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PRELIMINARY REPORT ON THE REGIONAL GEOLOGY, OIL AND GAS POTENTIAL AND ENVIRONMENTAL HAZARDS OF THE BERING SEA SHELF SOUTH OF ST. LAWRENCE ISLAND, ALASKA

BY

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in the area of the present outer shelf occurred contemporaneously with magmatism along the inner shelf. Plate convergence apparently ceased by the end of the Mesozoic or the beginning of the Cenozoic. Subsequently, the foldbelt underlying the outer shelf was eroded extensively and rifted extensionally to form large deep basins. On the average, the shelf has subsided more than 1.5 km. Subsidence and sediment burial of the eroded orogen formed the modern Bering Sea shelf.

Nine wells drilled along the northern coast of the Alaska Peninsula as well as several onshore Soviet wells in northeastern Siberia have direct significance to the submerged basins of the Bering Sea shelf. Although all of the wells on the Alaska Peninsula were abandoned as dry holes, significant shows of oil and gas were found. In addition, the USSR drilling resulted in the discovery of oil and gas in Miocene sandstone.

Regional geologic and geophysical mapping suggests that there are suitable source beds, reservoir rocks, and traps within the basins beneath the Bering Sea shelf. However, it is not known if hydrocarbons are present or if the possible reservoirs are of commercial size. A resource appraisal of the shelf out to 200 meters water depth indicates that between 0 and 6.2 billion bbl and 0 and 15.5 trillion cu. ft. of oil and gas respectively may underlie the Bering Sea shelf.

The major environmental hazards for petroleum exploration and development of the Bering Sea shelf include faulting and associated earthquakes, sea floor instability (slumping, erosion, etc.), volcanic activity in the southern shelf area, and seasonal ice flows (although the

open southern shelf is virtually ice-free). There is significant fishing activity in the southern shelf region between the Alaska Peninsula and the Pribilof Islands and any development of the outer continental shelf should be compatible with this industry.

INTRODUCTION

Location of OCS Areas

The virtually featureless Bering Sea shelf south of St. Lawrence Island is structurally underlain by at least 11 basins (Figs. 1, 3). Encompassing a combined area over 546,000 km^2, larger than the size of the state of California, most of the basins are either elongate structural sags, grabens, or half (asymmetric) grabens located beneath the outer shelf. The regional trend of these basins is northwest, parallel to the continental margin which extends from the Alaska Peninsula to eastern Siberia. Two of the basins, St. George and Navarin, contain more than 10 km of Upper Cretaceous(?) and Cenozoic sedimentary strata.

In recognition of the geologic importance and resource potential of the Bering Sea, the U. S. Geological Survey has conducted four expeditions to this area (since 1965) to undertake reconnaissance geologic and geophysical mapping. This report summarizes the data collected over the eastern area of the Bering shelf (Fig. 2) and outlines basins of interest to petroleum exploration.

Available Data, Public and Proprietary

Data presented in this report include seismic reflection profiles using 120- and 160-kj sparker-sound sources, although some 100 joule and 38 kj data from a 1965 cruise are included. The University of Washington (M. Holmes, written commun., 1974) kindly provided other reflection data utilizing 100 joule and 20 in^3 air-gun sound sources.

There has been a great deal of exploration activity within the eastern Bering Sea during recent years. However, the bulk of these data are proprietary and not publicly available. Only two sets of single channel seismic reflection

data have been published by Scholl and Hopkins (1968) and Scholl and Marlow (1970b). Multichannel seismic reflection records from the Bering shelf are not yet available to the public. NOAA has published a series of six bathymetric, magnetic, and gravimetric charts of a small area west of the southern Alaska Peninsula; these charts are available from the National Ocean Survey, Distribution Division, C4411, Riverdale, Maryland 20840 (Geophysics maps: 1711N-17G, 1711N-17M, 1711N-17B, 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, 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), NOAA (National Data Center, Marine Geology and Geophysics, Code D621, Environmental Data Service, Washington, D. C. 20235), and the Lamont-Doherty Geological Observatory, Columbia University, Palisades, New York.

