UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

RESOURCE REPORT FOR PROPOSED OCS LEASE SALE No. 70
ST. GEORGE BASIN, SHELF AREA, ALASKA

by

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This report is preliminary and
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SUMMARY

St. George basin is a long (300 km), narrow (30-50 km) graben whose long axis strikes northwestward, parallel to the continental margin of the southern Bering Sea. Located near the Pribilof Islands, and beneath the virtually featureless Bering Sea shelf, the basin is filled with more than 10 km of sedimentary deposits. These sedimentary rocks are ruptured by normal faults associated with the sides of the graben; these ruptures commonly correlate with offsets in the basement surface. Offset along these faults increases with depth implying that they are growth-type structures. Basement rocks, that floor and flank St. George basin are part of an assemblage of Mesozoic eugeosynclinal rocks that extends from southern Alaska to eastern Siberia beneath the Bering Sea margin and outer shelf. A parallel belt of igneous rocks of late Mesozoic and earliest Tertiary age may also extend from western Alaska to northeastern Siberia beneath the inner Bering Sea shelf.

The Bering Sea margin and adjacent shelf were apparently uplifted by the end of Mesozoic time, resulting in deep subaerial erosion. Following uplift, the outer Bering Sea shelf has undergone extensional rifting and regional subsidence. Differential subsidence has resulted in the formation of a series of basement ridges and basins whose axes parallel the Bering Sea margin. Some of these basins are very large to gigantic in size, e.g., St. George basin, and involve crustal subsidence exceeding 10 km. Such large scale crustal collapse suggests deep crustal or upper mantle processes, such as thermal metamorphism or stress-induced crustal migration.

Nine wells drilled along the northern coast of the Alaska Peninsula, as well as several onshore Soviet wells in northeastern Siberia, relate directly to the submerged basins of the Bering Sea shelf. Although all of the wells on the Alaska Peninsula were abandoned as dry holes, shows of oil and gas were

found. In addition, Soviet drilling resulted in the discovery of oil and gas shows in Oligocene and Miocene sandstone.

Regional geologic and geophysical mapping suggests that there are suitable source beds, reservoir rocks, and traps within St. George basin. However, it is not known if hydrocarbons are present or if the possible reservoirs are of commercial size. A resource appraisal of St. George basin out to 200 meters water depth indicates that, at 5 percent probability, 6.4 billion barrels of oil and 18.6 trillion cubic feet of gas may be in the basin; at 95 percent probability 0.8 billion barrels of oil and 4.5 trillion cubic feet of gas may be in the basin. The statistical mean of the appraisal is 2.7 billion barrels of oil and 10.3 trillion cubic feet of gas.

A large number of faults, evidence for recent movement along some of the faults, and high seismicity all indicate that faulting is a major environmental concern for the outer continental shelf region of the southern Bering Sea, especially in St. George basin. Most of the faults are potentially active and their movement is probably influenced by the local geology, including basement structures and sediment loading. Unstable sediment masses pose potential threats to resource development in the vicinity of the Pribilof Canyon. Volcanic activity along the Aleutian arc south of St. George basin may also pose an environmental hazard to petroleum development in the area. Another environmental hazard is the presence of shallow gas pockets, which could pose such problems during drilling as blowouts and liquefaction of bottom sediment.

INTRODUCTION

Location of Proposed Area

This report is a summary of data concerning St. George basin and the surrounding portion of the southern Bering Sea shelf. The area discussed is bounded on the north by 59° N, on the west by the 171 meridian, on the east by the 165 meridian, and on the south by the 200 meter bathymetric contour defining the edge of the shelf, (Fig. 1). No discussion is made of the proposed lease area that includes the deepwater area south of St. George basin and the Aleutian shelf area (Fig. 2).

Publicly Available Data

Recent interest in the resource potential including the hydrocarbon prospects of the Bering Sea has stimulated marine geophysical and geologic mapping of the area. Since 1965 the U.S. Geological Survey has conducted numerous expeditions to the Bering Sea, (Fig. 2) and two of these cruises resulted in the collection of more than 2,800 km of 24-channel seismic-reflection data over the southern Bering Sea shelf in the vicinity of St. George basin. Data presented in this report were derived from 24-channel seismic reflection profiles that were collected using an array of five airguns (1,326 cu. in.; 21,723 cc) as a sound source . Published bathymetric, magnetic, and gravimetric charts of the area west of the southern Alaska Peninsula are available from the National Ocean Survey, Distribution Division, C4411, Riverdale, Maryland 20840 (Geophysical maps: 1711N-17G, 1711N-17M, 1711N-18G, 1711N-18M, and 1711N18B). A detailed bathymetric chart of the shelf area by R. Pratt and F. Walton (Bathymetric Map of the Bering Shelf,

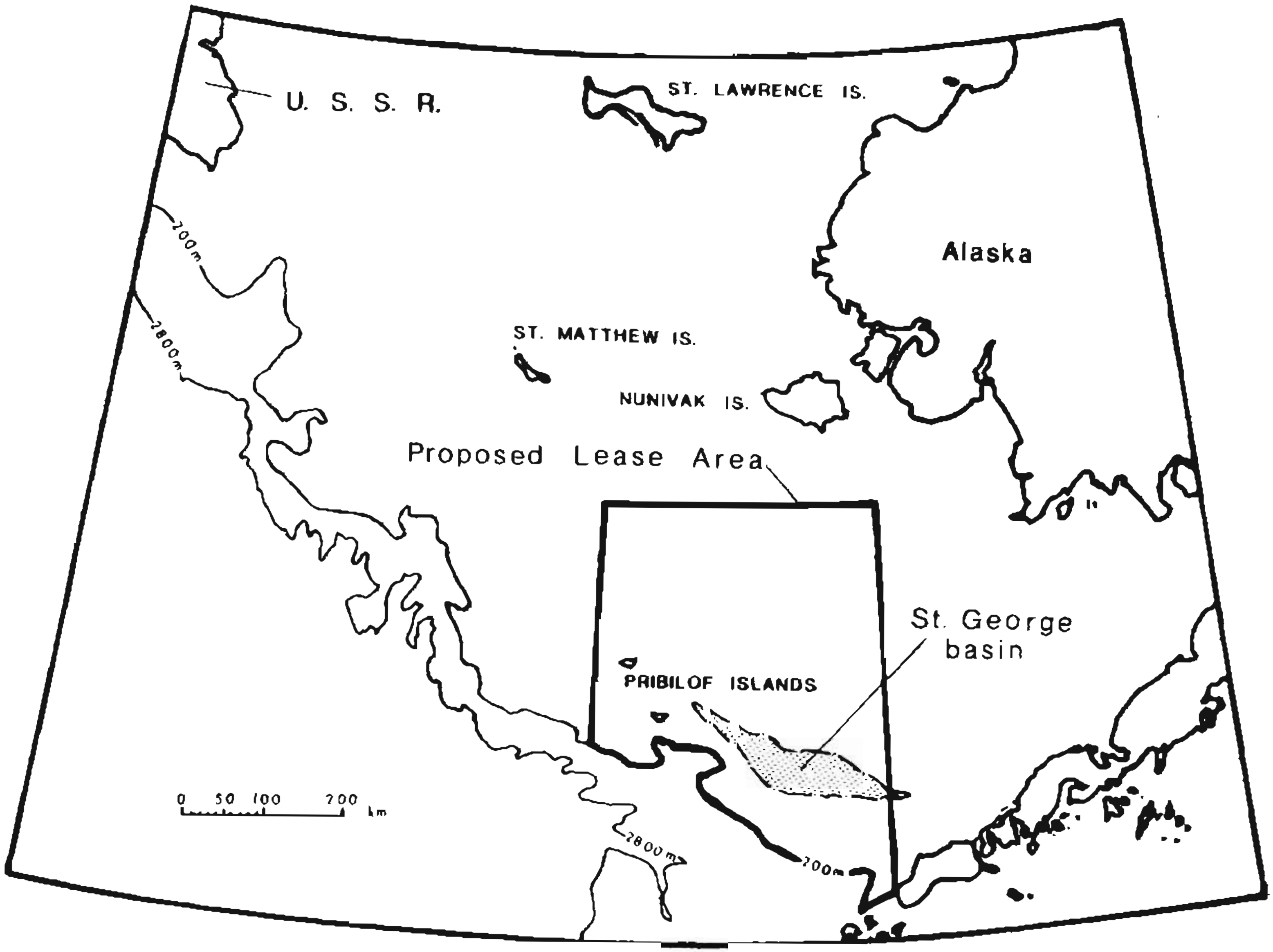


Figure 1. Location of proposed lease area and outline of St. George Basin.

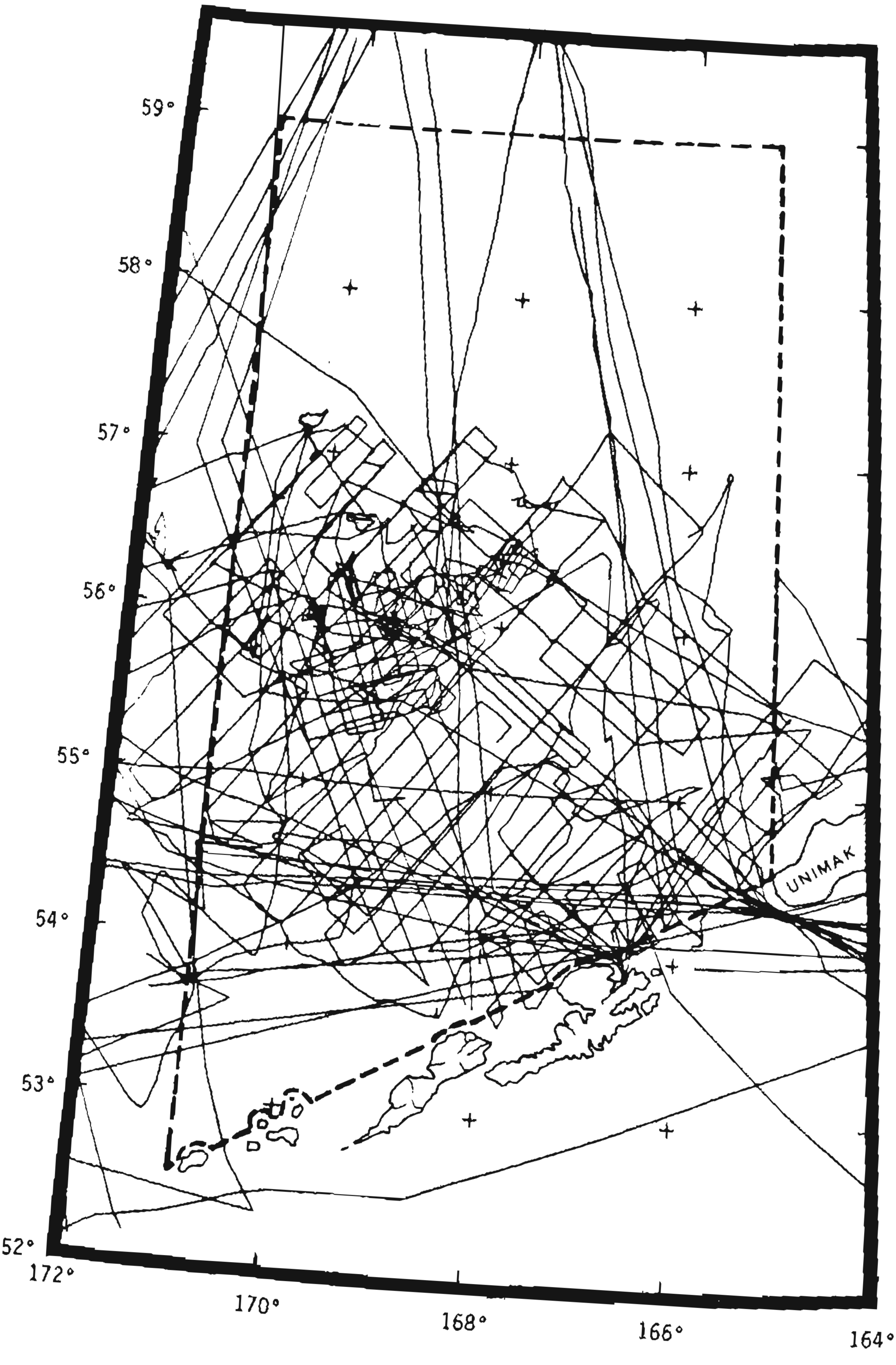


Figure 2. Index map of all publicly available geophysical and geological surveys in the proposed lease area.

1974) is available from The Geological Society of America, Inc., 3300 Penrose Place, Boulder, Colorado 80301. Additional offshore magnetic and gravity data may be obtained from the Bedford Institute (Dartmouth, Nova Scotia, Canada), National Oceanic and Atmospheric Administration, Environmental Data and Information Service D6, National Geophysical & Solar - Terrestrial Data Center, Boulder, Colorado 80303, and the Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York.

The following sections include discussions of regional geology, petroleum geology, environmental hazards as background to discussion of the hydrocarbon potential and resource appraisal of the offshore area. A section on the technology and manpower needed and available for development of offshore resources is also included. For a discussion of resource potential of the entire Bering Sea shelf south of St. Lawrence Island, the reader is referred to Marlow and others (1976a), from which much of this report was derived.

FRAMEWORK GEOLOGY

Regional Geologic Setting of the Southern Bering Sea Shelf

A generalized geologic map of the onshore eastern Bering Sea region is shown in Figure 3. Detailed discussions of the geology of the Alaska Peninsula can be found in Burk (1965), Brockway (1975), (Lyle and others (1979), and McLean (1979) , of western Alaska in Hoare (1961) and Patton (1973), and of eastern Siberia in Churkin (1970) and Scholl and others (1975). For this report we will restrict our regional geologic discussion to the Alaska Peninsula, western Alaska, and the offshore area of St. George basin.

Complex geologic structures that include rocks as old as Precambrian are exposed in coastal mountains that flank the southern Bering Sea shelf (Fig. 3). Most of the significant structures that flank the shelf contain rocks of Mesozoic and Tertiary age. For example, the oldest exposed rocks in the vicinity of St. George basin are Upper Jurassic siltstone and sandstone of the Naknek Formation (Burk, 1965). The westernmost exposure of these rocks is in the Black Hills bordering the southern Bering shelf (Fig. 3). Seismic reflection data indicate that the Black Hills structure extends offshore as a subshelf basement ridge and that this ridge extends to and connects with the Pribilof ridge along the southern flank of St. George basin (Fig. 4; Marlow and others, 1979). Upper Jurassic siltstone and sandstone dredged from the top and the flanks of Pribilof ridge also imply that Jurassic rocks extend from the Alaska Peninsula to the northwest along the Bering Sea margin (Marlow and others, 1979).

Cretaceous and older Mesozoic eugeosynclinal rocks exposed in southwest Alaska north of Bristol Bay trend southwestward toward the Bering Sea shelf

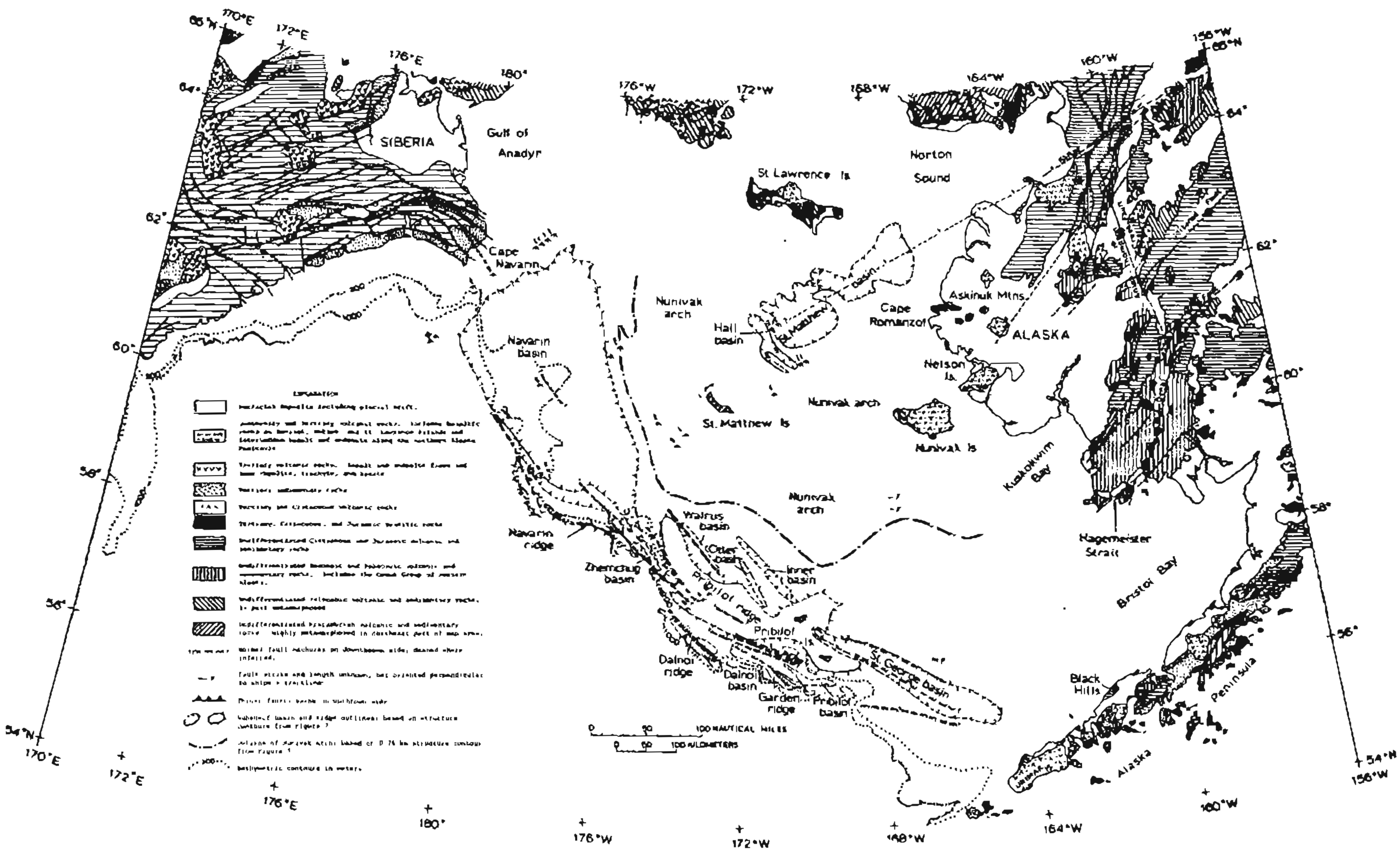


Figure 3. Generalized geologic map of western Alaska, the Alaska Peninsula, and eastern Siberia. Onshore geology is modified from Burk (1965), Beckman (1974), and Yanshin (1966). Offshore outlines of subshelf basins, ridges, and Nunivak arch from Marlow and others (1976a). The offshore extension of the Kaltag Fault is diagramatic in that the expression of the fault beneath the shelf may include all of St. Matthew basin.

