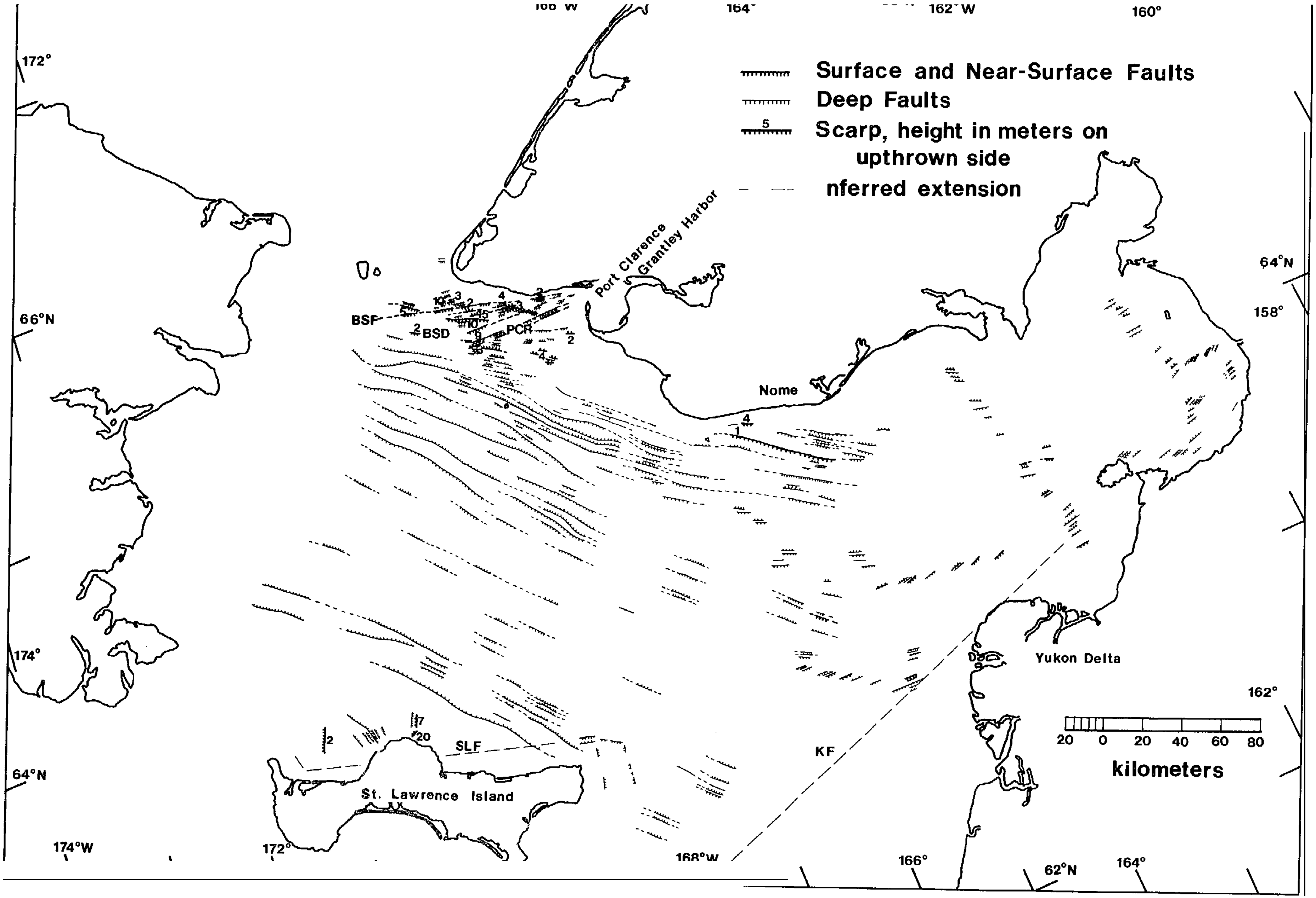
166°
162°


Surface and Near-Surface Faults
Deep Faults
Scarp, height in meters on upthrown side
nferred extension
Port Clarence
Grantley Harbor
Nome
BSF
BSD
PCR
SLF
KF
St. Lawrence Island
Yukon Delta
kilometers
20 0 20 40 60 80
172°
66°N
174°
64°N
174°W
172°
168°W
166°
62°N
164°
162°
158°
64°N
160°
162°W
164°