FRAMEWORK GEOLOGY

Regional Geologic Setting of the 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) and Brockway (1975), of western Alaska in Hoare (1961) and Patton (1973), and of eastern Siberia in Churkin (1970) and more recently by Scholl and others (1975). The island geology of the shelf is presented in later sections.

Complex geologic structures that include rocks as old as Precambrian are

exposed in coastal mountains that flank the Bering Sea shelf. Most of the significant structures that flank the shelf include rocks of Mesozoic and Tertiary age. For example, the oldest exposed rocks in the southern Alaska Peninsula 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). There is geophysical evidence (see below) that these anticlinally deformed rocks exposed here extend offshore northwestwardly along the Bering Sea margin.

Cretaceous and older Mesozoic geosynclinal rocks of southwest Alaska trend southwestward toward the Bering Sea shelf (Fig. 3; Payne, 1955; Hoare, 1961; Gates and Gryc, 1963; Patton, 1973). As noted by Scholl and others (1975), these interior Alaska geosynclinal trends did not form along a Mesozoic continental margin. As important structural features, they either disappear southwestwardly beneath the Bering shelf or they turn northwestward 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 southwestwardly the two major strike slip faults of western Alaska, the Denali and Kaltag faults, must either vanish or turn northwestwardly to parallel the Bering margin.

The Mesozoic rocks of eastern Siberia are divisible into two northwest-trending belts, the outer or coastal Kamchatka-Koryak eugeosynclinal complex and the inner Okhotsk-Chukchi volcanic and plutonic zone (King, 1969; Churkin, 1970; Scholl and others, 1975). The Koryak Range (Fig. 2) comprises mostly folded Jurassic to Upper Cretaceous volcanic and terrigenous rocks probably overlying oceanic crust (Bogdanov, 1970). Although principally deformed in Mesozoic and early Tertiary time, the range was affected by additional uplift

and folding during middle Miocene through early Pliocene time. Burk (1965) first noted the similarity of these folded Mesozoic rocks to those of southern Alaska and the Kodiak-Shumagin shelf. He suggested that these fold belts were connected via the Bering shelf, a supposition later supported by Scholl and others (1966; 1968; 1975), Hopkins and others (1969), Hopkins and Scholl (1970), and Marlow and others (1976). Thus, the northwest-trending Kamchatka-Koryak fold belt turns southeastward at Cape Navarin (Fig. 3). and continues beneath the outer Bering shelf and its margin toward the Alaska Peninsula. Also, the inner Siberian plutonic and volcanic terrain of late Mesozoic rocks turns southeastward near Chukotsk and continues beneath the Bering shelf to St. Matthew Island and perhaps to St. Lawrence Island (see below) (Patton and Csejtey, 1971; Scholl and others, 1975; Patton and others, 1976).

The Alaska Peninsula and Bristol Bay Basin

Bristol Bay basin lies north of the Alaska Peninsula and south of a line between Cape Newenham and the Pribilof Islands. From Kvichak Bay, the basin extends southwestward along the northern side of the Alaska Peninsula toward the edge of the continental shelf. The area of the basin is approximately 246,000 sq km (Fig. 4; Hatten, 1971). The basement morphology of the basin is asymmetrical in cross section. The northern flank of the basin is defined by a basement surface that dips gently southeast, whereas to the south it is more steeply inclined and crops out in the northern foothills of the Alaska Peninsula (Burk, 1965; Brockway and others, 1975). Approximately 80% of the basin lies offshore in water depths generally less than 60 m.

Stratigraphy of the Bristol Bay Basin

The Bristol Bay basin is filled with relatively flat-lying nonmarine and

shallow marine sedimentary rocks of Eocene to Holocene age (Hatten, 1971; Brockway and others, 1975). In the southwestern part of the basin, the Cenozoic sequence may be underlain by a folded sequence of Cretaceous and Jurassic sedimentary rocks. To the northeast, between Port Heiden and Becharof Lake, middle and and late Tertiary sedimentary rocks (Milky River and Bear Lake Formation; Figs. 4, 5) overlie Oligocene volcanic and volcaniclastic rocks as well as Jurassic granitic rocks (Hatten, 1971; Brockway and others, 1975).