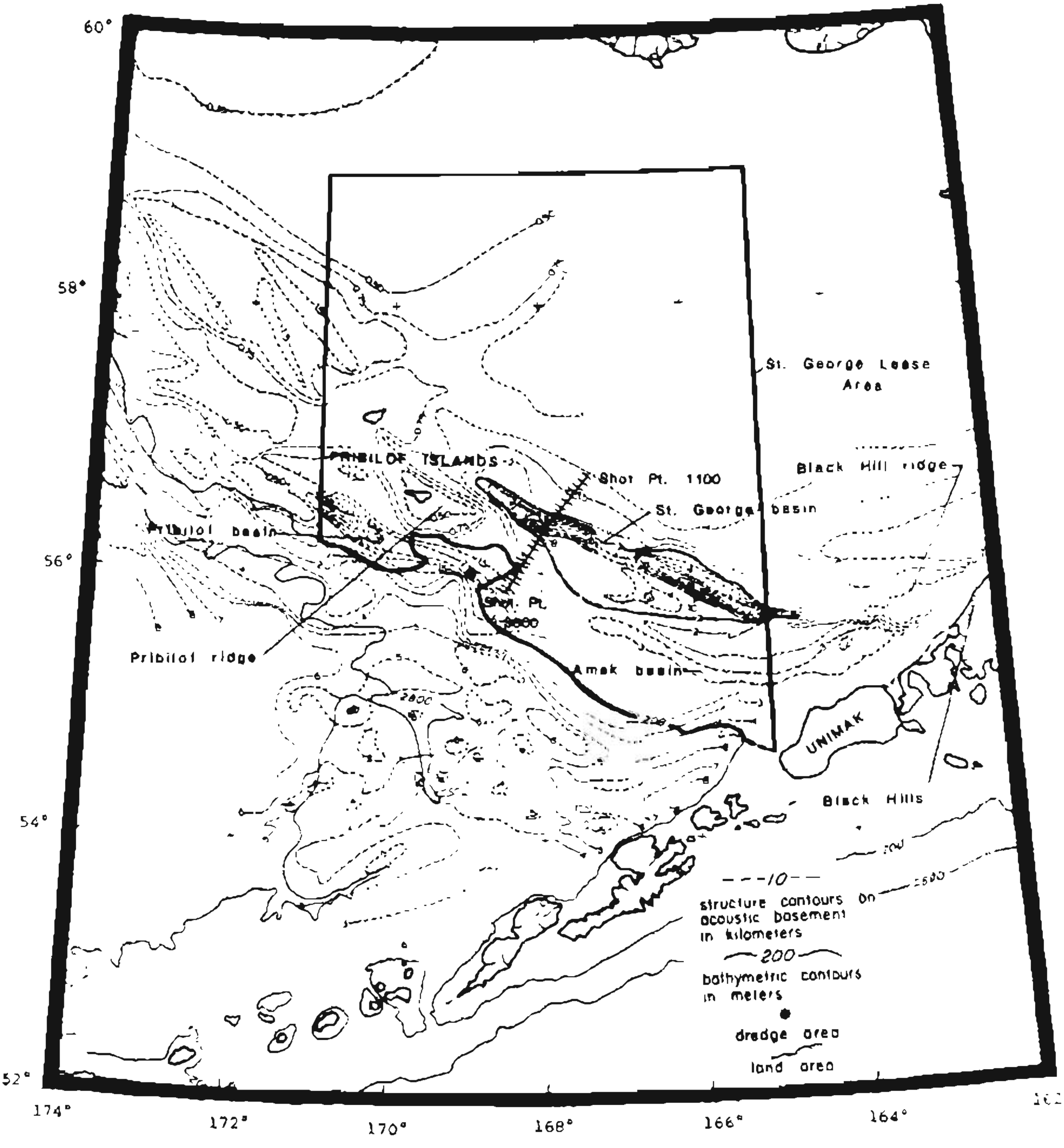


Figure 4. Structure-contours of acoustic basement beneath the southern Bering Sea shelf. Derived in part from Scholl and others (1968), Scholl and Hopkins (1969), Marlow and others (1976a,b,1977). Heavy solid line shows location of seismic-reflection profile interpreted in Figure 9.

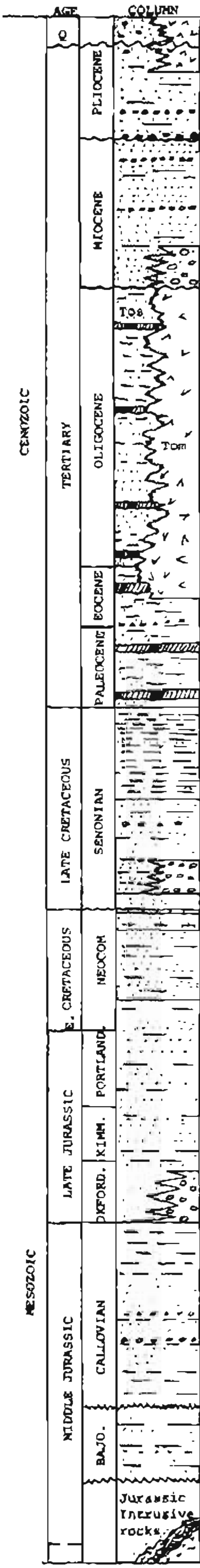
(Fig. 3; Payne, 1955; Hoare, 1961; Gates and Gry, 1963, Patton, 1973). These important structural features either disappear to the southwest beneath the Bering shelf or they curve to the northwest and merge with the belt of Mesozoic deformed rocks that underlies the outer part of the Bering shelf and its margin (Scholl and others, 1975). We also suspect that the two major strike slip faults of western Alaska, the Denali and Kaltag faults, either vanish to the southwest or turn to the northwest parallel to the Bering Sea margin.

Geology of the Alaska Peninsula

Mesozoic Rocks

The oldest sedimentary unit that crops out on the north side of the Alaska Peninsula, along the southern margin of Bristol Bay basin, is the Naknek Formation of Late Jurassic age, (Fig. 3) although older rocks are exposed on the Pacific side of the peninsula. Naknek strata are well exposed in the mountains of the Aleutian Range from Wide Bay southwest to the Black Hills, and consist of at least 1500 m of granitic conglomerate, arkosic sandstone, and thinly bedded siltstone (Fig. 5). The Naknek Formation was deposited in a neritic marine environment as evidenced by abundant *Buchia*. Conglomeratic units predominate in the base of the section and grade upward into sandstone and siltstone. The Naknek Formation conformably overlies sandstone, conglomerate, and siltstone of the Middle Jurassic Shelikof Formation in the Wide Bay area.

In the Port Moller area, siltstone of the Naknek Formation grades upward into arkosic sandstone of the Staniukovich Formation (Figs. 5, 6). The arkosic composition of the Naknek strata indicates that unroofing of the granitic Naknek Lake batholith occurred in Oxfordian (Late Jurassic) time.



FORMATION	DESCRIPTION
Quaternary-Recent Volcanics 300 m ±	Unconsolidated sediments and volcanic rocks.
Milky River Fm (Tpm) 920 m +	Conglomeratic rocks, sandstone and mudstone; clastic frac. Volcanic derived, fossiliferous, marine and nonmarine.
Bear Lake Fm (Tmb) 1500 m +	Sandstone and conglomerate with interbedded siltstone, mudstone, and coal, locally fossiliferous, marine and nonmarine.
Unga Conglomerate Member (Tmbu) Local unconformity	Sandstone, conglomerate, thin mudstone, locally volcanically-derived; locally fossiliferous.
Stepovak Fm (Tos 4550 m +	Volcanic sandstones and conglomerate and thick beds of black siltstone; all rock types locally carbonaceous with lignite seams in upper part of sequence: locally highly fossiliferous; volcanic flows near base and rare sills throughout; predominantly marine.
Meshik Fm (Tom)	Volcanic conglomerate sandstone, volcanic breccia, andesitic-basaltic extrusive volcanic rocks and local siltstone or shale. Present at surface and in subsurface from Chignik Bay northeast to Ugashik Lakes area; probably interfingers with Stepovak Fm. and upper part of Tolstoi Fm.
Tolstoi Fm (Tct) 1500 m +	Siltstone with interbedded volcanic sandstone and conglomerate; flows, sills, volcanic breccia; nonmarine to brackish water environment; rare marine fossils, common plant remains and very abundant in lower part of sequence.
Hoodoo Fm (Kh) 610 m +	Siltstone, silty shale, claystone with fine-grained sandstone. Black to dark grey color. Outer neritic to deep marine environment.
Chignik Fm (Kc) 460 m +	Sandstone, siltstone, minor mudstone and conglomerate; shallow marine.
Coal Valley Member of Chignik Fm	Conglomerate, sandstone, coal; nonmarine.
Herendeen Ls (Khl) 150 m	Calcarenite with abundant <u>Inoceramus</u> prisms.
Staniukovich Fm (Jks) 610 m	Feldspathic sandstone and arkose, thin siltstone, locally abundant <u>Buchia</u>; shallow marine environment.
Naknek Fm (Jn) 1500 to 3050 m	Claystone and siltstone, predominantly in upper part of unit; lower part consists largely of feldspathic sandstone with some interbedded claystone, siltstone, and conglomerate; locally abundant <u>Buchia</u> and belemnites; shallow marine to neritic environment.
Chisik Conglomerate Member (Jnc) 120 m	Pebble to boulder conglomerate consisting of largely granitic debris at base of Naknek Fm; crops out north of Wide Bay.
	Siltstone and shale with lenses of limestone; marine fossils abundant.
Shelikof Fm (Js) 2150 m	Sandstone, siltstone, conglomerate, marine environment.
	Siltstone, sandy siltstone, sandstone, ash beds and abundant calcitic concretions; marine fossils.
Kialagvik Fm (Jk) 530 m	Sandstone sandy shale and conglomerate, becomes more sandy near top of unit; marine fossils.
Rare, small outcrops of Early Jurassic, Triassic, and Permian sedimentary rocks	Limestone, chert, volcanic-rich rocks; crop out at Puale Bay* northward.

* Modified from Brockway and others (1975).

Figure 5. Composite columnar section of strata in the Bristol Bay and Alaska Peninsula regions.

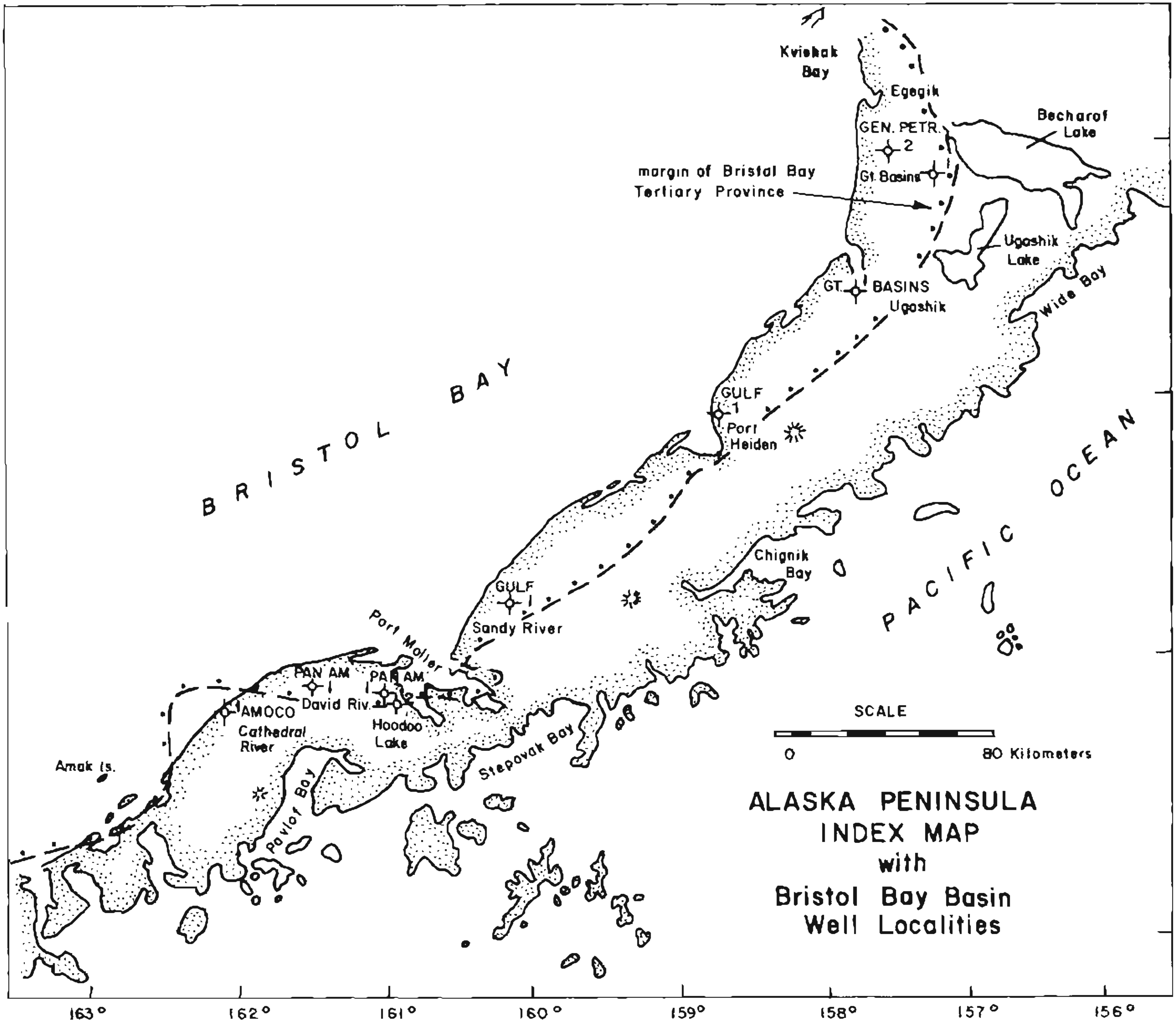


Figure 6. Alaska Peninsula index map of wells drilled along the peninsula.

On the Alaska Peninsula approximately 600 m of uniformly bedded arkosic marine sandstone and siltstone beds of the Staniukovich Formation conformably overlie the Naknek Formation. Strata of the Staniukovich Formation contain abundant large Buchia which are indicative of a Portlandian to Valanginian (Late Jurassic to Lower Cretaceous) age. The Staniukovich Formation is in turn conformably overlain in the Port Moller area by the Herendeen Limestone; which consists of 100 to 150 m of dense arenaceous limestone and calcareous sandstone that contain abundant Inoceramus prisms. The Herendeen Limestone is considered to be Hauterivian and Barremian (early Early Cretaceous) in age. Rocks of comparable age also occur near Cape Douglas at the south Cook Inlet, and in the Matanuska Valley in southern Alaska. The Naknek and Staniukovich Formations and the Herendeen Limestone are stratigraphically conformable with each other, but they are unconformably overlain by carbonaceous and locally coal-bearing sandstone, siltstone, and conglomerate of the Chignik Formation of Late Cretaceous age. Significantly, no rocks of definite Albian to Santonian age (late Early and early Late Cretaceous) are known in the Alaska Peninsula (Burk, 1965).

The Chignik Formation contains a largely nonmarine basal conglomerate, the Coal Valley Member, that is locally 450 m thick (Fig. 5). Clasts from this conglomerate consist of volcanic and granitic rock, and chert. The conglomerate thins laterally, grading into carbonaceous siltstone and sandstone that contain coal seams. The sandstone beds of the Chignik Formation consist of sub-graywackes and lithic arenites that contain one-fourth to three-fourths volcanic and sedimentary (claystone, siltstone, argillite) grains (Burk, 1965). Abundant coal as well as moderately abundant molluscan fauna indicate that the Chignik Formation was deposited in a nonmarine to shallow marine environment. The Chignik Formation was deposited unconformably on a gently dipping erosional surface cut into mildly folded pre-Chignik Formation rocks (Burk, 1965). Upper Cretaceous black siltstone and shale beds of the Hoodoo Formation conformably overlie the Chignik Formation. However, locally the Chignik Formation is unconformably overlain by Tertiary strata near Port Moller, where the Upper Cretaceous Hoodoo Formation has apparently been completely eroded. Electric well logs in this area indicate that the Upper Cretaceous Chignik Formation is unconformably overlain by Paleocene and Eocene rocks of the Tolstoi Formation (Brockway and others, 1975).

Cenozoic Rocks. Cenozoic rocks on the Alaska Peninsula consist of marine and nonmarine volcanic-rich clastic beds that have a cumulative thickness of 7500-9000 m (Burk, 1965). Lithologies are similar throughout the section, facies changes are common, and intrusive and extrusive activity has locally obscured stratigraphic relationships. The onshore section is intruded by numerous basaltic and andesitic dikes and sills. Presumably igneous rocks are not extensive in the offshore Cenozoic section of Bristol Bay north of the volcanic vents of the Aleutian volcanic arc. The Tolstoi Formation of Paleocene and Eocene age consists of at least 1500 m of siltstone interbedded with volcanic sandstone, conglomerate and breccia that have locally been intruded by dikes and sills (Fig. 5). Much of the section is nonmarine and plant remains are abundant in the lower part of the sequence.

Conformably overlying the Tolstoi Formation is at least 4500 m of chiefly marine volcanic sandstone, conglomerate, and black siltstone known as the Stepovak Formation (Fig. 5). The Stepovak Formation is similar to the Tolstoi Formation in lithology but units in the Stepovak Formation are better sorted and contain less angular grains and more even bedding than units in the Tolstoi Formation (Burk, 1965). Northeast of Chignik Bay on the Alaska

Peninsula. strata of the Tolstoi and Stepovak Formations gradationally interfinger with more extensive volcanogenic rocks that include flow, breccia, and conglomerate units (Figs. 5, 6). Radiometric dates from cores in the Gulf, Port Heiden and Great Basins-Ugashik wells confirm that volcanic rocks of the Meshik Formation are in part equivalent in age to Tolstoi and Stepovak strata. Meshik rocks occur in the northeast portion of Bristol Bay but are not present in the General Petroleum Great Basins Nos. 1 and 2 wells (Fig. 6; Brockway and others, (1975).

The Meshik and Stepovak Formation are unconformably overlain by the middle to upper Miocene Bear Lake Formation. The Bear Lake Formation consists of at least 2100 m of sandstone, siltstone and a basal conglomerate known as the Unga Conglomerate Member. Sandstone beds are typically more friable and better sorted than older Tertiary rocks. These sandstone units contain approximately equal amounts of quartz and chert, lithic fragments, and volcanic fragments. Conglomerates contain abundant black and white chert, argillite, sedimentary rock fragments and silicified wood (Burk, 1965).

The Bear Lake Formation is unconformably overlain by Pliocene and younger sedimentary rocks that include unconsolidated alluvium and glacial outwash locally interbedded with volcanic flows. The Pliocene Milky River Formation consists of at least 920 m of sandstone, conglomerate, and mudstone of marine and nonmarine origin (Brockway and others, 1975). Milky River Formation strata grade upward into younger unconsolidated sedimentary and volcanic rocks.

Igneous Rocks The oldest volcanic rocks known on the Alaska Peninsula consist of mafic flows and coarse debris interbedded with Permian carbonate and volcanogenic strata and Upper Triassic limestone at Puale Bay. A thick sequence of volcanic-derived sedimentary rocks accumulated during Early and

Middle Jurassic time but no flow rocks are known to be interbedded in the sedimentary sequence.

Active volcanism began again in the late Createaceous and early Tertiary, contributing large volumes of debris to the late Cretaceous and Paleogene rocks of the Alaska Peninsula (Burk, 1965; Lankford and Magoon, 1978). Volcanism appears to have abated during the early Neogene and became active again during Pliocene through Holocene time.

Two major plutonic episodes in the Jurassic and early Tertiary, are known to have occurred on the Alaska Peninsula. South of the Peninsula, an extensive episode of early Tertiary intrusive activity occurred in the adjacent Shumagin-Kodiak slate-graywacke belt of southern Alaska (Burk, 1965; Kienle and Turner, 1976; Armentraut, 1979). The first intrusive episode on the Alaska Peninsula occurred during Early and Middle Jurassic time (154 to 176 m. y., Reed and Lanphere, 1973). The second is Oligocene in age (26 to 38 m.y.).

Prospective Sections

Many of the late Mesozoic and Cenozoic sedimentary rock units exposed along the Alaska Peninsula appear to extend offshore to the vicinity of Bristol Bay and St. George basins. The positions of these basins, behind the Aleutian arc, has probably isolated them from the numerous episodes of volcanism and plutonism that have substantially reduced the petroleum potential of the sedimentary sequences along the Alaska Peninsula.