Mesozoic rocks. The oldest sedimentary rock 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, 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-derived 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 volcanic-derived sandstone, conglomerate, and siltstone of the Middle Jurassic Shelikof Formation in the Wide Bay area.

In the Port Moller area, siltstone beds of the Naknek Formation grade upward into arkosic sandstone of the Staniukovich Formation (Figs. 4, 5). The arkosic composition of the Naknek strata indicates that unroofing of the granitic Naknek Lake batholith occurred in Oxfordian (Late Jurassic) time.

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 indicative of a Portlandian to Valangian (Upper 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-Barremian (early Early Cretaceous) in age. Rocks of comparable age also occur in the Cape Douglas area of south Cook Inlet, and in the Matanuska Valley in southern Alaska. The Naknek and Staniukovich Formations and Herendeen Limestone are stratigraphically conformable to 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 unit, 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 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 basin 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 volcanogenic rocks that include flow, breccia, and conglomerate units (Figs. 4, 5). Radiometric dates

from cores in the Gulf Port Heiden and Great Basins-Ugashik wells confirm that volcanic rocks of the Meshik Formation are equivalent in age to Tolstoi and Stepovak strata. Meshik rocks occur in the northeast portion of Bristol Bay basin but are not present in the General Petroleum Great Basins Nos. 1 and 2 wells (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 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 early Tertiary, contributing large volumes of debris to the Paleogene rocks of the Alaska Peninsula. Volcanism

appears to have abated during the early Neogene and became active again during Pliocene-Holocene time.

Two major plutonic episodes Jurassic and early Tertiary, are known to have occurred on the Alaska Peninsula. South of the Peninsual, an extensive episode of early Tertiary intrusive activity occurred in the adjacent Shumagin-Kodiak slate-graywacke belt of southern Alaska (Burk, 1965). 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.).

Summary

Bristol Bay basin probably began to subside in late Mesozoic time; the rate of subsidence has approximately equaled the rate of deposition since this time. The maximum thickness of sedimentary rock in the deepest part of the basin is not well known but probably exceeds 3600 to 4000 m. The basin fill apparently has not been folded except locally along the northern shore of the Alaska Peninsula at the southern edge of the basin.

Many of the late Mesozoic and Cenozoic sedimentary rock units exposed onshore along the Alaska Peninsula appear to extend offshore within the Bristol Bay basin. The position of the basin behind the Aleutian arc has probably isolated it from the numerous episodes of volcanism and plutonism that have substantially reduced the petroleum potential of the sedimentary sequences along the Alaska Peninsula.

The northeastern half of Bristol Bay basin contains as much as 3200 m of relatively flat-lying Cenozoic sedimentary rocks that include marine and nonmarine sandstone, siltstone, shale units and local coal seams. From Port Heiden northward, the Cenozoic sedimentary sequence overlies Jurassic granitic

rocks although locally it covers 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, 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, the five wells 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.

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. 6). 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 has been drilled near Bethel.

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

Basement complex. "Economic" basement 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 quarzite 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 (Figs. 7, 8).

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 (Figs. 7, 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).

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, interlaminated 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 to up 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 (Figs. 7, 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).

Eastern Siberia and Anadyr Basin

Anadyr basin lies due west of Alaska's Norton Sound beneath the southwestern corner of the Anadyr Gulf, along the Siberian coast of the Bering Sea (Fig. 3). Approximately 35,000 km^2 of the basin are onshore and nearly 60,000 km^2 offshore. The estimated total volume of the basin's sedimentary fill is 300,000 km^3 (Grigorenko and others, written comm., 1974). Anadyr basin is considered to have substantial hydrocarbon potential within a thick, relatively flat-lying sequence of upper Cenozoic clastic rocks. Since 1969 several Soviet wells have been drilled onshore that resulted in discoveries

of methane gas and gas condensate.