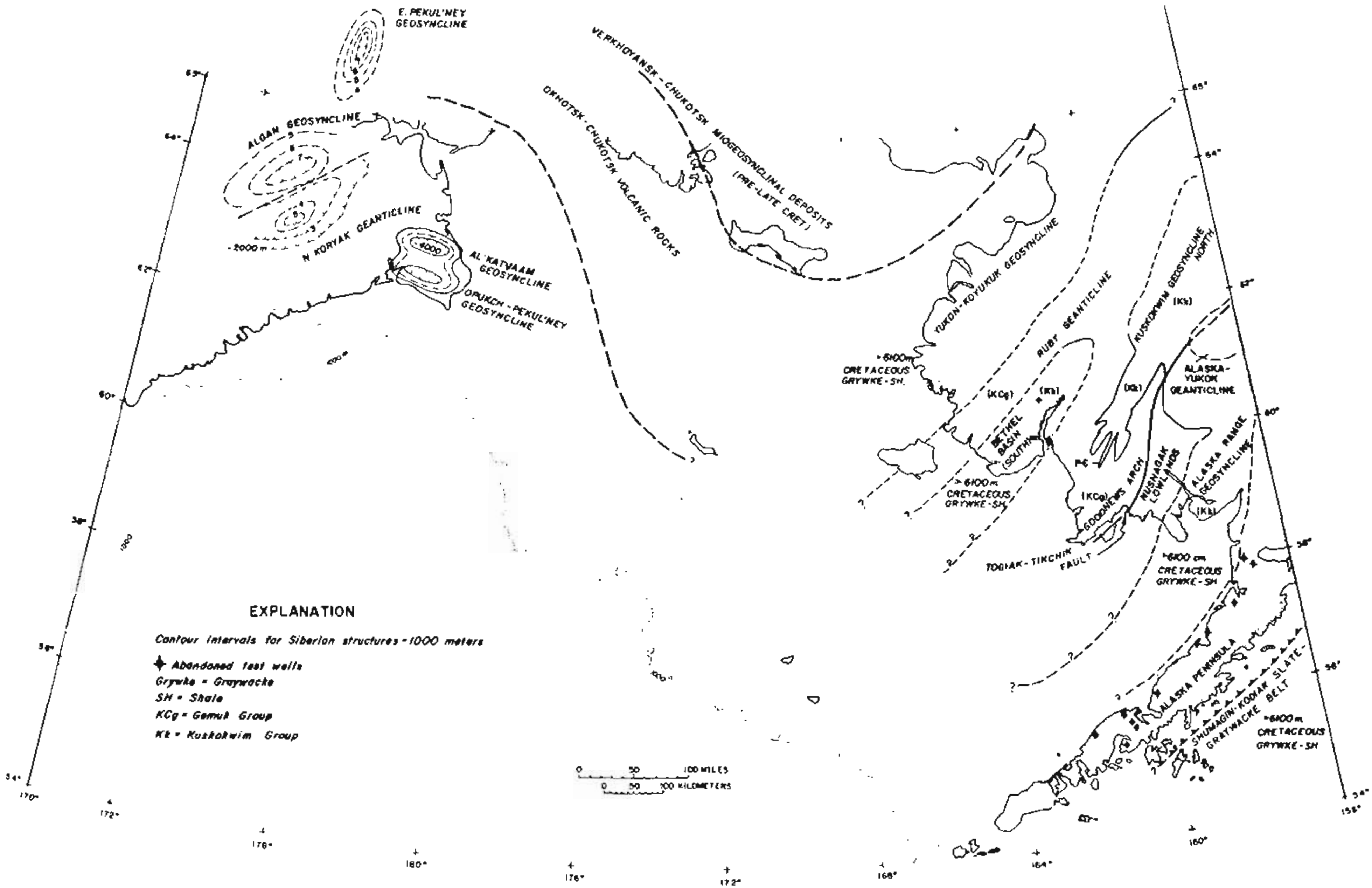
From Port Heiden northward, the Cenozoic sedimentary sequence unconformably overlies Jurassic granitic rocks and locally the sequence includes volcanic rock of Oligocene age. Southwest of Port Heiden, the underlying Oligocene volcanic rocks appear to grade into marine sedimentary facies of Oligocene and Eocene age. In wells drilled south and west of Port

Moller, Cenozoic sedimentary rocks unconformably overlie marine sandstone, siltstone and shale beds of Late Jurassic and Late Cretaceous age (possible source beds), a relationship that may enhance the petroleum potential of the offshore area between Port Moller and Amak Island. Of the nine wells drilled to date in the coastal lowlands of Bristol Bay along the Alaska Peninsula, five that are located south and west of (and including) the Gulf Sandy River well contain the best shows of oil and gas (Hatten, 1971; Brockway and others, 1975). A thick marine section within the Miocene Bear Lake Formation may occur in the Port Moller area and adjacent offshore region, this implies that better source rocks may occur in the southwest portion of Bristol Bay basin and further offshore in St. George basin.

Western Alaska - Bethel and Nushagak Lowlands

The areas here referred to as the Bethel and Nushagak lowlands occupy two flatland zones along the eastern edge of the Bering Sea between Norton Sound and Bristol Bay (Fig. 7). The Bethel area lies between the town of Bethel and Nunivak Island and is crossed by the lower portion of the Kuskokwim River. To the south, the Nushagak lowland is located between Nushagak and Kvichak Bays and occupies the delta region of the Nushagak River. Much of the area is covered by surficial deposits and water and exposures are limited. One exploratory well, near Bethel, has been drilled in this entire area.

Several northeast-trending tectonic belts cross the lowland areas and the intervening Kuskokwim Mountain Range; these include the Yukon-Koyokuk geosyncline, Ruby geanticline, and the Kuskokwim and Alaska Range geosynclines (Hoare, 1961; Payne, 1955). Exposures in the mountain ranges that separate the two lowland areas, as well as geophysical data, suggest that up to 6,000 m of Upper Cretaceous geosynclinal clastic sediments underlie the Bethel



PRESENT DISTRIBUTION OF MIDDLE EARLY TO MIDDLE LATE CRETACEOUS BERING SEA SEDIMENTARY BASINS

Figure 7. Tectonic map showing distribution of middle Early to middle Late Cretaceous Alaska and Bering Sea geosynclines and geanticlines. Based on data from Agapitov and Ivanov (1969), Burk (1965), Hoare (1961), Pratt and others (1972), and Patton and others (1976).

lowlands. A similar thickness of Upper Cretaceous graywacke may underlie the Nushagak lowland (Cady and others, 1955; Hoore 1961; Mertie, 1938).

Basement complex. Economic basement for petroleum exploration in the lowland areas generally consists of rocks older than Late Cretaceous or of rocks underlying the pre-Kuskokwim Group unconformity that has been dated as middle Early Cretaceous in age (Hoare, 1961). The basement complex has been severely deformed by several orogenic events. Basement rocks include: (1) gneiss, schist and quartzite of Precambrian age; (2) limestone of Devonian age (240-366 m thick and locally dolomitic); (3) the Gemuk group, composed of sedimentary and volcanic rocks and ranging in age from Carboniferous to Early Cretaceous; and (4) andesitic volcanic rocks of Middle and Late Jurassic age (Fig. 7).

The Gemuk group of rocks consist of 4500-9000 m of tightly folded, highly faulted argillite, chert, greenstone, limestone, graywacke, and tuff. In the western portion of the Kilbuck Mountains 60 miles east of Bethel, Middle and Upper Jurassic marine volcanic rocks 600-1500 m thick are interbedded with the clastic sequence. These rocks contain marine fossils indicative of a Jurassic age (Hoare, 1961).

Kuskokwim Group. The Kuskokwim Group consists of 6000-9000 m of strongly folded graywacke, shale, conglomerate with minor limestone beds, and local, highly calcareous sandstone beds; the group ranges in age from late Early Cretaceous to middle Late Cretaceous (Fig. 8). Clastic constituents of the graywacke are slate, chert, phyllite, quartz, feldspar, volcanic rock fragments, muscovite, and chlorite. Sorting is generally poor and portions of the Group consist of a "poured-in" type of sediment with very low porosities. The composition of these rocks suggest that they were derived from Lower Cretaceous geanticlinal uplifts (Hoare, 1961).

COMPOSITE COLUMNAR SECTION
NUSHAGAK LOWLANDS, ALASKA

AGE			COLUMN	FORMATION	DESCRIPTION
CENOZOIC	Q.			Holocene Quaternary	Unconsolidated glacial and post-glacial sand and gravel.
CENOZOIC	Tertiary	Neogene / Paleogene		Nushagak Fm. Spurr (1900) (thickness unknown)	Stratified gravel, coarse sandstone, arkose, and clay. Locally cross bedded and folded; nearshore marine-nonmarine environment. Some gravels show glacial striae. McKay (1881-1884) collected Mio-Pliocene fossils from head of Nushagak Bay. Quartz monzonite and granite stocks and plutons.
MESOZOIC	Cretaceous	Upper		(unnamed) (indeterminate thickness)	Graywacke and shale, few bands of conglomerate; calcite and quartz veinlets; zeolites abundant.
MESOZOIC	Cretaceous	Lower		Hauterivian-Valanginian 2100-3000 m	Impure quartzite, quartzose graywacke, siliceous argillite, slate, minor conglomerate. Local red-green chert and siliceous argillites. Contains *Buchia crassicolis*. Section strongly folded in divergent direction from underlying carbonaceous rocks.
MESOZOIC	Jurassic		absent		
MESOZOIC	Triassic			(thickness unknown) Noric Stage	Unnamed-thoroughly recrystallized white to cream colored limestone and limestone conglomerate. Contains *pseudomonotis*, *myochoncha*, *placites*.
MESOZOIC	Triassic		absent		
PALEOZOIC	Permian			Upper Volcanic sequence	Dark colored flows, agglomerate; basalt and diabase, tuff; much chloritized.
PALEOZOIC	Permian			Lower Limestone sequence 150-300 m	Limestone, moderately recrystallized; grades upward into volcanics; contains echinoids, corals, bryozoans and forams.
PALEOZOIC	Carboniforous			Mississippian(?)	Chert, grit, conglomerate; quartzite; an argillite group; also limestone, calcareous sandstone, and shale. All cut by dikes and sills; also sheared and semi-schistose (unfossiliferous).

Figure 8. Composite columnar section of the Nushayak lowlands derived from Mertie (1938).

Five lithologic units occur within the Kuskokwim Group The basal unit consists of a massive conglomerate that reaches a maximum thickness of 600 to 900 m and thins laterally to about 100 m. A second overlying unit consists of 300 to 1500 m of tightly folded and highly sheared thinly-bedded shale. The third unit is composed of interbedded graywacke, slaty shale and pebbly conglomerate beds 3-30 m thick. The fourth unit consists of thinly-bedded, inter-laminated graywacke and shale. The uppermost unit contains interbedded shale, fine- to coarse-grained graywacke, and pebbly conglomerate; this unit locally contains abundant fragments of carbonized wood in addition to thin coal beds (Hoare, 1961).

The Kuskokwim Group is generally highly deformed south and east of Bethel. There are rapid facies changes in rocks of the group. Hard sandstones that typically fracture smoothly across the grains are locally abundant The color of the graywacke varies from gray to black; finer-grained rocks are generally darkly-colored by disseminated carbon (Hoare, 1961). Fossils are absent in the lower part of the Kuskokwim group but a sparse fauna of pelecypods and cephalopod mollusks as well as carbonized remains of terrestrial plants occur in the upper units.

Tertiary Rocks. In the Bethel lowland area, post-Cretaceous sedimentary rocks consist of unconsolidated stream and glacier-deposited silt, sand, and gravel that vary greatly in thickness but do not exceed 450-600 m in total thickness. In the Nushagak area, unconsolidated to slightly consolidated marine sedimentary layers (the Nushagak Formation, Mertie, 1938) consist of gravel, sandstone, arkose and clay beds that locally dip up to 20^{o}. These rocks have been tentatively designated as Miocene or Pliocene in age on the basis of pelecypods and gastropods collected by C.W. McKay between 1881 and 1884. The thickness of this section is not known with certainty but probably is less than 600 m (Fig. 8).

Igneous Rocks. A variety of igneous rock types intrude the bedded rocks of Bethel basin and range in composition from rhyolite to dunite, but granitic rocks are most common. Small and medium-sized stocks, ranging in composition from diorite and gabbro to biotite granite, intrude the bedded rocks of the Kuskokwim Group. Thus, most of the intrusives are probably of Late Cretaceous or early Tertiary age. The youngest igneous rocks are horizontal basalt flows of late Cenozoic age. The flows appear to be fresh and unconformably overlie older rocks (Hoare, 1961).

STRUCTURAL FRAMEWORK AND EVOLUTION OF ST. GEORGE BASIN

Seismic Reflection Data

Earlier work by Marlow and others (Figs. 2 and 7, 1976) delineated the elongate, sediment-filled St. George basin, that underlies the flat, shallow Bering Sea shelf and trending northwest from near the southern Alaska Peninsula toward the Pribilof Islands. In that study, structure contours on acoustic basement derived from 3,000 km of single-channel seismic reflection data show this basin to be 300 km long, 50 km wide, and filled with more than 6.5 km of Cenozoic sedimentary rocks (Marlow and others, 1976). Multi-channel seismic reflection data recently acquired and in part described below, show that this graben is much deeper and that it represents a mammoth extensional rift in the crustal rocks of the southern Bering Sea shelf.

Profile 8B

A 24-channel seismic reflection profile across St. George basin, diagramatically interpreted in Figure 9, shows subshelf structures representative of the southern Bering Sea shelf and St. George basin.

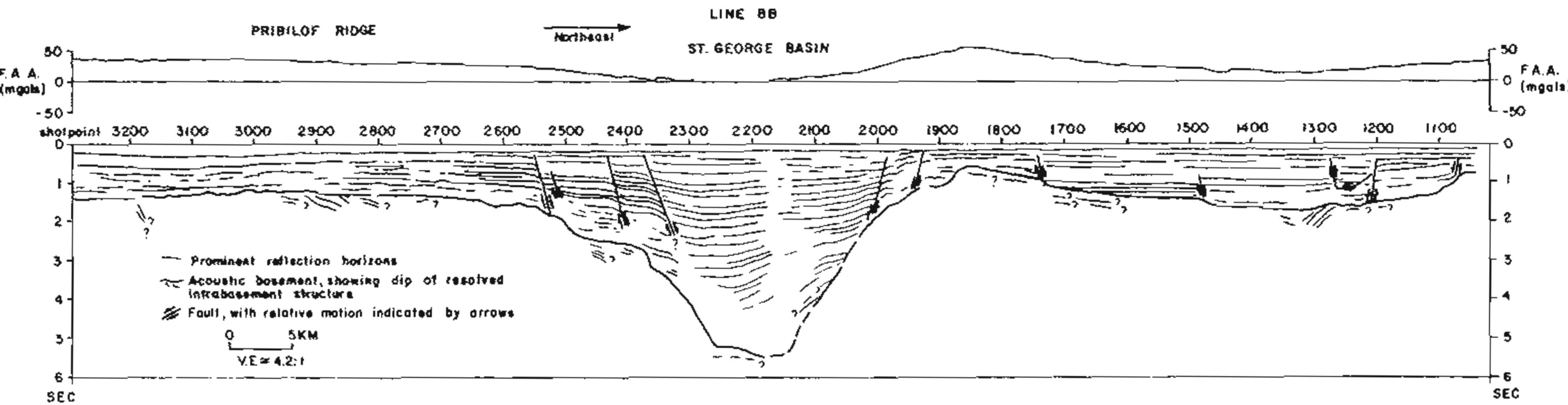


Figure 9. Interpretative drawing of a seismic-reflection profile published by Marlow and others (1977). Note that the vertical exaggeration applies only to the water layer (assumed velocity of sound in sea water of 1.5 km/sec) and will decrease with depth in the section. For location of profile see Figure 1.

The flat acoustic basement underlying the southwest end of profile 8B (*Fig. 9; between shotpoints 3200 and 2700*) is *Pribilof ridge,* which is overlain by a relatively undisturbed, layered sequence 1.3-1.4 km thick (1.3-1.4 sec). Within the acoustic basement, a number of gently dipping reflectors suggest that the basement includes folded sedimentary beds. Farther north, between shotpoints 2700 and 2200, the basement descends in a series of down-to-basin steps, plunging to a maximum subbottom depth of about 5.4 seconds (over 10 km) beneath the axis of St. Geroge basin. The overlying reflectors are broken by at least three major normal faults that dip toward the basin axis and appear to be related to offsets in the acoustic basement. Within the basin fill, the offset along the faults increases with depth, implying that these are growth structures. Strata are synclinally deformed about the basin's structural axis. The free-air gravity anomaly reaches a minimum of -1 mgal over the basin axis (a decrease of 55 mgal from the 54 mgal high over the basement high near shotpoint 1860).

From shotpoints 2200 to about 1860, the acoustic basement rises rapidly to a minimum depth of 0.55 second (0.5 km; Figs. 4 and 9). Again the overlying reflectors are broken by normal faults that dip down to the basin axis.

A gentle concavity in the basement extends from shotpoints 1860 to 1080; the maximum thickness of overlying strata is about 1.7 seconds (1.8 km) near shotpoint 1330. A corresponding relative gravity low of 41 mgal is centered over the swale. Intrabasement reflectors were resolved dipping at a gentle angle to the surface of the acoustic basement (between shotpoints 1200 and 1400). Reflectors in the lower part of the overlying sedimentary section wedge out against the acoustic basement (between shotpoints 1500 and 1720).

Structure Contours

To convert two-way traveltime on the seismic reflection records to depths in meters or kilometers, we used a generalized velocity function:

$D = 1.266t + 1.033t^2 - 0.117t^3$

where:

D = Depth or thickness in km

t = One-way traveltime.

This function was derived by fitting a polynomial curve to velocity data from 150 sonobuoy stations in the Bering Sea. The velocity function used here supersedes the curve published by Marlow and others (1976).

Our new multichannel data show that St. George basin is filled near each end with more than 10 km of sedimentary section. We do not know whether the section thickens toward the center of the basin. Two smaller basins south of and parallel to St. George basin contain 3 to 4 km of layered fill (Fig. 4).

Northwest of St. George basin, the shelf is underlain by a complex of smaller basins and ridges, also parallel to the margin (Fig. 4; Marlow and others, 1976). Most of these basins, like St. George basin, are structural grabens or half-grabens bordered by normal faults. The largest structural high or ridge in the western basement complex, the Pribilof ridge, is subaerially exposed in the Pribilof Islands (Fig. 4). To the southeast, the ridge flanks the southern side of St. George basin and extends toward the Black Hills ridge and the Alaska Peninsula (Fig. 4; Figs. 2 and 7, Marlow and others, 1976).

South of St. George basin, the acoustic basement deepens monoclinally toward the Aleutian Island arc, reaching depths greater than 11 km below sea level, within 20 km of Aleutian Ridge (Fig. 4; Figs. 2 and 7, Marlow and others, 1976). Unfortunately, we do not have sufficient seismic reflection data to determine the structural relation between the basement complex of the Bering Sea margin and the presumably younger one of the Aleutian Island arc (Scholl and others, 1975).

Geopotential Data

Gravity Data

A free air gravity anomaly map of the St. George basin area is outlined in Figure 10. A regional map of the Bering Sea region that includes this area has been published by Watts (1975). The irregular gravity low extending from the tip of the Alaska Peninsula northwestward toward the Pribilof Islands outlines St. George basin (Fig. 10). The southeastern end of the low, adjacent to the peninsula, is the signature of a separate basin, Amak basin (Fig. 4, Marlow and others, 1976). Immediately north of the Amak basin gravity low, a linear, 50-70 mgal gravity high extends about 70 km west of the Black Hills region of the Alaska Peninsula (Fig. 10). This high anomaly appears to turn and trend northwest along the southern flank of the gravity low associated with St. George basin, suggesting that the Jurassic rocks of the Black Hills area extend northwest and south of St. George basin. Furthermore, the structural and gravity data (Figs. 4 and 10) imply that Pribilof ridge extends from the Pribilof Islands along the south flank of St. George basin.

Magnetic Data

Figure 11 is a reproduction of a portion of a total-field magnetic anomaly map of the Bering shelf published by Bailey and others (1976). The St. George, Amak, and Bristol Bay basin complex is characterized by low-frequency, low-amplitude anomalies. This band of anomalies extends northwestward from the Alaska Peninsula to the Pribilof Islands area.

North of the low-amplitude, low-frequency anomaly belt, an arcuate zone

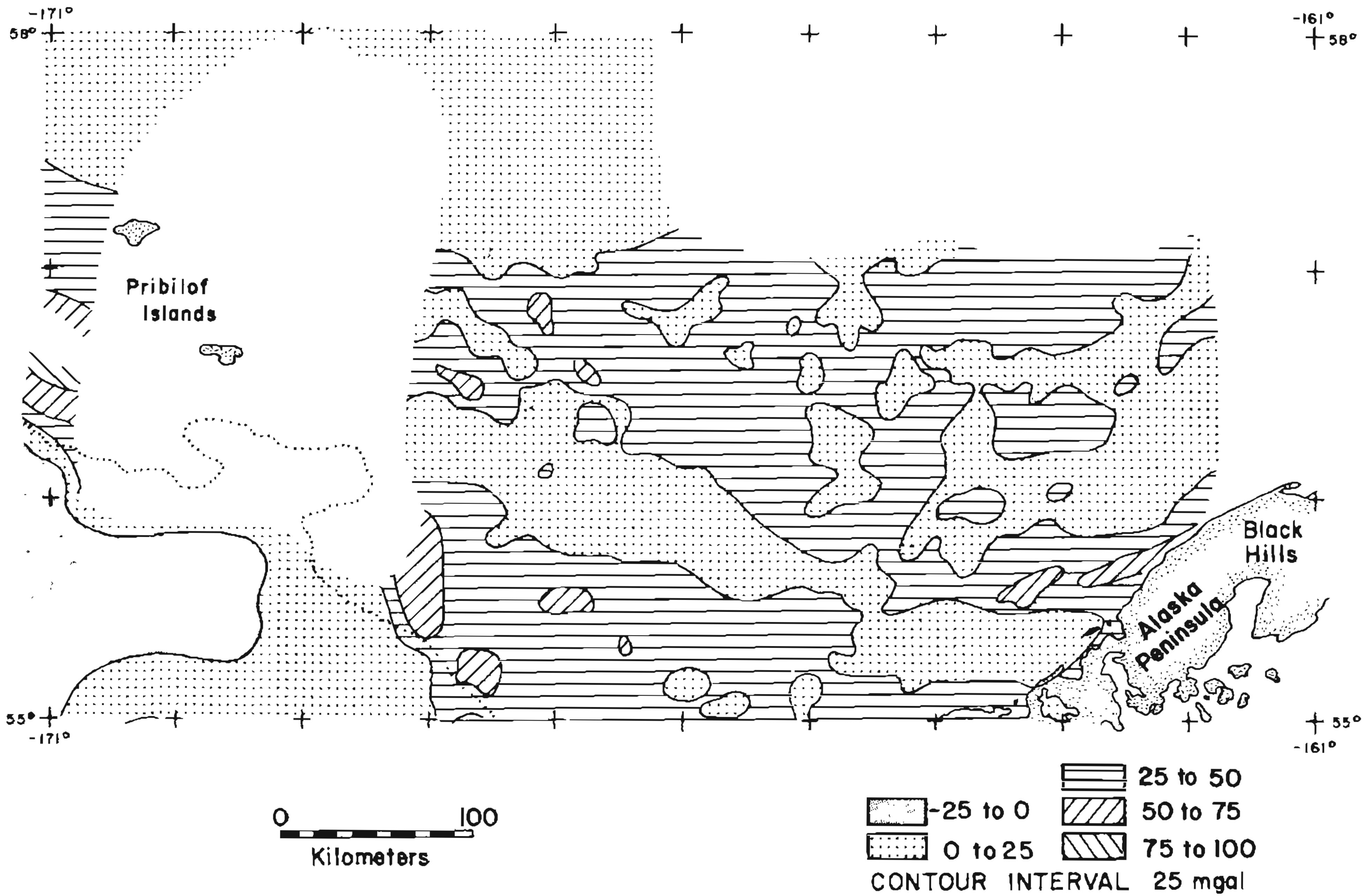


Figure 10. Map of free air gravity anomalies derived from Pratt and others (1972) and Watts (1975). Land areas shown by stipple pattern. Two hundred meter bathymetric contour shown by dotted line.

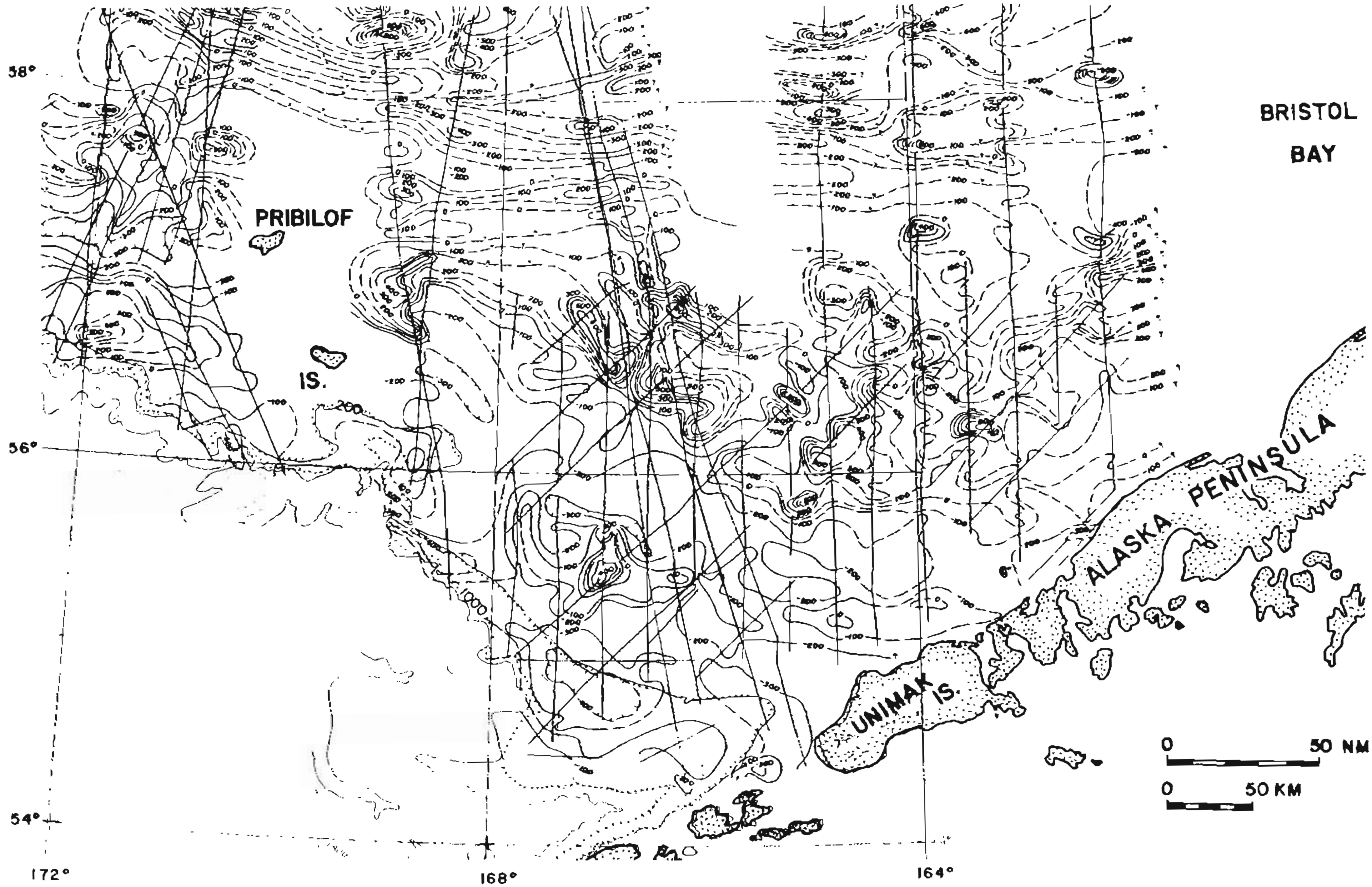


Figure 11. Map of total-field magnetic anomalies derived from Bailey and others (1976). Contour interval is 100 gammas. Individual profiles have been upward-continued to an elevation of one kilometer. Bathymetry in meters shown by dotted lines.

of high-amplitude, high-frequency anomalies is traceable from east to west (Fig. 11). This belt of high anomalies is part of a larger, arcuate zone of similar anomalies that swings across the central and inner Bering Sea shelf (Marlow and others, 1976).

Geologic History

Mesozoic Structural Trends

Gravity, magnetic, seismic-reflection, and dredge data suggest that the Upper Jurassic shallow-marine rocks exposed in the Black Hills on the Alaska Peninsula extend west to northwest along the south flank of St. George basin and connect with Pribilof ridge (Fig. 4). In addition, Upper Cretaceous (Campanian) rocks were dredged from the southern flank of this ridge in nearby Pribilof Canyon (Fig. 4; Hopkins and others, 2969). Seismic-reflection data indicate that the Cretaceous dredge samples may have been recovered from a relatively isolated intra-basement basin perched on the flank of Pribilof ridge. Other dredge samples from the margin northwest of Pribilof ridge indicate that the Mesozoic basement complex is unconformably overlain by shallow-water, diatomaceous mudstone of early Tertiary age (Marlow and others, 1979). This belt of upper Jurassic rocks apparently occupied the former site of the Mesozoic margin of the Bering Sea and was a resistant high, that began to collapse in early Tertiary time.

We speculated earlier that a Jurassic, Cretaceous, and earliest Tertiary magmatic arc extended parallel to and inside (landward to the east towards Alaska) of the outer belt of shallow-water deposits (Marlow and others, 1976). This igneous belt is characterized by high-amplitude, high-frequency magnetic anomalies (Fig. 11). The magmatic arc is exposed as calc-alkalic volcanic and intrusive rocks of late Mesozoic and earliest Tertiary age on St. Matthew and St. Lawrence Islands on the Bering shelf and as similar rocks in southern and western Alaska and eastern Siberia (Fig. 3; Patton and others, 1974, 1976; Reed and Lanphere, 1973; Scholl and others, 1975; Marlow and others, 1976).

Tertiary Deactivation and Crustal Collapse

In 1975 and 1976 we postulated that the arcuate geosynclinal and magmatic trends of the Bering Sea margin resulted from convergence and subduction of oceanic lithosphere (Kula (?) plate) beneath the Bering Sea continental margin, (Cooper and others, 1976a; Scholl and others, 1975; Marlow and others, 1976). Thus, we predicted that either deep-water trench or slope deposits would have accumulated along the former base of a Mesozoic convergent margin. However, rocks dredged in 1978 suggest that the margin was composed, in part, of a resistant basement high that was emergent, from Late Jurassic to early Tertiary time (Marlow and others, 1979). If former Mesozoic trench or slope deposits do exist, then they must be buried beneath the thick sediment accumulations presently draping the base of the margin. Alternately, the former Mesozoic margin may have been the site of predominantly strike-slip (transform) motion until early Tertiary time. Thus, the former Mesozoic slope deposits would have been tectonically "rafted" to the northwest, perhaps into Siberia.

Plate motion along the Mesozoic Bering Sea margin apparently ceased with the formation of the Aleutian Island arc in late Mesozoic or earliest Tertiary time, when the subduction zone (transform fault?) shifted from the Bering Sea margin to a site near the present Aleutian Trench, thereby trapping a large section of oceanic plate (Kula?) within the abyssal Bering Sea. Cessation of plate motion apparently tectonically deactivated the Bering Sea margin. In early Tertiary time, the margin underwent extensional collapse and differential subsidence, which has continued during most of Cenozoic time.

Elongate basins of great size and depth, examplified by St. George basin, formed in the vicinity of the modern outer Bering Sea shelf (Figs. 4, 9; Marlow and others, 1976). Extensional deformation of the folded rocks of the Mesozoic basement has continued to the present as evidenced by normal faults flanking the outer shelf basins that are growth-type structures which commonly rupture the entire Cenozoic basin fill. Collapse of the outer shelf and adjacent margin may have been aided by Cenozoic sediment-loading of the adjacent oceanic crust (Kula(?) plate) flooring the abyssal Bering Sea.

PETROLEUM GEOLOGY

Alaska Peninsula

Drilling History

Since 1959, nine onshore wells have been drilled along the northern coastal lowland area of the Alaska Peninsula. Only one COST well has been drilled offshore south of St. George basin. Data for this well are proprietary and cannot be discussed in this report. For descriptive purposes, the wells on the Alaska Peninsula are divided here into a northern group of four wells, that bottomed in volcanic or granitic rocks, and southern group of five wells that bottomed in either Tertiary or Mesozoic sedimentary rocks.

The northern group includes the General Petroleum Great Basins No. 1 and 2, Great Basins Ewerath Ugashik No. 1, and the Gulf-Alaskco Port Heiden No. 1 (Fig. 12). The southern group includes the Gulf Sandy River Federal No. 1, Pan American Hoodoo Lake No. 1 and 2, Pan American David River No. 1-a, and the Amoco Cathedral River No. 1 (Brockway and others, 1975).

In the northern group of wells, the thickness of the flat-lying Tertiary sequence varies from about 1220 m to 3350 m and consists of interbedded non-marine to shallow marine sandstone, siltstone, claystone and coal (Hatten, 1971). Granitic basement penetrated by the General Petroleum Great Basins No.

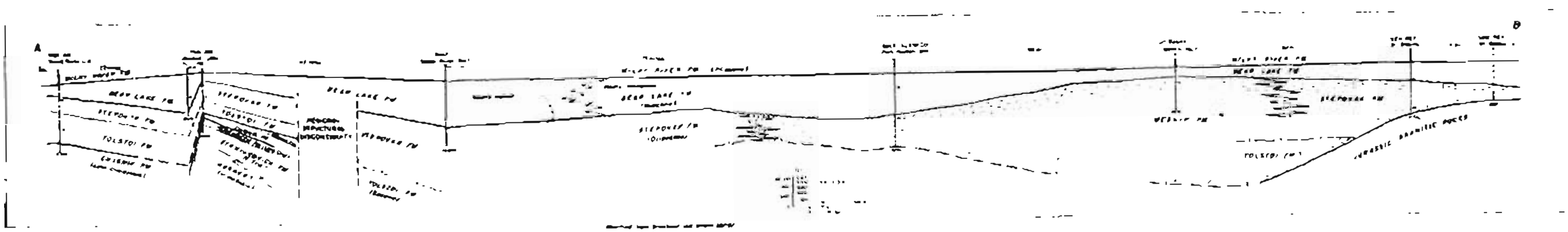


Figure 12. Generalized stratigraphic cross-section of Bristol Bay basin along the Alaska Peninsula. Modified from Brockway and others (1975). See Figure 5 for columnar section of Bristol Bay and Alaska Peninsula regions.

1 and 2 wells has been dated radiometrically as approximately 177 m.y. old (late Early Jurassic). Radiometric ages from the volcanic sequence underlying the flat-lying Tertiary sedimentary rocks in the Gulf Port Heiden and Great Basins Ugashik wells range from 33 + 1.5 to 42 + 4 m.y. (Brockway and others, 1975; Oligocene to late Eocene, according to the time scale of Berggren, 1969). No significant show of oil or gas have been reported from the northern group of wells. To the south the Gulf Sandy River well encountered gas associated with coal in the middle part of the Bear Lake Formation (Miocene) between 1970 and 1940 m. Oil and gas shows were also encountered in the basal sandstone beds of the Sandy River well. However, in this well the oil encountered within the basal portion of the Bear Lake Formation may have been derived from source rocks within the underlying Stepovak Formation.

In offshore areas where the flat-lying Cenozoic sequence overlies older, folded and truncated sedimentary rocks, such as the Mesozoic strata of the Black Hills, oil may have migrated upward into the more porous sandstone beds of the underlying Bear Lake Formation. The possibility of oil and gas migration from older sedimentary formations renders the offshore area between Port Moller, Amak Island and the Pribilof Islands more prospective than the area north of Port Heiden, where the basement consists of volcanic and granitic rocks. The offshore arcuate gravity and magnetic discontinuity described by Pratt and others (1972), which extends from the Pribilof Islands toward Port Moller, may define two different basement rock types beneath the flat-lying Cenozoic sequence. The high amplitude magnetic anomalies on the northeast side of the discontinuity may represent volcanic or granitic and metamorphic basement rock, and the low amplitude anomalies on the southwest side may reflect a thick sequence of early Tertiary or late Mesozoic sedimentary rocks. The flat-lying sequence of Cenozoic sedimentary rocks is locally folded and uplifted along the foothill belt of the Alaska Peninsula. Further offshore the strata may be depositionally draped over fault blocks within the acoustic basement (Hatten, 1971). Data on the size and extent of structures are not publicly available. The rocks considered to have the greatest petroleum potential in the offshore area of St. George basin are flat-lying to gently folded Cenozoic sandstone, siltstone, and shale beds. These rock units probably range in age from Eocene to Holocene.

Source Beds

The best source rocks in the Tertiary sequence appear to be the black marine siltstone and shale beds in the Oligocene Stepovak Formation. On the Alaska Peninsula, the Stepovak Formation is locally at least 4500 m thick (Burk, 1965). Scattered shows of oil and gas in Stepovak rocks have been reported from three Alaska Peninsula wells, Gulf Sandy River, Pan American Hoodoo Lake No. 2, and Pan American David River 1-A (Fig. 12; Brockway and others, 1975). Potential source rocks may also occur in the Miocene Bear Lake Formation because locally the basal portion containing marine siltstone and shale may have been buried deep enough to generate hydrocarbons. Marine shale of Late Jurassic and Late Cretaceous age might also be considered as potential source rocks. These rocks are often in angular discordance with overlying Cenozoic sandstone reservoir beds.

Core chips and drill cuttings from eight of the nine wells drilled along the Bering Sea lowlands of the Alaska Peninsula were subjected to lithologic and paleontologic analyses by McLean (1977). Results suggest that at least locally, sedimentary rocks of Tertiary age (excluding Paleogene strata) contain oil and gas source and reservoir rocks capable of generating and accumulating liquid and gas hydrocarbons.

Paleogene strata on the Alaska Peninsula are rich in organic carbon but they are immature. However, strata in offshore basins to the north and south (St. George and Bristol Bay basins) may have been subjected to a more productive thermal environment. Total organic carbon content of fine-grained Neogene strata appears to be significantly lower than in Paleogene rocks, possibly reflecting nonmarine or brackish water environments of deposition. Neogene sandstone beds locally yield high values of porosity and permeability to depths of about 8,000 feet (2,439 m; McLean, 1977). Below this depth, reservoir potential rapidly declines.

The General Petroleum, Great Basins No. 1 well drilled along the shore of Bristol Bay reached granitic rocks. Other wells drilled closer to the axis of the present volcanic arc indicate that both Tertiary and Mesozoic sedimentary rocks have been intruded by dikes and sills of andesite and basalt. Although the Alaska Peninsula has been the focus of igneous activity throughout much of Mesozoic and Tertiary time, thermal maturity indicators such as vitrinite reflectance and coal rank suggest, that on a regional scale, sedimentary rocks have not been subjected to abnormally high geothermal gradients.

Recently, Lyle and others (1979) studied 14 stratigraphic sections along the Alaska Peninsula totaling 5000 m. They found that 63 percent of the total measured stratigraphic section is potential Tertiary reservoir sandstone. However, the porosities and permeabilities for these sandstones were generally low in most areas due to pervasive pore-filling mineralization. The best preserved and most probable reservoir rocks are sandstone beds in the Bear Lake Formation of Miocene age. In studying potential Tertiary source rocks, Lyle and others (1979) found that the total organic carbon for their samples ranged from less than 0.2 to 8.0 percent, that the hydrocarbon C_{15+} extracts averaged 362 ppm, that the major or organic constituents are herbaceous-spore debris, and that most samples have a thermal alteration index of 2- to 2+.

They concluded that dry gas is the most probable hydrocarbon to form in Tertiary source rocks on the Alaska Peninsula.

Reservoir Beds and Seals

The rocks that have the greatest reservoir potential for oil and gas in the offshore area of Bristol Bay and St. George basins are probably the sandstone units equivalent to the Bear Lake Formation of middle to late Miocene age (Lyle and others, 1979). Bear Lake sandstone beds are both marine and nonmarine and contain a combination of volcanic grains, dioritic grains and chert, and sedimentary lithic fragments. Most of the sandstones could be classified as lithic subgraywackes and others as lithic arenites (Burk, 1965). Shows of oil and gas have been reported from the basal Bear Lake Formation sandstones in the Gulf Sandy River and Pan American David River wells.

Sandstones in the older Tertiary formations, Tolstoi and Stepovak, have an abundance of volcanic detritus as well as matrix clay. These rocks are dense and highly indurated and thus are not considered good reservoir beds.

Traps and Timing

The majority of potential oil and gas traps in the offshore St. George basin area are probably anticlinal structures. Anticlines in the Cenozoic sequence are primarily formed by draping and differential compaction of strata over erosional and block-fault highs that developed within the acoustic basement complex. The resultant structures are probably large in area but have a limited amount of closure. Structural traps in the offshore area probably formed during the early filling of St. George basin. Most structures appear to decrease in amplitude upward through the Cenozoic section, and the upper 100 to 200 m of strata are often flat-lying and undeformed.

Stratigraphic traps formed by buttress onlap during transgression around topographic highs, by local truncation of sandstone beds, and by lenticular sandstone bodies probably occur in the Cenozoic sequence, but their size and number are unknown.

Western Alaska

Drilling History

The petroleum potential of the Bethel and Nushagak lowlands is difficult to assess because the bulk of prospective rocks are concealed by a thick mantle of alluvial deposits and only one exploratory well has been drilled in the area. In the 1961, Pan American Oil Company drilled the Napatuk Creek No. 1 well to a depth of 14,877 feet (4500 m) about 56 km west of Bethel (Fig. 7). No hydrocarbon shows were reported in the well. The well penetrated approximately 300 m of Quaternary sediment that unconformably overlies a relatively flat-lying sequence of Upper Cretaceous graywacke and shale. Several mafic volcanic dikes of unknown age were encountered in the Cretaceous section. Rapid facies changes have been noted within the Kuskokwim Group and thus, adequate reservoir rocks may occur elsewhere within the Bethel basin (Hoare, 1961). Reconnaissance aeromagnetic data indicate that the maximum depth to magnetic basement in the vicinity of the Napatuk Creek No. 1 well is approximately 20,000 feet (6100 m) J. M. Hoare, oral commun., 1975). Magnetic basement probably consists of Jurassic and older igneous rocks, so perhaps as much as 6,000 feet (1800 m) of Cretaceous rocks remain undrilled below the bottom of the well.

No wells have been drilled in the Nushagak basin. Limited outcrop data from around the margin of the basin suggest that pre-Tertiary rocks have a very limited petroleum potential because they are highly indurated and deformed. No data are publicly available on the thickness of Cenozoic rocks underlying the Nushagak lowlands.

St. George Basin

Source Beds

Only one COST well (data that is proprietary) has been drilled in St. George basin; thus little is known about possible source beds in the basin. Cretaceous mudstone dredged from the nearby continental slope in Pribilof Canyon contains as much as 1 percent organic carbon (Marlow and others, 1976, p. 179).

Other rocks dredged from the Beringian continental slope include lithified volcanic sandstone of Late Jurassic age, mudstone of Late Cretaceous age, and less consolidated deposits of early Tertiary age. Geochemical analyses of some of these rocks are listed below:

Table 1. Geochemical analyses of rocks dredged from the Bering Sea Conetinental Margin. See Marlow and others (1976c) for locations.