Summaries of the basin geology, stratigraphy and exploratory drilling onshore through 1971 have been published by Agapitov (1970, 1971) and by Meyerhoff (1972a, b). The geologic evolution and formation of the basin is summarized by Kostylev and Burlin (1966); Dolzhanskiy and others (1966) present geophysical evidence for structural interpretation and subdivision of major rock units. In the eastern Koryak Mountains, rocks similar to the Franciscan complex of western North America are faulted against rocks similar to the Great Valley sequence of California (Bogdanov, 1970). These units flank the Anadyr basin to the southeast.

General Basin Geology. The basement beneath the Anadyr basin consists of three major rock sequences of pre-Senonian (Late Cretaceous) age (Fig. 9). The thickness, distribution, and general induration of these older sequences have been tentatively established by seismic refraction surveys (Dolzhanskiy and others, 1966).

The oldest rocks, as defined by seismic profiles, appear in the southeastern and eastern parts of the basin at depths of 5-6 km and probably consist of Precambrian(?) crystalline rocks. Crystalline basement is overlain by a 1-2 km thick sequence of strongly folded metavolcanic tuff and marine graywacke of Paleozoic to Early or Middle Triassic age (Dolzhanskiy and others, 1966). The two older sequences are overlain by a 3-4.5 km equence of Upper Jurassic to Valanginian (Lower Cretaceous) spilitic-keratophyric and weakly metamorphosed graywacke that locally contains isoclinal and fan-like folds (Dontsov and Ivanov, 1965).

The oldest rocks in the Anadyr basin that may have petroleum potential are a 1.2 to 2 km thick sequence of continental, coal-bearing units

that range in age from Senonian (Cretaceous) to Danian (Paleocene). Folding appears to have been active during the deposition of these rocks because they are absent on many flanking structures and wedge out against these structures (Meyerhoff, 1972a, b; Dontsov and Ivanov, 1965).

A Paleogene sequence consisting of continental and marine clastics up to 2.0 km thick unconformably overlies the Senonian-early Paleocene section (Fig. 9). These rocks, derived from older metamorphic and volcanic units, become increasingly marine in origin from north to south and, like the underlying section, are absent over major fold structures. The Paleogene and older sequences have not been drilled (Agapitov, 1970, 1971; Dolzhanskiy and others, 1966).

Middle Miocene and younger sedimentary rocks form a continuous cover across the basin and have an average thickness of 1.2 km (thickness varies from several hundred meters to 2.1 km; Dolzhanskiy and others, 1966). This section consists of a marine and continental deltaic complex of sandstone, siltstone, and shale, interbedded with local coal seams (Agapitov and others, 1970). In all the wells drilled prior to and during 1971, the middle Miocene section was found to directly overlie Lower Cretaceous strata. The wells appear to be located on structures where the pre-Neogene section has been uplifted by block-faulting; the Neogene section has been transgressively deposited over the resultant topographic highs. Folds in the Neogene section were probably formed by draping and differential compaction over these buried highs. Similar structures within the Neogene section occur beneath Bristol Bay and along the north coast of the Alaska Peninsula (Hatten, 1971).

Middle Miocene sedimentary rocks in the Tsentraluyi depression of the Anadyr basin are 2-3.5 km thick and are considered likely areas of oil

and gas accumulation. Seismic and gravity data have defined approximately 50 local onshore anticlinal uplifts (Fig. 10) that range in size from 5 km by 7 km to 7 km by 10 km; the average closure over these highs is 100-300 m over an area of 32 km^2. Flank dips are generally low, averaging 2-3^o, in contrast to dips of 40^o or more in the underlying Senonian-Paleogene sequence. Folding of the Cenozoic section resulted from block movements on northeast-trending faults in the folded basement. Folds within the middle Miocene section vary from circular to oval structures in the northern and central area to complex, linear compressional folds in the southern sectors. Intensity of folding decreases upward in the section, and the overlying Pliocene sedimentary units are undeformed. Seismic data and drilling results both confirm that the Neogene section thins over buried highs (Fig. 9).