Sample number	Lithology	Age	Organic carbon (Wt%)	Pyrolytic hydro-carbon (Wt.%)	Vitrinite reflectance (Avg. %)
S6-77-BS					0.38
DR1-20	Volcanic sandstone	Late Jurassic	0.79	0.24	
DR1-26	Volcanic sandstone	Late Jurassic	0.26	0.01	1.14
TT-1-021					
001	Mudstone	Late	0.62	0.11	.40
L5-78-BS					
5-5	Sandstone	L.Jurassoc	0.27	0.02	.63
2-3	Mudstone	Paleogene	0.33	0-.02	.41
16-9	Mudstone	M.Eocene	0.83	0.04	.31

Pyrolytic analyses of these rocks indicates that none are good source beds for petroleum. However, the outcrops sampled by rock dredging are generally sandy units that may not be representative of finer grained possible source beds that are exposed either along the margin or within the subshelf basins.

Other Tertiary mudstone also crops out on the continental slope; these rocks commonly contain more than 0.25 percent organic carbon (Marlow and others, 1976, p. 178). However, many of these rocks crop out too far down on the continental slope to be representative of the lower sediment sections in the basins. Because the stratigraphically lower basin beds wedge out against the flanks of the basins correlative outcrops are virtually unknown along the nearby continental slope

Reservoir beds

The porosities of Eocene to Pliocene-Pleistocene rocks dredged from 15 sites along the Bering Sea continental margin range from 14 to 70 percent (avg, 44 percent) as shown in Table 2.

The Cenozoic samples are generally porous - probably because of abundant diatom frustules. The permeability of these rocks is variable, probably because of submarine weathering and subsequent cementation effects. These Cenozoic outcrops can be traced as seismic reflectors to the subshelf basins, where, if the beds remain diatomaceous, good potential reservoir beds may occur.

These samples may be equivalent to the upper sedimentary section in St. George basin, implying that good reservoir beds may be present in the basin. Neogene reservoir rock beds of shallow-water origin are also likely to be present in St. George basin because sedimention has matched subsidence, which averaged 100 to 200 $m/10^6$ yr during Cenozoic time (Marlow and others, 1976b). The thick sections of the basins beneath the Bering Sea shelf accumulated near the mouths of major Alaskan and Siberian rivers, including the Yukon and Kuskokwim. During Neogene time, the shelf was swept by numerous marine transgressions and regressions (Hopkins, 1967; Hopkins and Scholl, 1970). All these factors suggest the likely deposition of neritic and deltaic strata and hence good reservoir beds in the basin.

Table 2. Physical properties of rocks dredged from the Bering Sea continental margin. For locations, see Marlow and others (1976b, 1979b).

Sample number	Lithology	Age	Permeability (md)	Porosity (%)
70-B93-3*	Calcareous wacke	Pliocene-Pleistocene	--	14.0
70-B101-1S2*	Diatomaceous mudstone	L. Miocene	--	59.0
70-B97-1S1*	Diatomaceous siltstone	M. or L. Miocene	--	57.0
L5-78-BS-28-1	Sandy mudstone	L. Miocene	1.35	54.5
L5-78-BS-9-2	Glauconitic mudstone	L. Middle Miocene	29.00	34.4
L5-78-BS-7-3	Mudstone	M.Miocene	1.67	57.4
L5-78-BS-2-5	Diatomacoues mudstone	E. Miocene	0.92	40.9
L5-78-BS-5-3	Diatomacoues mudstone	E. Miocene	1.49	22.0
L5-78-BS-6-7	Diatomaceous mudstone	L.Oligocene or E. Miocene	1.75	61.1
L5-78-BS-2-4	Sandy mudstone	L.Oligocene	5.46	68.3
L5-78-BS-2-11	Calcareous siltstone	L.Oligocene	1.25	45.1
L5-78-BS-5-10	Andesite tuff	L.Oligocene	19.00	50.7
70-B97-1S2	Pebbly conglomerate	M.Oligocene	--	29.0
L5-78-BS-4-3	Distomaceous mudstone	E.Oligocene(?)	9.67	46.9
L5-78-BS-16-12	Mudstone	Eocene(?)	0.77	57.0
L5-78-BS-27-1	Sandy siltsone	Eocene(?)	3.61	55.9
L5-78-BS-22-2*	Glauconitic sandstone	--	8.43	70.6
70-B92-3S1*#	Calcareous argillite	--	--	21.0
70-B92-3S2*#	Lithic wacke	--	--	21.0
690B92-3S5*#	Lithic wacke	--	--	17.0

Note: * These values from Marlow and others (1976). No permeability values measures.

\# No age given because of a lack of diagnostic fossils.

The stratigraphically lower sections of St. George basin are presumed to include upper Mesozoic and lower Tertiary beds. The geologic evolution of the Bering Sea shelf and margins suggests that in late Mesozoic and early Tertiary time, the then-forming shelf basins were flanked by coastal mountains, peninsulas, and islands. These subsiding, yet relatively high, land masses of Mesozoic rock would have shed coarse clastic debris into the adjacent basins during early Tertiary time, and these beds could also be good prospective reservoirs.

Traps

Within St. George basin structural traps include broad anticlinal closures and tighter folds associated with normal faults. Closure and fault offset increase with depth; hence, growth-type structural traps formed continuously with basin filling.

Potential stratigraphic traps are recognizable in the thinning and wedging of the beds of the older stratigraphic sequence toward the flanks of St. George basin (Fig. 9). These beds dip toward the axis of the basin, hence up-dip migrating fluids could be trapped against the much denser and less permeable rocks of the Mesozoic basement. The basin's lower stratigraphic sequence is discordantly overlapped by the younger acoustically reflective sequence. Hydrocarbons migrating up-dip along the lower beds might, therefore, be trapped beneath the overlapping upper sedimentary sequences.

Summary

Although there is no direct evidence that oil and gas have been generated in St. George basin, shows in associated rocks on the Alaska Peninsula suggest this may be so. The implications of the rocks sampled at submerged outcrops, the structure and reflective characteristics of the basin fill, which is thicker than 10.0 km, and regional geologic studies combine to indicate that St. Geroge basin may be a potential oil and gas province.

ENVIRONMENTAL GEOLOGY

Introduction

Major potential geologic hazards in the southern Bering Sea in the area of St. George basin include faulting and earthquakes, sea floor instability due to erosion and slumping, volcanic activity, and ice. This section on environmental hazards is derived mainly from Gardner and others (1979) although some parts are taken from Lisitsyn (1966), Askren (1972), Nelson and others (1974), Sharma (1974), and Marlow and others (1976). Faulting and sea floor stability are probably the greatest potential hazards in the region, although other hazards may be important locally. A section on sediment distribution is also included.

Seismicity and Faulting

Classification of Faults

Two aspects of faults provide a basis for their evaluation as potential hazards - their magnitude and their recency of movement. Magnitude can be estimated from the amount of offset and recency of movement can be determined by the age of the strata that are displaced. Faults that offset the sea floor must be considered as potentially active.

The following seismic-reflection systems were used to delineate faults in this area: 1) 3.5 kHz; 2) 1.5 kHz; 3) single-channel seismic-reflection (60 KJ to 160 KJ sparker, and up to 1326 in^3 air-gun sources); and 4) 24-channel system using a 1326 in^3 air gun array. The resolutions of the seismic systems, which determine the minimum offset we can detect with each system, are shown in Table 1. The resolutions were calculated using the velocity of sound in water and by following the procedure of Moore (1969).

Table 3. Ranges of resolution for seismic systems.

Approximate Peak Frequency	Range of Minimum Resolution (m)
40 Hz (multichannel)	9.4 to 28.1
100 Hz (single channel)	3.2 to 11.2
1.5 kHz	0.15 to 0.5
3.5 kHz	0.1 to 0.3

Faults are classified as surface, minor, and major faults. Surface faults are any faults detected that offset the surface of the sea floor. In St. George basin, these faults offset the sea floor no more than a few meters. Minor near-surface faults are resolved on 2.5 kHz and/or 3.5kHz records, but not on single or multichannel seismic-reflection profiles. These faults typically displace reflectors less and than 0.006 sec (5 m). Most minor faults are close to but do not break the sea floor; in places sediment drapes over these features. Major faults are defined as those resolved on multichannel and single-channel seismic-reflection profiles. These faults generally are growth structures and many displace the acoustic basement. Boundary faults are major faults that mark the boundaries of St. George basin.

Fault Distribution

Distribution of faults is shown in Fig. 13. The strike of most faults is unknown because of the relatively wide spacing of tracklines. Faults found on northeast-southwest tracklines, perpendicular to the long axis of St. George basin, greatly outnumber those observed on northwest-southeast tracklines which indicates that the majority of the faults have a northwest-southeast trend and parallel the trend of the basin. Faults bounding St. George basin can be confidently traced between tracklines. We believe that most faults

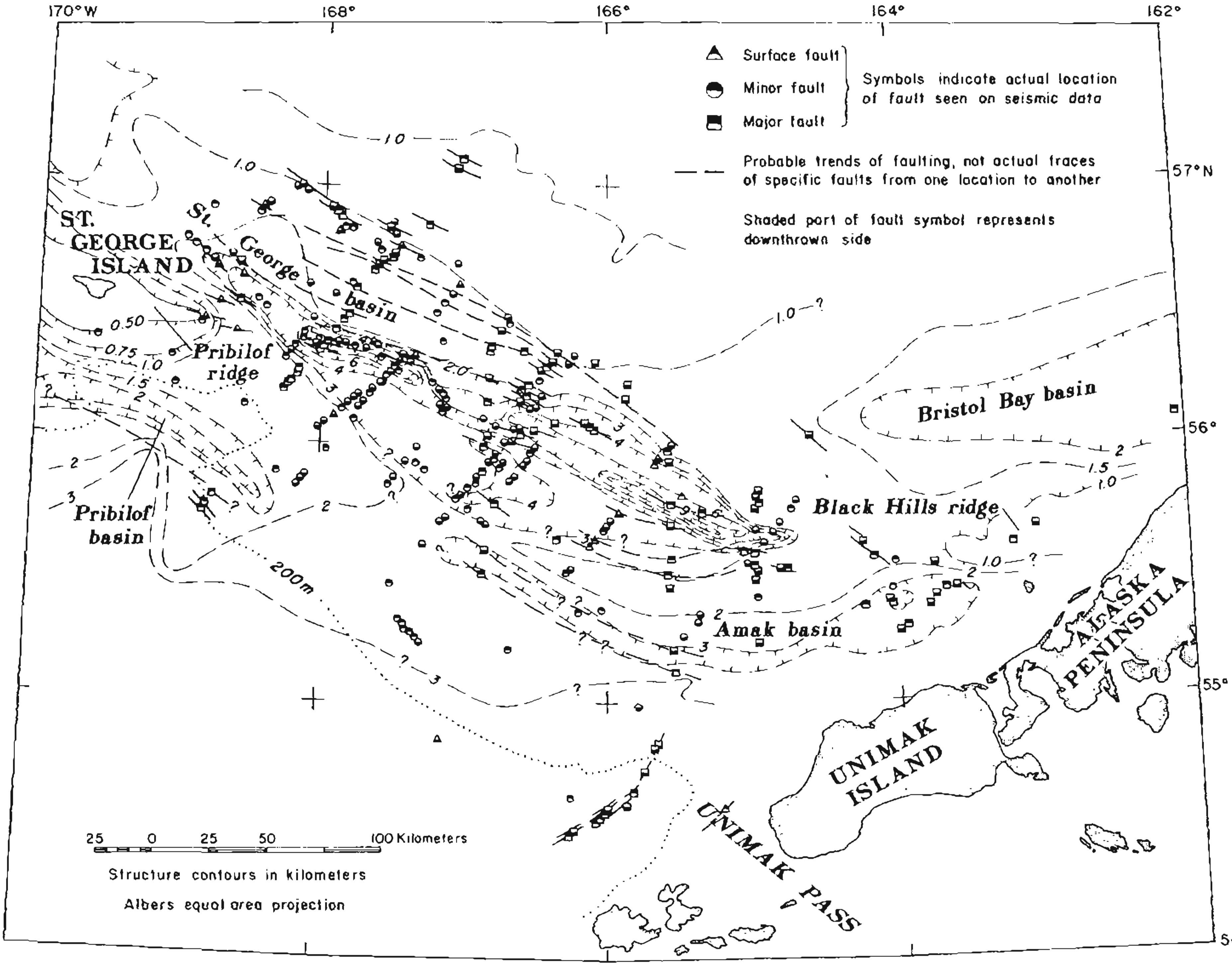


Figure 13. Distribution of faults in the southern Bering Sea. Lines through fault symbols are inferred trend of the fault, not any known strike. Structure-contours of acoustic basement from Figure 4.

beneath the shelf and those in St. George basin in particular, trend northwest-southeast parallel to the basin and to the margin.

Boundary faults clearly delineate St. George basin, and the north side of the Pribilof ridge. These faults are normal faults, occur in groups, and exhibit increased offset with depth, which indicates growth-type structures. These faults in many places cut nearly all of the sedimentary section, and often offset acoustic basement, but rarely offset the sea floor.

Major faults (other than boundary faults) principally occur within St. George basin, although a few occur within Amak basin (Figure 14). This class of fault decreases in abundance toward the Pribilof Islands. Major faults showshow displacements that generally are much less than the larger boundary faults but offsets greater than 0.08 sec (60 m) occur in the central region of St. George basin. Major faults are not always offset in the same sense as adjacent boundary faults.

Surface faults tend to be more abundant along the southern side of St. George basin and along Pribilof ridge than in the center of the basin (Figure 14). Most surface faults can be traced from high-resolution to low-resolution records, which suggests that most surface faults are expressions of major faults and of boundary faults.

Minor faults (Figure 15) occur throughout the southern outer shelf, although, like other classes of faults, they are also concentrated in the middle region of St. George basin, away from the Pribilof ridge. Minor faults are more frequent south of the ridge than to the north (Figure 15). Most minor faults offset reflectors less than 0.006 sec (5 m) and almost all these faults cut the top 0.005 sec (approximately 4 m) of the sedimentary section. Diatoms recovered in sediment from gravity cores up to 2 m long are younger

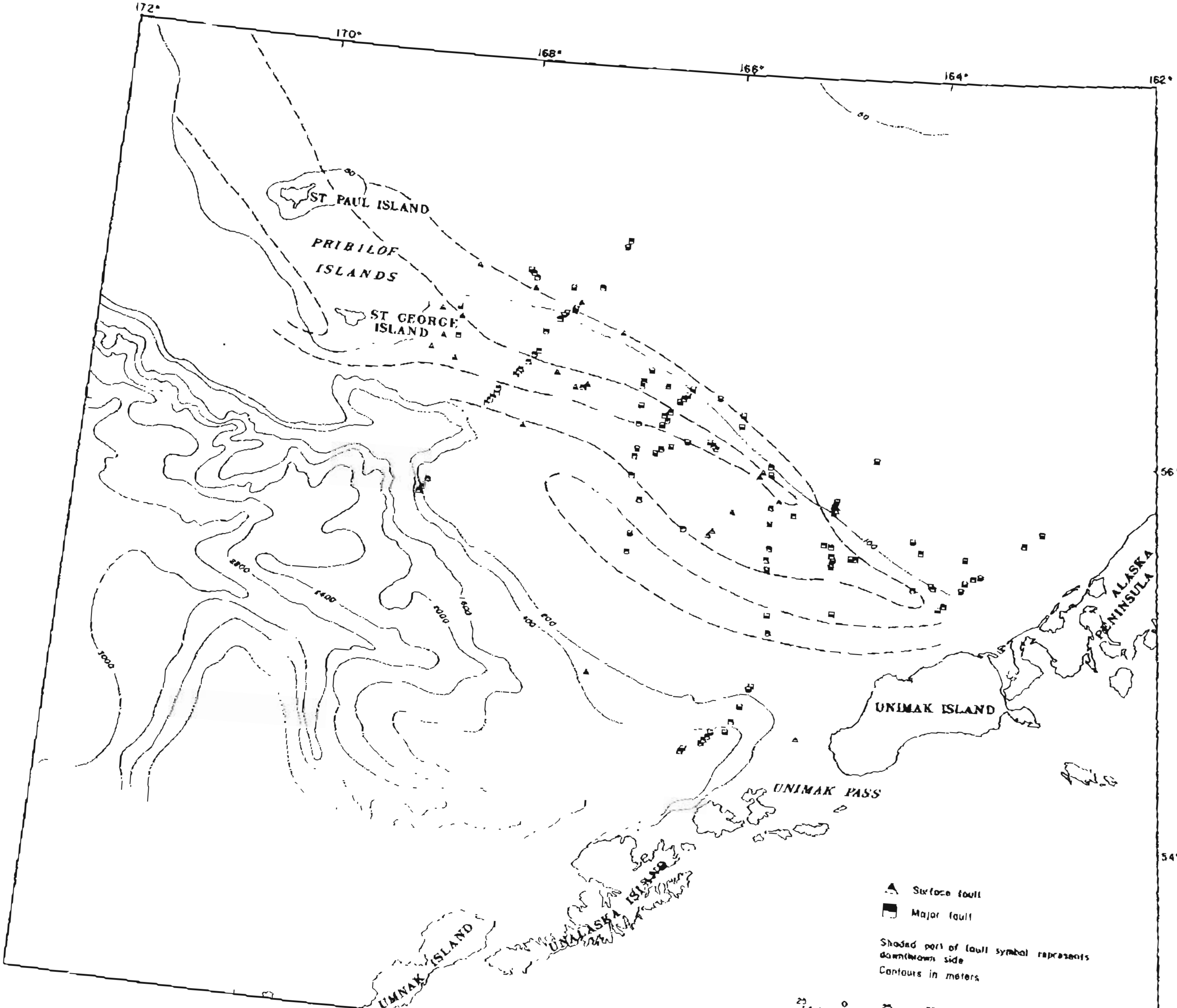


Figure 14. Distribution of surface and major faults. Structure-contours of acoustic basement from Figure 4.

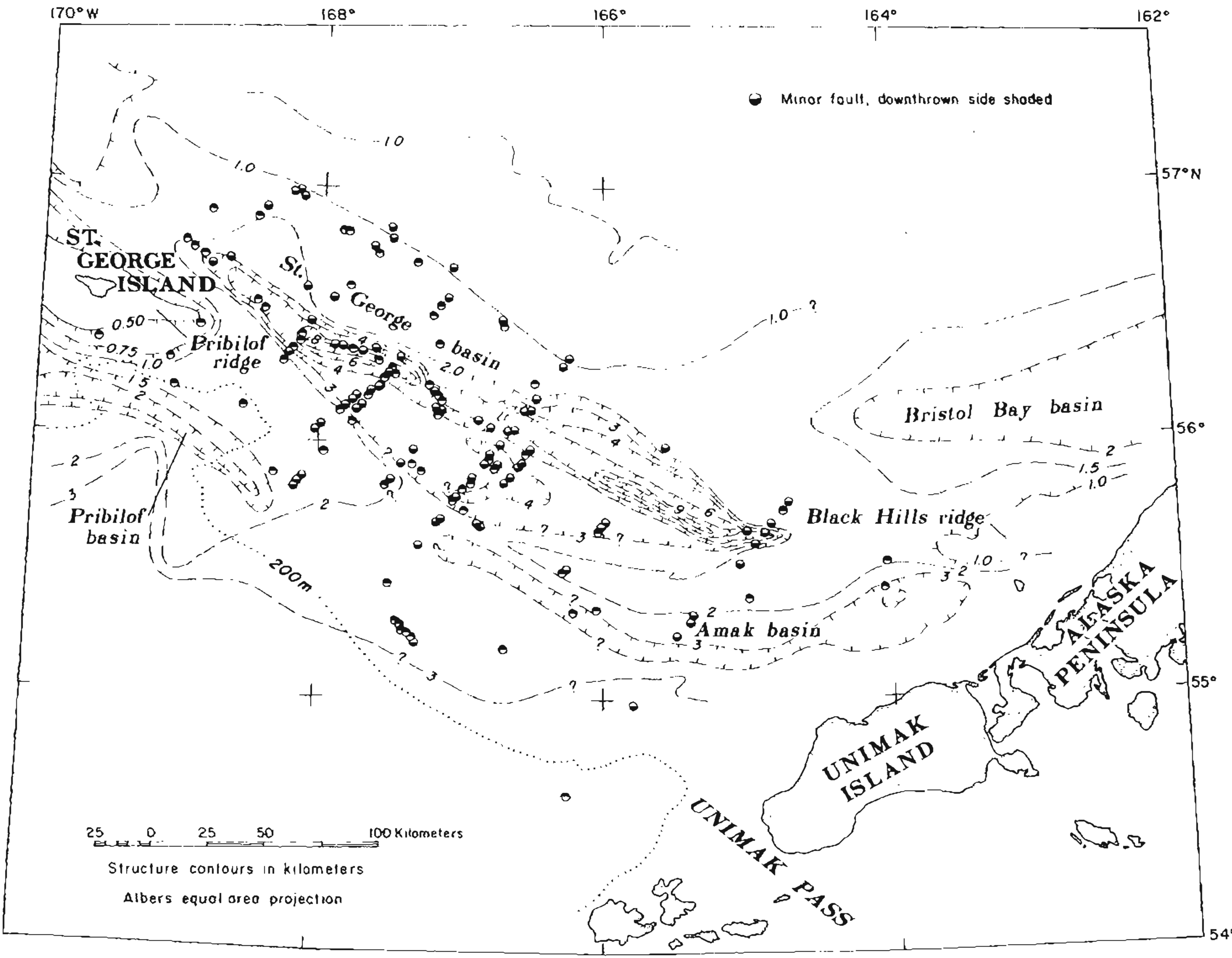


Figure 15. Distribution of minor faults. Structure-contours of acoustic basement from Figure 4.

than 260,000 years (all within the Denticula seminae Zone; John Barron, pers. commun., 1976, 1977). If we assume that a 2 m core just penetrated the entire Denticula seminae Zone, then the minimum accumulation rate is 0.8 cm/10^3. If we assume that this minimum accumulation rate is typical for the top 4 m of sediment (the thickness recently affected by minor faults), then the maximum age of the sediment, calculated using 0.8 cm/10^3 yr. is 520,000 YBP. Thus, minor faulting may be no older than Pleistocene in age. Accumulation rates may be much greater, for example 10 cm/10^3yr. as suggested by C^{14} dates from areas farther north (Askren, 1972), in which case the minor faults could cut sediment as young as 40,000 YBP.

Earthquakes

The southern Bering Sea margin is within 500 km of the Aleutian Trench, the present site of subduction between the Pacific and North American plates. Several intermediate - to deep-focus (71 to 300 km deep) and many shallow-focus (less than 71 km deep) earthquakes were recorded beneath the southern Bering Sea margin from 1962 to 1969 as shown in Figure 16. The St. George basin and surrounding areas have been subject to earthquakes with intensties as high as VIII (modified Mercalli scale), which corresponds to a magnitude 5.7 earthquake (Meyers and others, 1976). Recurrence rates of earthquakes for the area bounded by latitudes 50° and 60° N and longitudes of 160° to 175° W have been as high as 6.4 earthquakes per year from 1963 to 1974 for magnitudes of 4.0 to 8.4, and 0.013 earthquakes per year of magnitude 8.5 to 8.9 (1 every 130 years) from 1899 to 1974 (Meyers and others, 1976).

The correlation of earthquakes to shallow faulting is not well understood (Page, 1975). We believe, however, that many of the faults in the southern Bering Sea are active and that they probably respond to earthquake-induced energies and possibly to sediment loading in St. George basin.

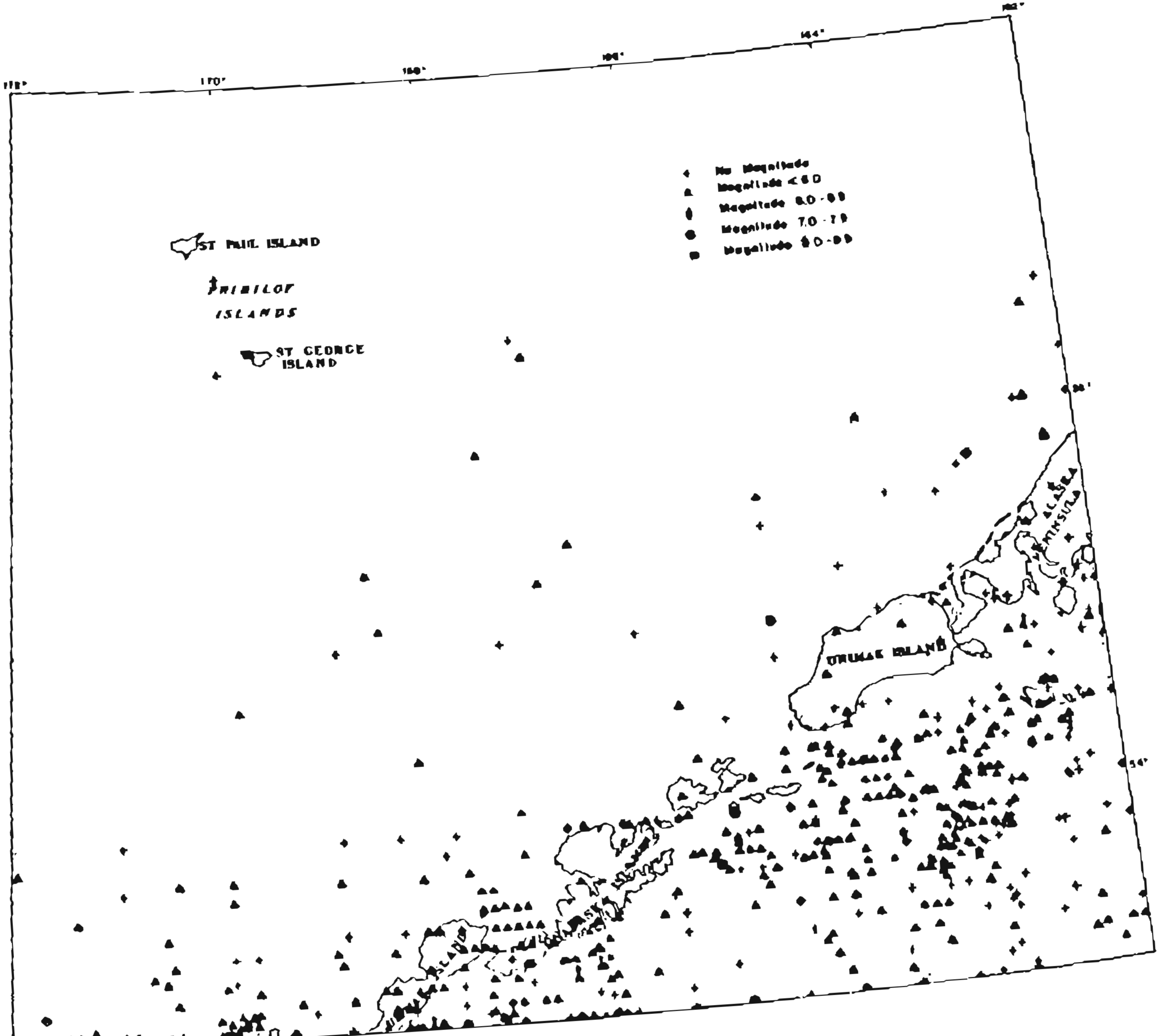


Figure 16. Epicenters up through 1964.

Summary

Seismic-reflection data are used to identify and map faults beneath the outer continental shelf of the southern Bering Sea. We studied more than 10,000 km of single-channel and 600 km of multichannel seismic-reflection profiles. Our seismic systems can resolve offsets that range from a fraction of a meter to several kilometers. Faults are classified as major, minor, and surface based on the type and amount of displacement. Major faults are those resolved on both multichannel and single-channel seismic-reflection records. These faults generally penetrate from several hundred meters to several kilometers beneath the sea floor and some displace reflectors more than 60 meters. Major faults are principally distributed along or near the borders of St. George basin and they trend NW-SE parallel to the basin's long axis. Major faults often offset the seafloor and like surface faults, are most abundant along the boundaries of St. George basin. Minor faults are widely distributed throughout the outer shelf; however, to the east they are concentrated in the middle of St. George basin. Most minor faults exhibit displacements of 5 m or less and almost all approach the sea floor to within 4 or 5 m. The precise age of faulting is not known although both surface and minor faults do offset upper Pleistocene sediment. Major faults are probably related to stress fields established by Mesozoic and Cenozoic plate motions and minor faults are related to high seismicity in the nearby Aleutian subduction zone.

Seafloor Instability

Areas of potentially unstable sediment masses (Fig. 13) were determined from the seismic reflection records by using one or more of the following criteria: 1) surface faults with steep scarps and rotated surfaces; 2) deformed bedding and/or discontinuous reflectors; 3) hummocky topography;

4) anomalously thick accumulation of sediment; and 5) acoustically-transparent masses of sediment. Regions that show unstable sediments (e.g. gravity slides, slumps, creep, scarps, etc.) are confined to the continental slope and rise and the Pribilof and Bering Canyons. Zones of creep, as shown by irregular, hummocky topography, begin near the shelf break at depths of about 170 m and continue onto the upper continental slope. Hummocky topography occurs on the continental slope on a large scale and mass movement is a common feature. We suspect the entire continental slope and the walls of the major submarine canyons to be zones of potentially unstable sediment. Regimes of active sediment movement could respond to a variety of energy sources including earthquakes, storms, internal waves, and gravity.

Earthquake-, tide-, and wind-induced waves affect sediment movement in the southern Bering Sea around St. George basin according to Lisitsyn (1966, p. 96-98). Earthquakes and associated tsunamis can affect shallow water sedimentary deposits. Tides also have a strong affect in shallow water, particularly in funnel-shaped estuaries such as Kuskokwim Estuary, where the tide ranges up to 8 meters and current velocities can exceed 200 cm/sec (Lisitsyn, 1966). Wind-induced waves influence sedimentation in depths up to 100 meters in the Bering Sea. Storms in the area are frequent, and the probability of storm waves several meters in height exceeds 20% during any given year (Lisitsyn, 1966, p. 98). The strongest and most prolonged storms occur during fall and winter seasons. In late summer and early fall waves generated by Pacific typhoons often penetrate the Aleutian Island arc and reach the southern Bering Sea.

Volcanic Activity

The Bering Sea shelf and margin near St. George basin are bounded on the south by the volcanically active Alaska Peninsula and eastern Aleutian Islands. Coats (1950) lists 25 active volcanoes in the Aleutian Islands and 11 on the Alaska Peninsula and mainland. Volcanism to the north, in the Pribilof Islands, may still be active (Hopkins, oral communication, 1976). Hazards from volcanic activity are associated with eruption of lava and ash and the attendant earthquakes. The distribution of ash is dependent on the magma composition, eruption character, wind speed and direction at the time of eruption, height of eruption, volume of material, and specific properties of the pyroclastic debris. Eruptions from the large andesitic cones on the Alaska Peninsula and Aleutian Islands are mostly the explosive-type and can spread pyroclastic materials over large areas, whereas eruptions from basaltic volcanoes, such as those on the Pribilof and Nunivak Islands, are not as explosive and would have only local effects.

The largest known quantity of volcanic material erupted in historic times in the Alaska area, some 21 km^3 of ash, was erupted by Katmai volcano in 1912, when ash was carried over distances of 2000 km or more. At a distance of 180 km from the volcano, ash was deposited with a density of about 45 g/cm (Lisitsyn, 1966). According to historical data, individual ash deposits in the Bering Sea region extend 200 to 2000 km from the source, averaging about 500 km. Hazards are associated not only with the volume of ash that might be deposited but also with ground motion that often accompanies major eruptions. These forces, including base surges from caldera eruptions, may affect manmade structures and also shake loose pre-existing, unstable, and undercompacted sediment bodies.

Ice

Parts of the southern Bering Sea continental shelf and margin in the vicinity of St. George basin are covered with ice for several months a year (Fig. 17). Ice development reaches its maximum during March and April when unstressed floes reach 1 to 2 m in thickness (Lisitsyn, 1966). Both migratory and stationary ice form; the latter occurs along the shorelines and ranges in width from a few meters to as much as 80 km from the shore. Some ice gouging occurs around the shorelines where the ice is thickest, and man-made structures, pipelines, and ports may be affected by ice-ramming and bottom scouring.

Sedimentology and Geochemistry of Surface Sediment

General Description and Texture of Surface Sediments

The surficial sedimentary cover of the outer continental shelf is generally olive gray, greenish gray, to grayish olive green silt to silty sand. Evidence for extensive burrowing, such as color mottling, discrete burrows, and total homogenization with no internal structures, is common throughout all cores. Some cores have thin interbeds 5 to 15 cm thick of coarser-grained material, but this is not a general feature. Four cores from the outermost part of the continental shelf (Fig. 18, cores G113, G116, G118, and G119) have an upper layer, 50 cm thick, of diatom-bearing greenish gray silt overlying a gray silty clay with very few diatoms. Almost all of the other cores show a uniform lithology. Askren (1972) reported benthonic foraminifera in sediment from this area. We examined 124 surface sediment samples and did not find any benthonic foraminifera. The reasons for this discrepancy remain a mystery.

The gray and greenish hues of the sediment indicate reducing conditions or at least reduced iron oxides in the clay minerals. The water column is

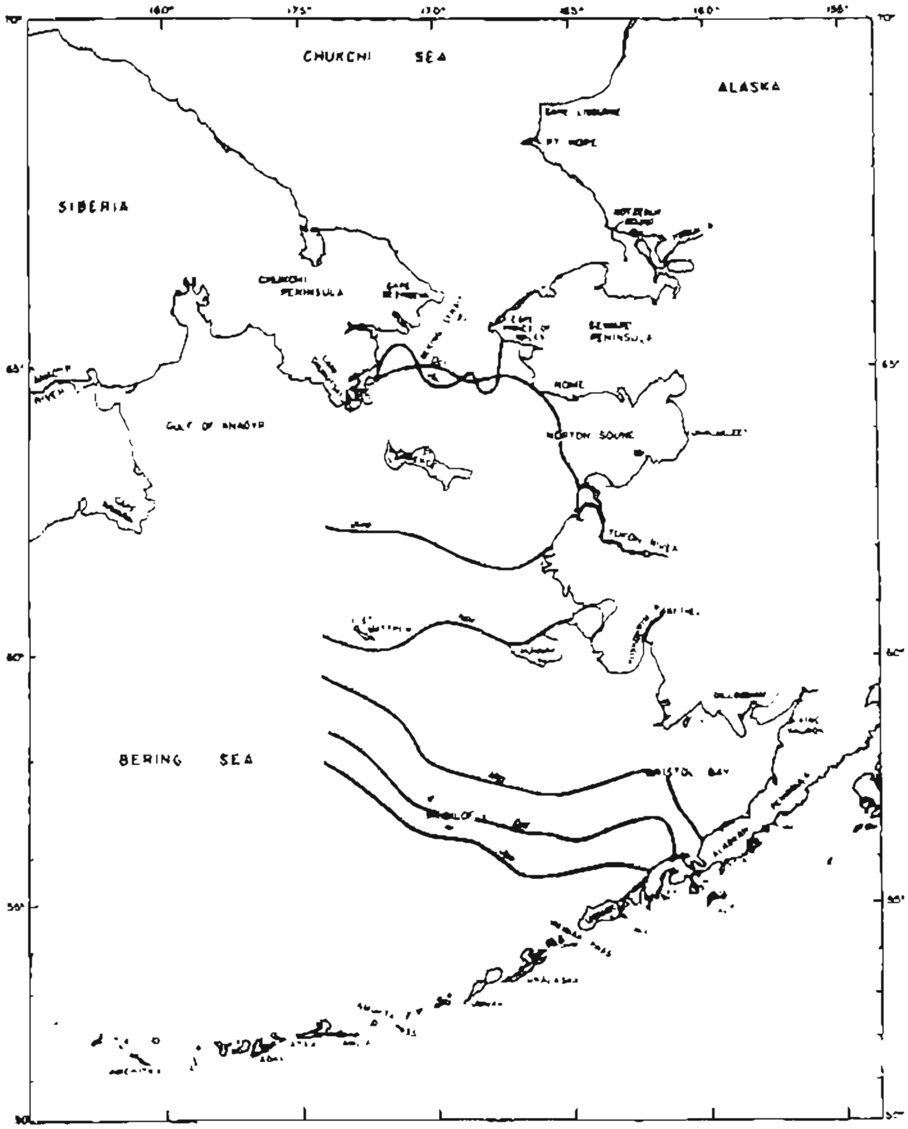


Figure 17. Ice cover of the Bering Sea. From McRoy and Goering (1974).

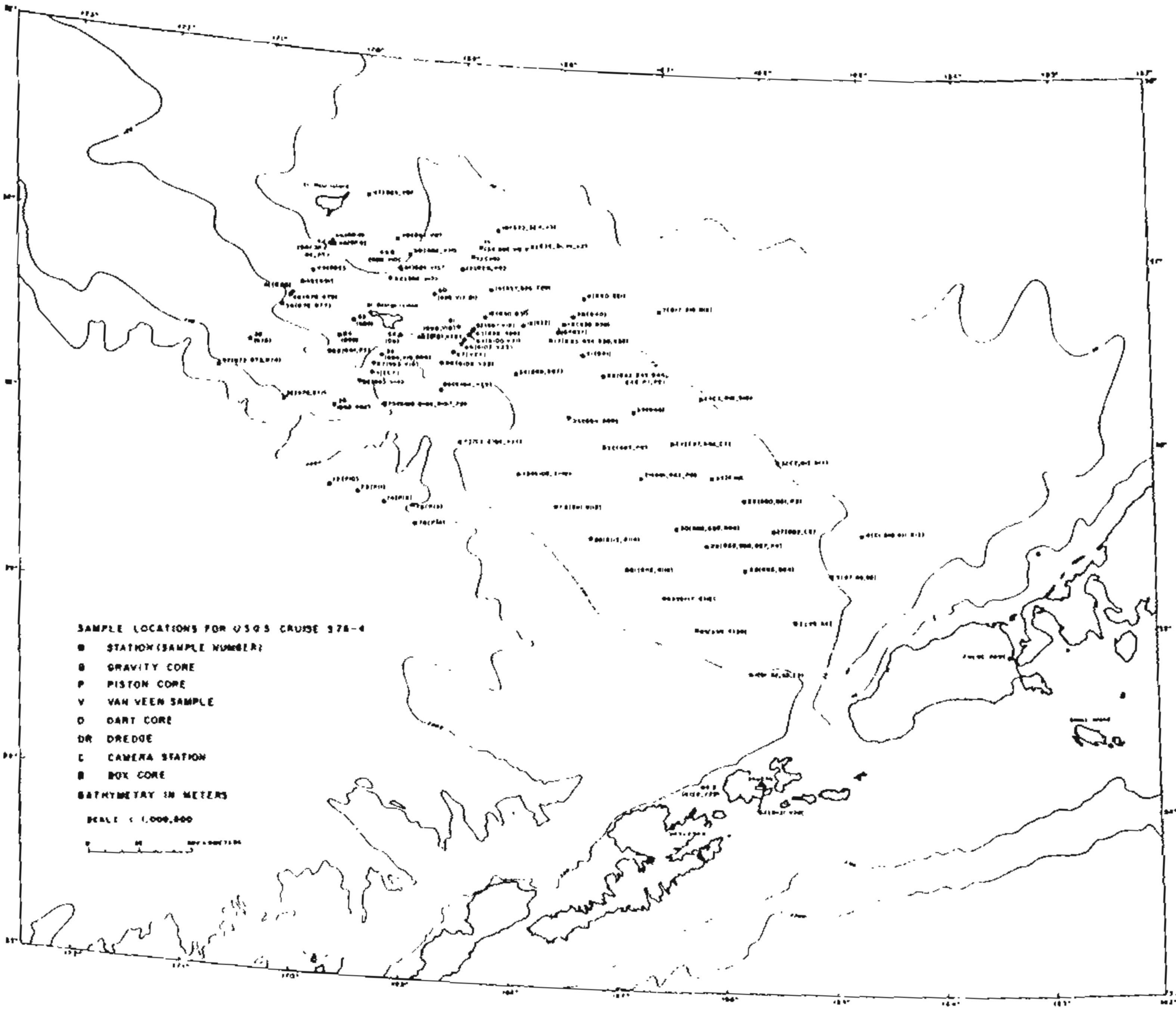


Figure 18. Sample locations for cruise S4-76. From Gardner and others (1979).

certainly not anaerobic at any level; thus the reducing environment is diagenetic. Because the region is one of very high biological productivity (Hattori and Wada, 1974), it seems most likely that large volumes of organic debris from plankton and nekton settle to the sediment surface. Burrowing attests to high epifaunal and infaunal activity on and in the sediments. Aerobic bacteria, in the presence of abundant organic debris, use up all available interstitial oxygen. The sediment becomes reduced because of high biological demand, even though the overlying bottom water is richly oxygenated. The salient features of the distribution of grain sizes is a bull's-eye pattern of finer grain size over St. George basin, and a broad band of rapid size change around the head of Pribilof Canyon and the northwestern margin of Bering Canyon (Fig. 19). The bull's-eye pattern reflects the occurrence of finer grain sizes in the center of the graben that forms St. George basin. The band of rapid size change coincides with areas of high topographic relief, with coarser sediment at shallower depths.

Sediment in the central portion of St. George basin is very poorly sorted (Fig. 20), which reflects the lack of significant winnowing. The northwestern border of the Bering Canyon, the head of Pribilof Canyon and the topographic high of Pribilof ridge all show moderately-sorted sediment. The size-frequency distribution for most sediment in St. George basin region is leptokurtic to very leptokurtic, but in the vicinity of the Pribilof Islands the distributions are mesokurtic. The distributions are fine to strongly fine-skewed throughout the region. Summary statistics of grain-size data (median grain size, mean grain size, sorting, skewness, and kurtosis) are given in Table 4.