Mesozoic Sedimentation - Western Alaska and Eastern Siberia

The Mesozoic tectonic history of the Penzhina-Anadyr region of Siberia is similar to that of the Kuskokwim-Nushagak area. A primary cycle of eugeosynclinal sedimentation occurred throughout much of Jurassic time and was terminated by an episode of Early Cretaceous folding and the emplacement of large granitic plutons. The Jurassic cycle of sedimentation was accompanied by extensive silicic volcanism that comprise andesitic flows, tuff, and breccia (Fig. 6; Agapitov and Ivanov, 1969).

In the Penzhina-Anadyr region, the primary cycle of geosynclinal sedimentation lasted from Late Jurassic to Valanginian (Early Cretaceous) time, during which 3,000 to 4,000 m of sediment accumulated in a series of elongate north to northeast-trending basins. In the Kuskokwim

Mountains-Nushagak area, the primary geosynclinal stage is represented by the Gemuk Group, which includes rocks ranging in age from Mississippian(?) to Early Cretaceous and local, andesitic-rich rocks of Middle to Late Jurassic age. Thickness estimates of the Gemuk group range from 4500 to 9000 m (Hoare, 1961).

After deposition and folding of the geosynclinal rocks in western Alaska and eastern Siberia, a second cycle of eugeosynclinal deposition began in Barremian (Early Cretaceous) time. During the second cycle, 6000-9000 m of graywacke, shale, and conglomerate accumulated in five elongate basins around the Bering Sea. Four of these basins are located in western Alaska and one in the Penzhina-Anadyr region of Siberia. By middle Senonian (middle Late Cretaceous time), deposition was succeeded by folding and plutonism that locally continued into early Tertiary time.

A third or "late" stage of sedimentation occurred in the Penzhina-Anadyr region during Paleogene-Neogene time. Continental and shallow marine sedimentary rocks and widespread nonmarine basaltic volcanic rocks accumulated in isolated block-faulted basins. Tertiary sediment is sparse within the Bethel and Nushagak lowland areas. Most Tertiary rock consists of flat-lying nonmarine basalts.

Structure of the Outer Bering Sea Shelf

Three interpretative drawings of seismic reflection profiles, S-16, S-5, and B-92, reveal structures representative of the outer or southern Bering Sea shelf and its margin (Figs. 11, 12, and 13). Other profiles have been published previously by Scholl and others (1966; 1968), Scholl and Hopkins (1969), and Scholl and Marlow (1970b).

Profile S-16 . Line S-16 extends northward from near Unimak Island to the western tip of Nunivak Island (Figs. 2 and 11). Acoustic basement, shown

by a heavy line underlain by dots, has been sampled at the nearby dredge site TT-1 in Pribilof canyon (Fig. 2). Here deformed and lithified mudstone, siltstone, and sandstone of Late Cretaceous (Campanian) age were recovered (Scholl and others, 1966; Hopkins and others, 1969; see below). Near the shelf edge (1000-1400 hrs, Fig. 11), a 50-km-wide ridge of these and related rocks that form the acoustic basement underlies more than 3 km of flat-lying to gently deformed sedimentary beds. North and south of the ridge, basement disappears from the seismic record at depths corresponding to a one-way reflection time greater than 2 seconds (i.e., approximately 6.3 km; Fig. 14).

The northern edge of this ridge forms the southern flank of St. George basin, a narrow, fault-bounded basin extending northwestward from near Unimak Island to the Pribilof Islands (Figs. 3, 11, and 15). Beneath the axial part of the basin the acoustic basement is deeper than 2 sec. (6.3 km). North of the basin the acoustic basement lies near a subbottom depth of 1 km (0600-1600 hrs, Fig. 11). Numerous limbs of erosionally beveled folds are resolvable within the basement (Fig. 11). The strike of these intra-basement structures is not known in detail, but our profiles indicate a strike generally parallel to that of the Bering Sea margin, i.e., northwestwardly (Figs. 2 and 3).