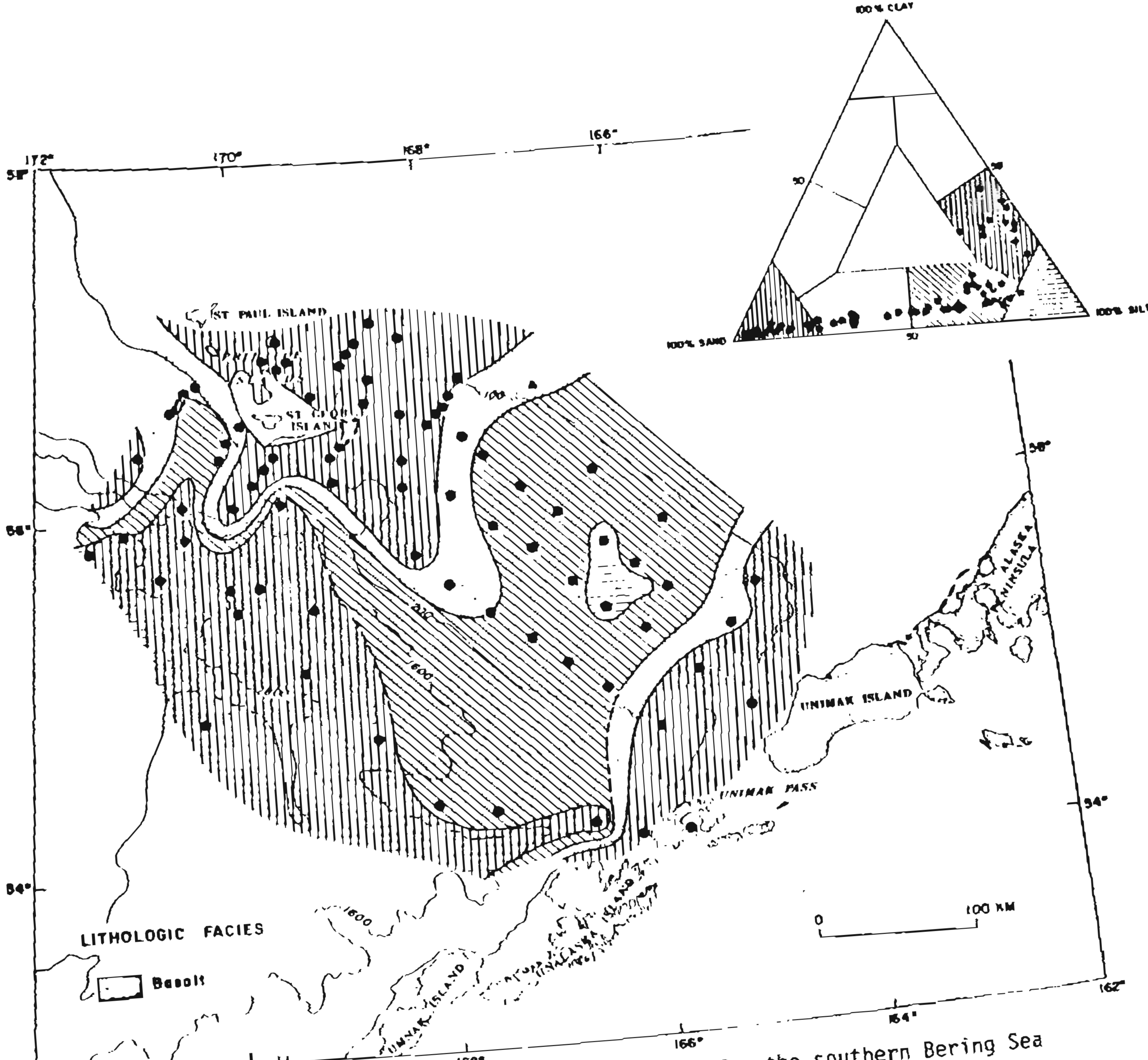


Figure 19. Lithologic facies of surface sediment for the southern Bering Sea continental margin.

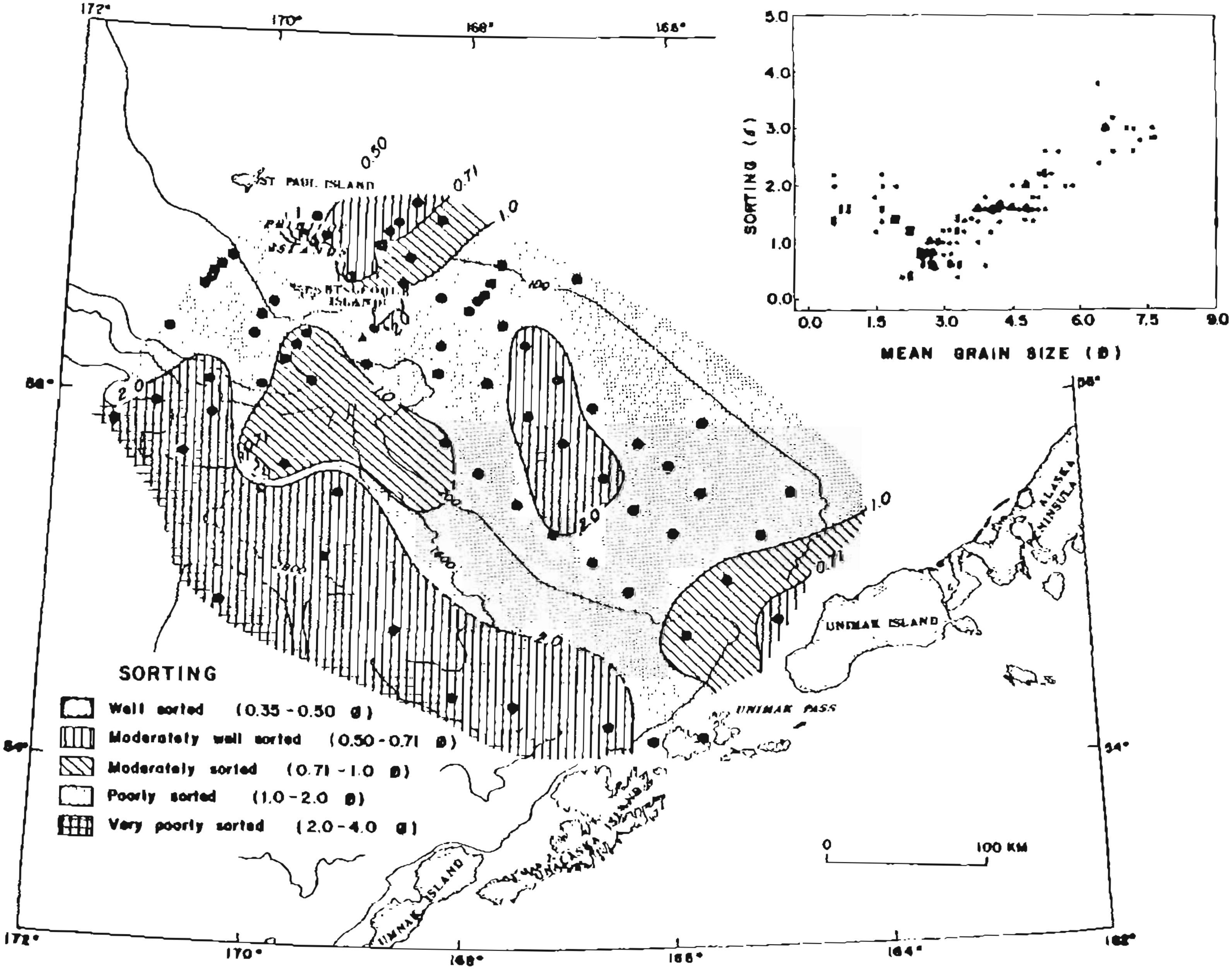


Figure 20. Distribution of sorting values from surface sediment in the southern Bering Sea. Inset is a plot of sorting versus mean grain size.

TABLE 4

GRAPHICAL STATISTICS FROM GRAIN SIZE ANALYSIS

(Folk and Ward, 1957)

SAMPLE	MAP INDEX NUMBER	MEDIAN (Md) (ϕ)	MEAN (M_z) (ϕ)	SORTING (σ)	SKEWNESS (Sk_i)	KURTOSIS (K_g)
76-G4	6	3.54	3.81	1.05	0.63	2.71
76-G5	7	3.72	3.88	0.69	0.55	3.02
76-G8	8	3.66	3.98	1.20	0.46	1.27
76-G10	9	3.20	3.52	1.32	0.43	1.66
76-G19	34	3.45	3.85	1.52	0.46	1.16
76-G20	47	3.01	3.33	1.32	0.49	1.44
76-G28	56	3.18	3.53	1.36	0.55	2.06
76-G30	54	3.18	3.29	1.05	0.38	2.38
76-G32	48	3.06	3.29	1.19	0.49	2.12
76-G33	43	3.14	3.71	1.68	0.59	1.54
76-G36	43	3.21	3.83	1.70	0.62	1.20
76-G37	44	3.04	3.32	1.30	0.46	1.46
76-G38	45	3.28	3.70	1.47	0.52	1.42
76-G39	45	3.29	3.75	1.52	0.53	1.35
76-G40	46	3.15	3.39	1.26	0.40	1.25
76-G43	33	4.84	4.80	2.06	0.13	1.08
76-G48	25	5.63	5.80	1.97	0.25	1.71
76-G51	17	4.92	4.81	1.69	0.07	1.37
76-G52	10	4.91	4.89	1.45	0.10	1.61
76-G54	11	4.60	4.52	1.66	0.07	1.30
76-G56	16	4.85	4.89	1.60	0.19	1.56
76-G57	16	5.12	5.26	1.57	0.28	1.72
76-G59	20	5.35	5.32	1.90	0.16	1.48
76-G60	20	5.26	5.11	2.17	0.06	1.16
76-G62	24	5.34	5.25	2.27	0.09	1.15
76-G67	40	2.00	1.93	1.45	0.19	5.24
76-G69	59	2.90	3.05	1.12	0.50	2.45
76-G71	73	6.52	6.76	3.27	0.17	0.93
76-G75	77	2.99	3.37	1.28	0.55	1.68
76-G77	78	3.79	4.15	1.60	0.43	1.16
76-G79	79	3.75	4.16	1.61	0.46	1.15
76-G80	80	4.60	4.64	1.67	0.16	1.05
76-G89	70	3.69	4.19	1.36	0.68	1.63
76-G90	71	4.94	5.01	1.70	0.20	1.44
76-G94	62	0.75	0.65	1.53	0.02	0.63
76-G103	49	1.72	1.77	2.06	0.19	2.27
76-G105	58	6.16	6.60	2.97	0.30	0.86
76-G107	58	5.36	6.66	3.08	0.60	0.97
76-G109	31	2.64	2.87	0.94	0.59	2.90
76-G111	29	3.02	3.71	1.59	0.69	1.06
76-G113	23	4.04	4.50	1.57	0.49	1.21
76-G116	21	4.68	4.80	2.04	0.12	1.34
76-G118	15	4.73	4.57	1.96	0.03	1.04

TABLE 4 cont.

SAMPLE	MAP INDEX NUMBER	MEDIAN (Md) (ϕ)	MEAN (Mz) (ϕ)	SORTING (σ)	SKEWNESS(S_{k_i})	KURTOSIS(K_g)
76-G119	12	4.48	4.57	1.50	0.22	1.27
76-G121	4	4.64	4.75	1.51	0.27	1.13
77-G14	5	6.56	6.77	2.61	0.21	1.14
77-G16	13	5.11	5.18	2.65	0.11	1.43
77-G19	14	5.34	5.48	2.69	0.17	1.22
77-G20	22	7.40	7.58	2.76	0.17	1.09
77-G22	30	7.08	7.30	2.74	0.19	1.13
77-G23	37	7.12	7.25	2.56	0.19	1.38
77-G24	38	7.36	7.61	2.84	0.19	0.85
77-G25	38	7.12	7.24	2.90	0.12	0.97
77-G26	75	6.23	6.51	2.35	0.30	1.19
77-G29	74	6.90	7.01	2.91	0.14	0.99
76-V2	55	2.58	2.59	0.76	0.26	2.41
76-V3	67	2.75	2.75	0.68	0.19	1.94
76-V4	66	2.59	2.66	0.68	0.36	1.79
76-V5	65	2.65	2.71	0.79	0.38	2.10
76-V6	64	2.80	2.99	0.72	0.48	3.34
76-V7	59	3.19	3.19	1.11	0.31	2.41
76-V9	84	2.14	2.13	0.43	0.14	2.22
76-V10	83	2.23	2.22	0.44	0.09	4.58
76-V11	68	2.80	2.80	0.66	0.11	1.66
76-V12	69	2.17	2.20	1.18	-0.03	3.13
76-V14	60	3.00	2.94	0.87	0.22	2.86
76-V15	61	1.42	0.93	1.56	-0.32	0.51
76-V16	62	0.45	0.65	2.10	0.36	1.07
76-V17	63	2.64	2.73	0.64	0.50	2.11
76-V18	57	2.84	2.81	0.64	0.06	1.33
76-V19	53	3.04	3.03	0.91	0.21	2.48
76-V21	51	2.93	2.90	0.69	0.21	2.42
76-V22	86	2.85	2.86	0.97	0.29	2.63
76-V23	50	2.66	2.67	0.93	0.33	2.96
76-V24	87	1.87	1.61	1.57	-0.12	1.86
76-V25	49	1.68	1.43	1.78	-0.01	2.36
76-V26	88	1.96	1.60	1.33	-0.34	2.11
76-V28	4	4.66	4.83	1.48	0.29	1.08
76-V29	91	1.86	1.93	1.33	0.12	3.64
77-V4	89	1.79	1.49	1.23	-0.32	1.94
77-V6	2	3.22	3.25	0.68	0.49	5.47
76-P3	26	5.02	5.06	1.75	0.17	1.56
76-P6	32	5.36	5.36	2.21	0.17	1.14
76-P7	55	5.13	5.14	1.69	0.15	1.16
76-P8	70	6.46	6.47	3.79	0.05	1.32
76-P11	73	7.73	7.72	3.08	0.06	0.89

Summary of Sediment Distribution

Mineralogical and inorganic geochemical data show three major sources of sediments and one sediment sink. The Alaska mainland source forms a mineralogical and chemical background to most samples from the shelf. The dominant source, is the Pribilof Islands. St. George basin has served as a sink for fine-grained sediment.

Sediment distributions do not appear to reflect present day deposition. Rather, we believe that the distributions are the result of accumulation during periods of lower sea level in the Pleistocene, modified by present-day processes. The concentration of Aleutian sediment, between the 100 m and 200 m isobaths, which exhibit a strong gradient, or "plume", that decreases away from Unimak Pass into St. George basin is evidence for the conclusion. Lack of present-day currents sufficient to move even clay-size material and the presence of the Bering submarine canyon between the Aleutian Islands and the outer continental shelf and slope indicate that Holocene sediment dynamics cannot be used to explain the observed distribution of surface sediments derived from the Aleutian Islands. We believe it is logical to suggest that this distribution pattern is relict and is the result of sediment dynamics during lower sea levels.

Hydrocarbon Gases in Near Surface Sediment

Gardner and others (1979) and Kvenvolden and Redden (1979) have shown that hydrocarbon gases are present in surface and near-surface sediment of the southern Bering Sea shelf and slope. Concentrations of hydrocarbons are about the same in shelf and slope sediment in the interval from 0 to about 60 cm. On the shelf, acoustic anomalies ("bright spots" or "wipe-out zones") are thought to be due to gas concentrations (Fig.21) and are generally 200 to 300 m deep. However, these acoustical anomalies do not produce hydrocarbon gas

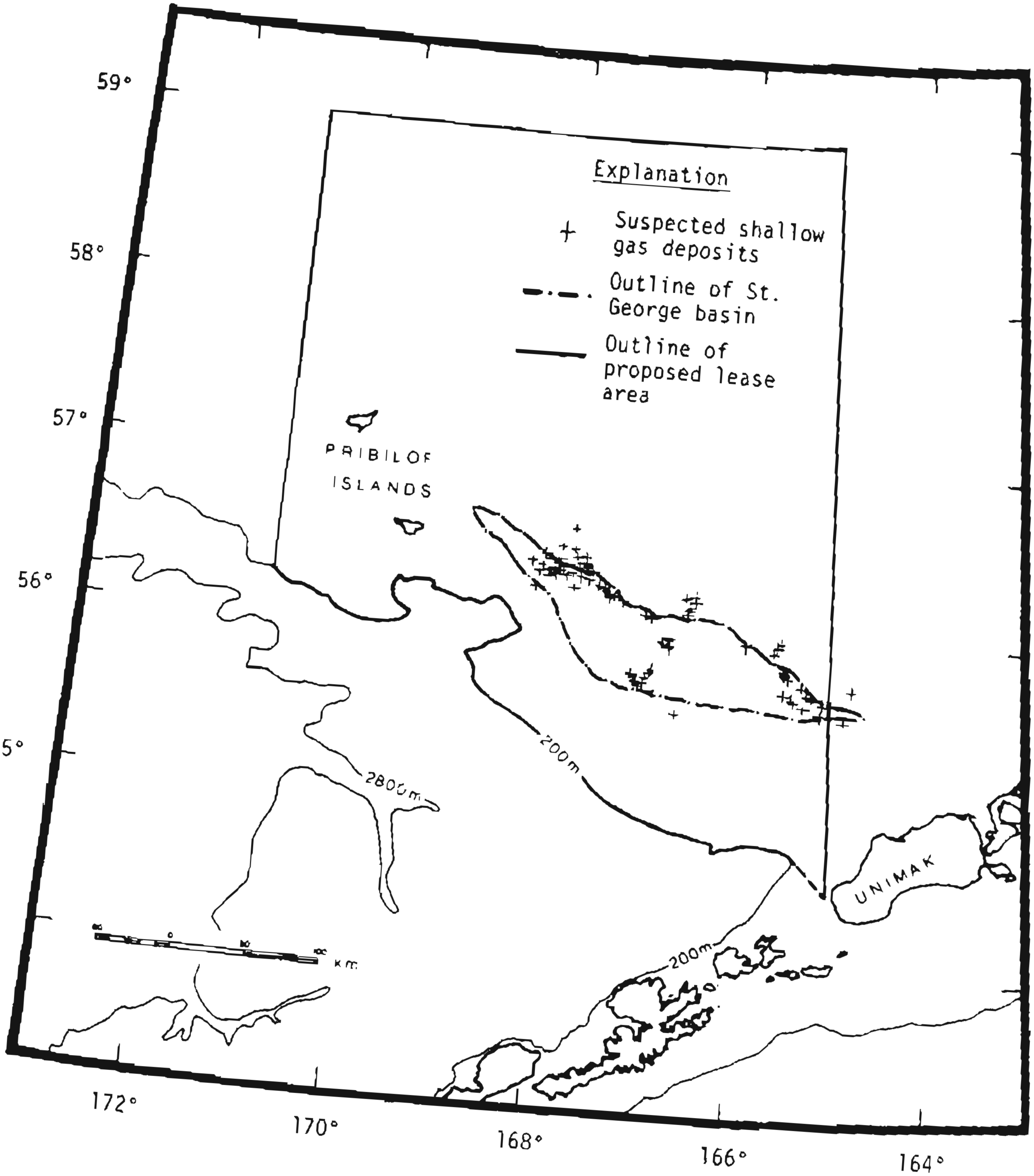


Figure 21. Distribution of acoustic anomalies ("bright spots" or "wipe-out zones") detected in seismic reflection data and thought to be due to shallow accumulations of gas.

anomalies in the near-surface sediment above them, except for one station (9-12, S-6-77- BS; Kvenvolden and Redden, 1979). The concentrations and distributions of hydrocarbon gases in the sediment examined from cores taken in the areas shown on Fig. 22 do not indicate that gas seeps are active in the areas sampled or that the gas in the sediment constitutes a geologic hazard because of high concentrations. We should emphasize that these samples are shallow (few meters) cores and may not be representative of gas-associated hazards in the sedimentary section at greater depths. Unsubstantiated rumor indicates that when the COST well was drilled south of St. George basin in 1977, engineering problems were encountered with shallow pockets of gas. To evaluate the hazards of pockets of high-pressured gas, a program of shallow-drilling is needed before leasing in the St. George basin area.

RANKING OF AREAS CONSIDERED PROSPECTIVE FOR HYDROCARBON DEPOSITS

Figure 23 outlines the area being considered for lease in the southern Bering Sea. Within this area we have ranked three subregions as to their probability of containing hydrocarbon deposits. The region with the greatest chance for hydrocarbon accumulations is the zone underlain by St. George basin (most prospective area, Fig. 23). As outlined in previous sections of this report, St. George basin contains thick (10 km) sedimentary sections that are broken by high-angle normal faults flanking the basin. Offset along these faults increases with depth, indicating that they are growth structures and possible traps for hydrocarbons. Regional geologic studies indicate that suitable source and reservoir rocks are probably present within St. George basin.

The area of secondary ranking is that shelf area in water depths less than 200 m that surrounds St. George basin. Although this area is underlain by

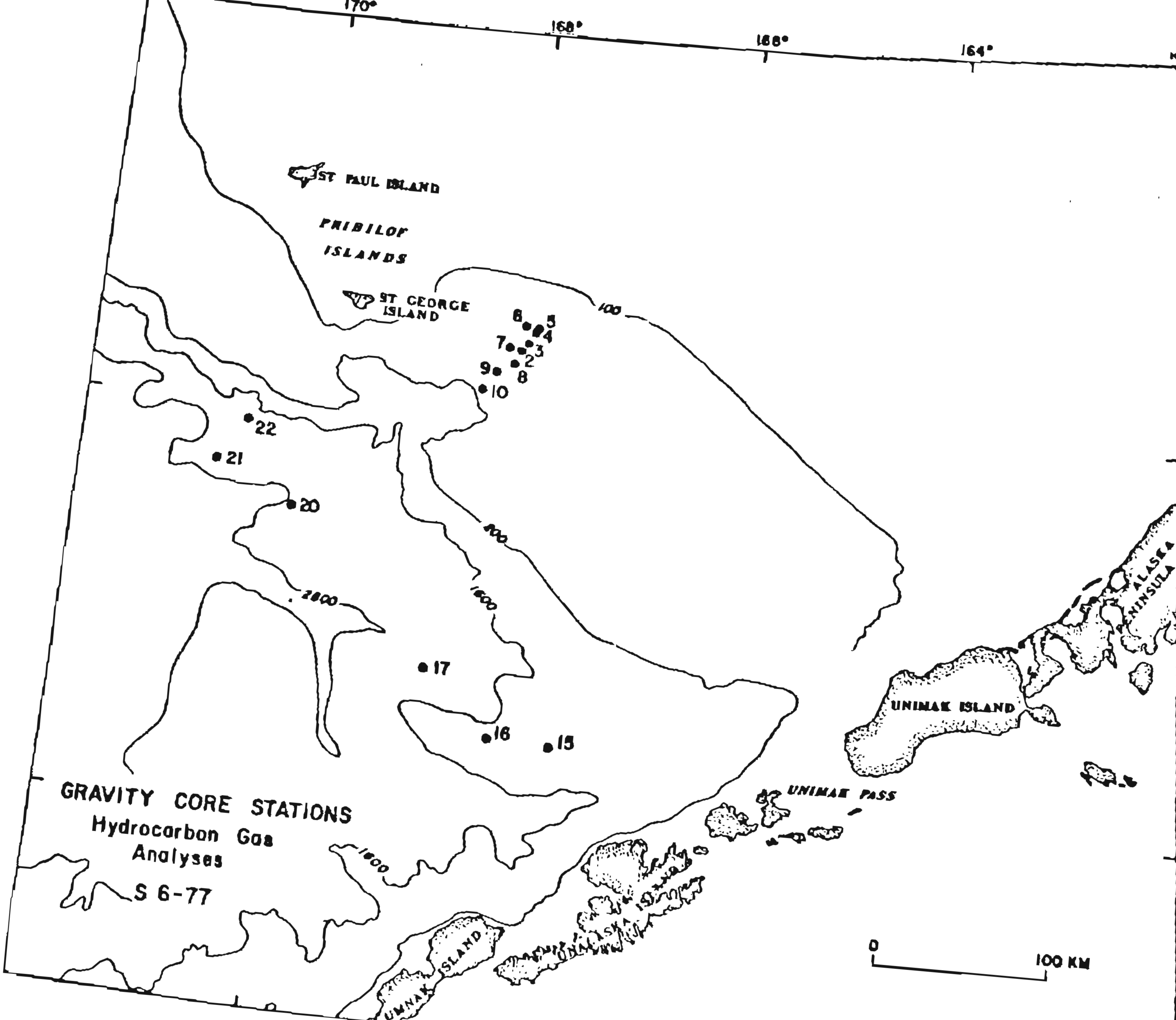


Figure 22. Locations of samples that were collected for hydrocarbon gas analysis.

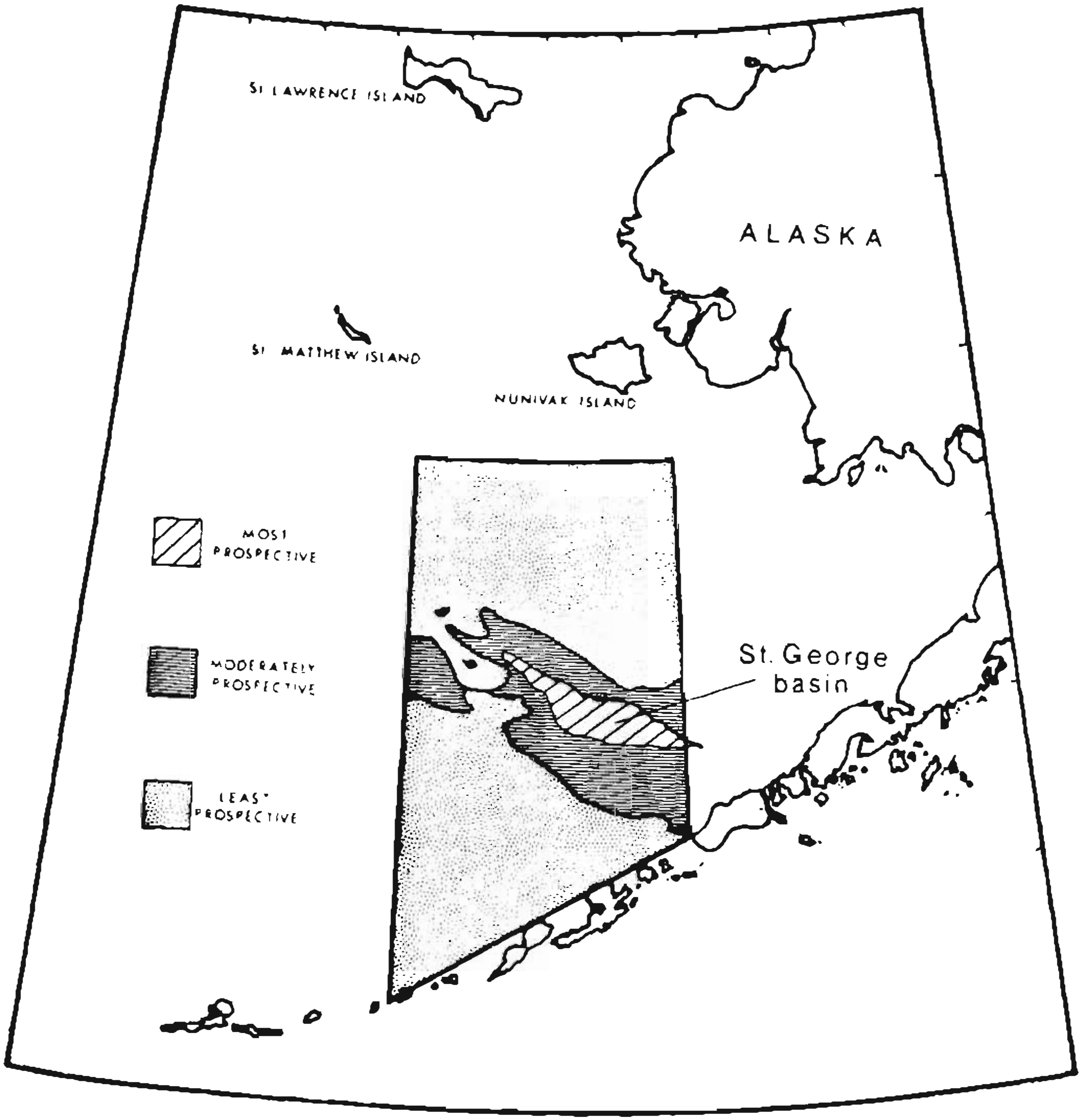


Figure 23. Ranking of areas in proposed lease sale area as to potential for containing hydrocarbon deposits. Note that the southern, least prospective area is in water depths exceeding 200 m, beyond present drilling and development technology. When deepwater drilling becomes feasible, then this area should be evaluated separately from that area to the north.

sedimentary sections 1-3 km thick, regional geologic studies indicate that these sections probably do not contain structures capable of trapping hydrocarbons. Subtle stratigraphic traps, however, may be present here and hence, it is only in relation to the known large structural features in St. George basin proper, that the surrounding areas underlain by 1-3 km of section are ranked second.

The areas considered to have the least potential are also outlined in Figure 23. The part of these areas north of St. George basin is underlain by a sedimentary section less than one kilometer thick, probably too thin for the generation of hydrocarbons, at least in the section overlying acoustic basement. Thus, any exploration targets would have to be structures within the basement complex of the shelf. Size, extent, and even existence of such features is unknown and hence the low ranking of this area.

RESOURCE APPRAISAL

The St. George basin OCS Lease Sale area assessed for undiscovered recoverable oil and gas resources was limited to that area of the shelf considered prospective for these commodities. The assessed area falls within the central portion of the total proposed sale area, and covers more than 49,000 km^2, and is restricted to that portion that lies in water depths of less than 200 m, which have at least 1 km of sediment and includes the two areas that are shown on Fig. 23 that are ranked as "most prospective" and "moderately prospective."

The "least prospective" area shown on Figure 23 is divided into two parts. The southern part is in water depths greater than 200 meters, and in places, exceeds 2000 m. The northern portion of the least favorable area contains a very thin sedimentary section of Cenozoic rock, which decreases to the north. Thus, the potential of this section in terms of undiscovered oil and gas is considered to be negligible.

Estimates of hydrocarbons for the proposed sale area of St. George basin are based on analytical and subjective probability techniques described in U.S. Geological Survey Circular 725 (1975).

Geologic input used in making the resource estimates include structural contour and sediment thickness maps made from seismic data that are described and illustrated in this report. Stratigraphic information was extrapolated from dredge samples obtained from the Bering shelf and from wells and surface samples on the Alaskan Peninsula to the east.

Geologic analogs for the St. George basin are largely lacking, other than the currently non-productive basins along the margin of the Bering shelf such as the southern portion of the Navarin basin. Only speculative analogies may be drawn with other basins of the Pacific margin of the U.S. However, resource potential is considered on a per unit sediment volume basis to be somewhat lower for oil than U.S. basins as a whole and about average for gas, when considering estimated conditional mean values.

The conditional estimates of undiscovered recoverable oil and gas for the St. George basin are:

	Probability		Statistical
	95%	5%	Mean
Oil (billions of bbls)	0.8	6.4	2.7
Gas (trillions of cu. ft.)	4.5	18.6	10.3

The curves show the probability distribution of conditional and unconditional estimates of undiscovered recoverable oil and gas (Figure 24). The conditional estimates show the least amounts which are expected, based on the assumption (condition) that commercial oil or gas actually exist.

A marginal probability is assigned to the probability of occurrence of oil and gas because St. George basin is a frontier province. In this instance, the marginal probability of finding commercial oil is estimated to be approximately 60% and the marginal probability of finding commercial gas is approximately 84%. The dashed lines on the probability distributions are the unconditional estimates and reflect the application of these marginal probabilities.

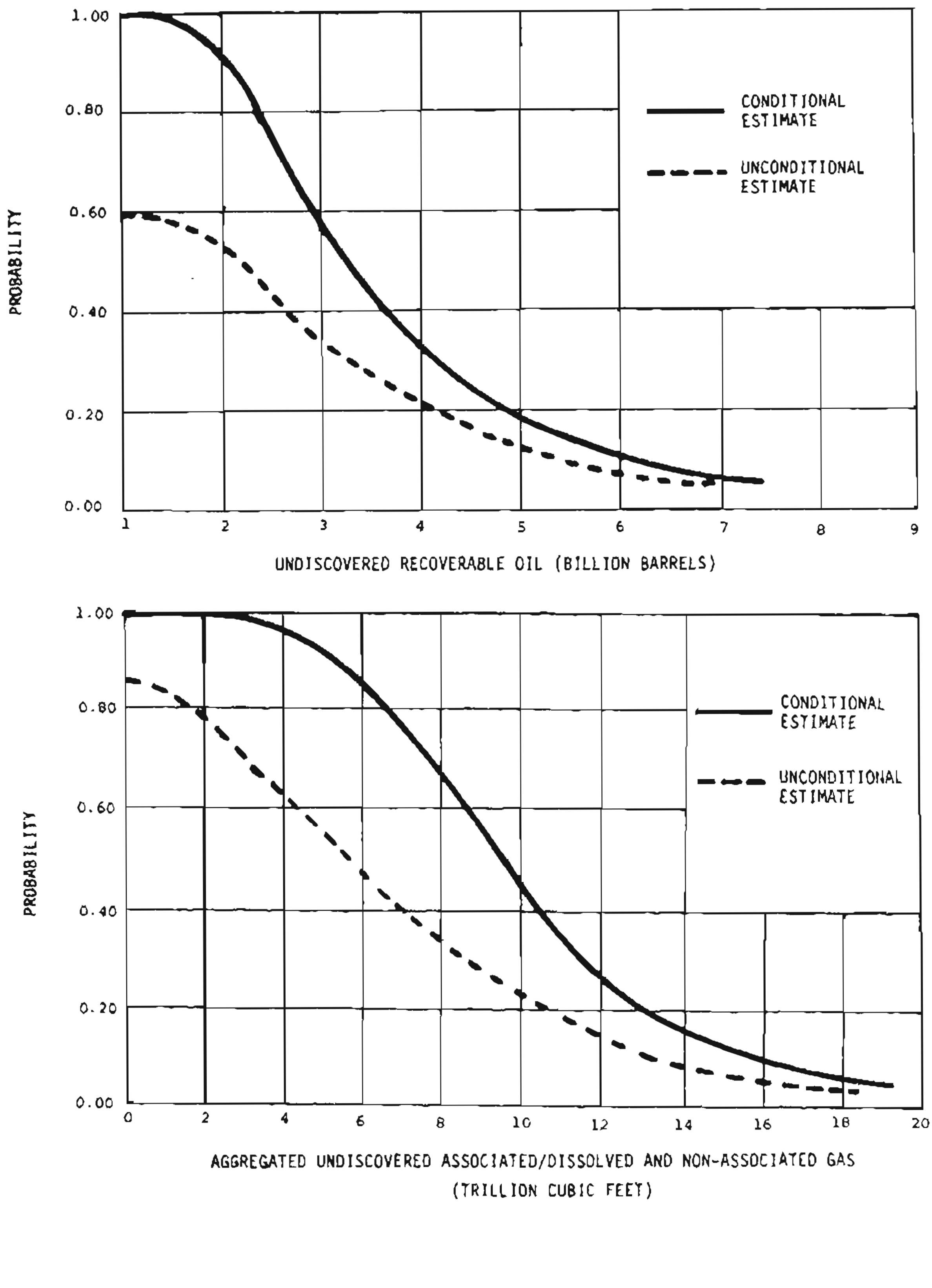


Figure 24. Probability distribution for undiscovered recoverable oil and gas in St. George basin, Alaska.

TECHNOLOGY AND MANPOWER

Location of Proposed Lease Sale

Figure 23 shows the locations of the proposed sale area considered in this section on technology and manpower. The following resource estimates are for waters less than 200 m deep and sediments at least 1000 m thick. The surface area within these restraints is 12.1 million acres or 4.9 million hectares.

Estimated Development Timetable

Weather data is incomplete but is somewhat similar to that of the North Sea. The area is much more remote than the oil fields of the North Sea, with Seattle some 3,000 miles distant, being the closest industrial and supply base. Because of the severe weather and remotness, significant reserves and advanced production technology are required for successful commercialization.

Based on experience gained in upper Cook Inlet, the Gulf of Alaska and first lower Cook Inlet lease sale, it is estimated that exploratory drilling would commence one year after leases are issued. Assuming exploratory success, production platform installation would begin during the fifth year after leases are issued and would be completed in the fifteenth year.

Peak oil production, as limited by market facilities, would occur in the tenth year after the lease sale.Individual fields would have a twenty-five year life and all platforms will have been removed by the fortieth year after production begins.

A comparison with the Magnus discovery in the North Sea may be useful for estimating what can possibly be encountered in the Bering Sea. Magnus is the furthest north discovery, about 61.8° north latitude, in nearly 600 feet of water and is estimated to contain over 400 million barrels of oil. It will have one platform with perhaps 36 wells and maybe a half dozen wells completed on the sea floor Six to ten of the wells may be water and gas injectors. Production will peak at 125,000 barrels per day. The Magnus field is considered to be just barely economically viable.

We estimate that a typical field in the Bering Sea might be eight miles by three miles in size, thus requiring some undersea completions. Wells would be drilled at about ten per year per platform, so would take about four years per platform.

For the mean case, we would thus have perhaps five fields, averaging a little larger than Magnus. Only two fields would exist in the 95% case and counting a larger average size of field for the 5% case, that case would have about ten fields. Our field census (excluding dry gas fields) would thus be:

	95% Probability	Stat. Mean	5% Probability
Oil fields	2	5	10
Wells (incl. service)	80	250	450
Peak production (10^3 bbls/day)	150	375	750
Peak gas (10^6 Cu.Ft./day)	165	415	825

The dry gas cases would have these resources:

	95% Probability	Stat. Mean	5% Probability
Gas (10^{12} cu. ft.)	2.6	6.3	16.1
Fields	1.0	2.0	5.0

For dry gas we estimate 20 years constant-production life for each field, so production "peak" would be:

	95% Probability	Stat. Mean	5% Probability
Gas (10^6 Cu.Ft./day)	350	850	2050

We estimate that an economic gas well would have to produce, about 30 million CFD and the fields would require no injection wells, so the estimated census of gas wells and platforms is:

	95% Probability	Stat. Mean	5% Probability
Gas wells	12	28	68
Platforms	1	2	5

The center of the basin is about 150-175 miles from Dutch Harbor and Cold Bay where the oil and gas may be piped ashore and then into ships. It is assumed that LNG plants are the only way to ship the gas out to market. The gas from any oil field would have to be moved ashore by pipeline after primary separation on the platforms.

Estimated Facilities

Exploration bases would probably be at Cold Bay, 175 miles (281 kilometers) from the center of the basin, and Dutch Harbor, 150 miles (241 kilometers) from the basin. Docks and other installations are now being built there to support a rapidly expanding fishing industry.

Recent experience drilling in lower Cook Inlet indicates that heavy duty semi-submersibles may be the only equipment capable of sustained winter operations in climates this severe. A drill ship was unable to operate in the strong (80 knot) winds during winter and spring in lower Cook Inlet while a semi-submersible continued operations. Larger drill ships may be more successful. The weather of the Bering Sea is expected to be worse than that in Cook Inlet.

Production facilities would compare with those of the North Sea if equivalent reserves are discovered. Tentatively, one scenario for this basin would be subsea completions with gathering lines to a bottom-anchored floating production platform (with associated storage) and with tanker pickup for oil. It is doubtful if a floating LNG plant could operate in the strong winds and high seas of the basin, so gas would have to be piped ashore. Another scenario would be subsea completions plus platforms with the oil piped ashore to a facility on the Alaska Peninsula, Unimak or Unalaska Island. The land nearest to the center of the basin, Cape Mordivinol on Unimak Island is 120 miles (193 kilometers) distant.

Manpower

Approximately 80 percent of the exploration manpower would probably come from outside Alaska. For production and construction manpower, approximately 80 percent would come from personnel already in Alaska.

Drilling Equipment Availability

We expect that there will be enough big semi-submersibles available after the sale occurs. It depends partly on what success Norway has in its waters north of 62° north latitude. Drilling supplies, pipe, mud, etc., should be in adequate supply. Our lease sales have been extended somewhat, relative to the earlier schedule.

Weather and Water Conditions

The following are several observations of the weather taken from Volume 9 of the U.S. Coast Pilot (1979) published by the National Oceanic and Atmospheric Administration, page 297. "The weather over the Bering Sea is generally bad and very changeable. Good weather is the exception and does not last long when it does occur. Wind shifts are both frequent and rapid. The summer season has much fog and considerable rain. In early winter the gales increase, the fogs lessen, and snow is likely any time after mid-September. Winter is the time of almost continuous storminess. Heavy winds in any direction are usually accompanied by precipitation. Poor visibility can be a problem all year-around. At St. Paul Island, fog and haze occur 20 to 28 days per month (May through August). At St. Paul the minimum recorded temperature has been $-26^{\circ}F$ with an extreme high of $64^{\circ}F$."

Meterological tables in U.S. Coast Pilot 9 for stations in Bering Sea are incomplete, but from the sparse data that are available, it is obvious that severe conditions of wind, temperature, sea state and visibility prevail throughout the year. Numerous delays can be anticipated because of bad weather.

Access

Unimak Pass between Ugamak and Unimak Islands is the gateway to the Bering Sea and the best sea route to St. George Basin from Cold Bay and the south where all equipment, personnel and supplies will come from.

Reeve Aleutian Airways operates scheduled service with Lockheed Electras, DC-6's, and C-46's and YS-11's between Anchorage, Cold Bay, Dutch Harbor and points west as well as a direct Seattle-Cold Bay route.

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