Northward along Line S-16 the surface of the acoustic basement rises gradually. Adjacent to Nunivak Island the basement rises to within a few hundred meters of the sea floor. This shallow, platform-like basement high has been called the Nunivak arch by Scholl and Hopkins (1969).

Beneath the shelf, sedimentary rocks overlying acoustic basement were informally named the "main layered sequence" by Scholl and others (1968; 1975); they describe the sequence as semiconsolidated terrigenous and diatomaceous deposits of low velocity (1.7 km/sec; Shor, 1964). The sequence is thought to be mainly of Neogene age, although some middle Oligocene rocks have been dredged from the sequence near Zhemchug Canyon (Table 2, Fig. 2; Scholl and others, 1966; 1975; Hopkins and others, 1969). As revealed beneath the southern end of Line S-16 (Fig. 11), the main layered sequence appears to be separable into two acoustic units. The upper unit consists of strongly reflecting, undeformed beds, whereas the lower unit is made up of weakly reflecting, almost transparent layers that are moderately deformed. Although this interpretation is subject to uncertainties induced by multiple reflections and down-section signal attenuation, regional seismic lines, dredge data, and stratigraphic information gained at Deep Sea Drilling Project (DSDP) sites in the Bering Sea (Creager, Scholl and others, 1973) suggest that the main layered sequence consists of at least two major units. Near the shelf edge, the upper unit of late Miocene and younger age is richly diatomaceous, whereas the lower unit consists of terrigenous clastics of early Tertiary through early Miocene age.

Both the upper and lower sedimentary units are broken by basinward-dipping normal faults (Figs. 3 and 11). Deeper beds are progressively more offset than overlying beds, indicating that the faults are growth-types and that the deposition in St. George basin has been contemporaneous with basin subsidence. Basinward thickening of beds in the lower sequence also suggests that subsidence and sedimentation occurred simultaneously. Furthermore, a subtle but definite divergence in dip between the upper and lower units implies

that the ratio of the rate of sedimentation to subsidence increased during deposition of the upper sequence. North of the basin, beds of the main layered sequence are virtually flat-lying; here they bury a gently concave basement surface (0100-0600 hrs, Fig. 11). Beds in the lower section appear to onlap onto the flanks of a basement swale near 57°N. Those of the upper section lap northward over the southern flank of Nunivak arch, which evidently has remained relatively stable during regional subsidence of the inner Bering Sea shelf.

Profile S-5. North of its outcrop on the continental slope, between 0100 and 0700 hours on profile S-5 (Fig. 12), the surface of the acoustic basement rises to form two distinctive highs, Garden and Pribilof ridges. Steeply dipping and truncated reflectors within the basement suggest that Pribilof ridge is antiformal in structure. North of the ridge the top of the slightly undulating surface of the basement descends below 1.5 km. A low rise separates two of the basement lows, Inner and Otter basins. To the north (between 50° and 60°N) the basement surface rises to within a hundred meters of the sea floor. This high is part of the broad Nunivak arch, which is subaerially exposed at nearby St. Matthew Island (Figs. 2, 3 and 12). The island is underlain by igneous and sedimentary rocks of Late Cretaceous and early Tertiary age (Patton and others, 1976). Faint reflectors below the acoustic basement outlining the arch dip to the south, or away from the island.

The Cenozoic sedimentary sequence overlying the basement is nearly flat-lying. Strongly reflecting beds make up the entire section, which may indicate that only the upper unit of the main layered sequence is present here. Vertical to steeply dipping faults break the sedimentary section in only a few areas south of 58°N; only one fault (0400 hrs, Fig. 12) appears

to offset basement rock. The beds of the main layered sequence onlap basement highs, again indicative of a slow transgression over a subsiding basement.

Profile B-92. A third seismic line, B-92 (Figs. 2 and 13), traverses the northwestern shelf area between St. Matthew Island and near Cape Navarin. At the southern end of the profile the acoustic basement crops out on the upper continental slope. Discontinuous reflectors indicate that the basement is in part deformed sedimentary beds. Rocks thought to be from the basement, dredged at a water depth of 2,500 m, are calcareous argillite and calcareous lithic volcanic wacke (samples 70-B92 -3S1, -3S2, -3S5, -3S7, Table 2). Many of these rocks are fractured and secondarily cemented; no diagnostic fossils were found. Immediately north of the continental slope, the surface of the acoustic basement ascends over a broad basement high centered near 1130 hrs (profile B-92, Fig. 13). Farther north along the southern flank of Navarin basin, the basement descends below a sub-shelf depth greater than 2.0 sec. (Figs. 13 and 14). A basement high peaks near 0300 hrs (at a depth of 1.7 sec, 4.8 km) and divides the basin into two parts, each of unknown depth. North of about 61^{o}N, acoustic basement climbs irregularly to within 500 m of the sea floor as Nunivak arch is approached. Only a few discontinuous sub-basement reflectors were resolved near the northern end of the line. Near 2100 hrs these reflectors dip to the north, but closer to the crest of the arc (as along Line S-5), the reflectors dip to the south.

Navarin basin is an enormous sediment-filled basin nearly 190 km wide (1000-2100 hrs, Fig. 13). The layered sequence filling the structural basin consists of a lower and an upper unit. The lower unit, like that recorded in St. George basin (profile S-16, Fig. 11), is made up of weakly reflecting

beds that thicken toward the basin center. Along the northern flank of Navarin basin (0000-2100 hrs, Fig. 13) the gently dipping lower unit is overlain discordantly by the upper sequence. The upper unit extends across the entire shelf and onlaps northward onto Nunivak arch. Both sedimentary sequences are broken by vertical or high angle normal faults. The fault near 2330 hrs and that near 0600 hrs show increasing offset with depth, similar to the growth faults that break the main layered sequence of Line S-16 (Figs. 11 and 13).

Bering Sea Shelf - Structural Provinces

The structural contour map of Figure 15 is based on approximately 23,500 km of seismic reflection data (Fig. 2). Depths in time from the sea floor to acoustic basement (thought to be an angular unconformity mostly separating Mesozoic and Cenozoic rocks) have been converted to distance using the thickness versus travel time curve shown in Figure 14. This curve is based on data gathered over different areas of the Bering Sea, thus its application to the main layered sequence of the outer Bering Sea shelf is warranted only for the calculation of approximate or general thicknesses.

Based on the thickness and distribution of the Cenozoic deposits (Fig. 15), the central and southern Bering Sea shelf can be divided into three structural provinces - a southern province of narrow northwest-trending basins extending along and parallel to the continental margin between Unimak Island and Zhemchug Canyon, a northwestern province that comprises the huge Navarin basin of the outer Bering Sea shelf, and a northern province of thinner deposits that includes Nunivak arch and the northeast-trending

St. Matthew basin (Figs. 2, 3 and 15).

Southern Province. The southern province is bordered to the north by Nunivak arch (Figs. 3 and 15; Scholl and Hopkins, 1969), a broad, thinly-mantled basement high (Figs. 11, 12, and 13). To the south the province is flanked by the moderately steep (3-7 degrees) Bering Sea continental slope leading to the abyssal depths of the Aleutian Basin. This province is characterized by a series of northwest-trending linear basement ridges and basins buried, respectively, beneath as little as a few hundred meters to more than 6.3 km of sediment (Figs. 3 and 15, Table 1). St. George basin, the largest basin in the province, is at least 300 km long and 50 km wide. A free-air gravity low (Pratt and others, 1972; Fig. 17) suggests that a closely related, or possibly a separate basin, may lie on strike to the southeast of St. George basin. This smaller basin (Amak basin, not shown) trends northwest-southeast and extends to within 10 km of the Alaska Peninsula. Acoustic data indicate that the sedimentary sequence of St. George basin is more than 6.3 km thick; depth solutions from magnetic data suggest a possible maximum depth of 10-12 km to magnetic basement.

Flanking St. George basin along its southern side are two basement ridges; these extend northwestward to the vicinity of the Pribilof Islands (Figs. 3, 11, and 15), where they connect with a 500-km-long ridge, Pribilof ridge, that is subaerially exposed at the Pribilof Islands (Figs. 3, 12, and 15). The northern of the two flanking ridges, outlined by the 1.0 km contour on Figure 15, is rather deeply buried beneath Cenozoic deposits and its relief is not great. In contrast, the southern ridge, defined by the 0.5 to 3.0 km contour on Figure 15, has considerable relief (2.5 km), which lessens to the southeast where the ridge is more deeply buried.

Gravity data suggest that this ridge may cross, and therefore close off, the southeast end of St. George basin, possibly in alignment with a linear belt of gravity highs extending offshore from the Black Hills on the Alaska Peninsula (Pratt and others, 1972, Fig. 3; Figs. 3, 15 and 17). Unfortunately, we have no seismic data coverage in the area to validate these gravity trends.

The northwest-trending Pribilof ridge bifurcates much of the southern shelf province (Figs. 2 and 15). Three elongate sedimentary basins north of the ridge, Walrus, Inner, and Otter, trend parallel to the ridge and exhibit moderate structural relief of 0.3 to 0.5 km beneath a virtually flat shelf floor (Figs. 12 and 15, Table 1). South and west of Pribilof ridge are four sediment-filled depressions, Pribilof, Garden, Dalnoi, and Zhemchug basins; two of these linear basins, Pribilof and Zhemchug, were initially described by Scholl and Hopkins (1969). Both of these basins, although fundamentally structural depressions, also exhibit considerable sea floor geomorphic relief (1.0 to 2.0 km) because their sedimentary fills have been partly removed by headward cutting of the exceptionally large Pribilof and Zhemchug Canyons (Figs. 2, 3, and 15; Scholl and Hopkins 1969; Scholl and others, 1970a).

Underlying the outer edge of the southern shelf province are two basement ridges, Garden and Dalnoi (Figs. 3, 13, 15; Table 1). Like Pribilof ridge, both ridges strike parallel to the northwestward trend of the Bering Sea margin. Garden ridge rises to within 0.75 km of the shelf floor; the top of Dalnoi ridge is slightly deeper. The surface of the folded basement rock forming the southwestern flanks of both ridges plunges southward beneath

the continental slope toward the floor of the Aleutian Basin. Irregular bathymetric contours along the slope in part reflect erosional relief cut into the basement flanks of Pribilof, Garden, and Dalnoi ridges by an episode of late Cenozoic canyon cutting (Scholl and others, 1774; 1975).

A number of faults can be mapped regionally (Fig. 3) in the southern province. For example, the basement underlying St. George basin is down-faulted on both flanks, implying that this basin is a graben. Other linear basins (e.g., Pribilof, Walrus, Zhemchug, and Dalnoi) are flanked on one or both sides by normal faults, implying that these basins are either grabens or half (asymmetric) grabens. Linear fault scarps also border Pribilof, Dalnoi, and Garden ridges; however, only one flank of these ridges appears to be fault controlled, thus they are probably rotated or tilted fault blocks rather than simple horsts.

Northwestern Province. The northwestern shelf province is also bordered to the north by Nunivak arch (Figs. 3 and 15). This province is dominated by the enormous Navarin basin (Table 1). Although our seismic coverage of the northern half of Navarin basin is poor, we estimate that the basin is at least 400 km long and 190 km wide. Seismic lines indicate that its sedimentary fill is at least 6.3 km thick (Figs. 13, 14 and 15). However, by projecting the downward sloping subsurface flanks (acoustic basement) of the basin towards its axis, a thickness closer to 10-11 km is indicated. The volume of the sedimentary fill, based on an area of 80,000 km^2 over deposits thicker than 2 km, is more than 400,000 km^3 (Table 1).

Beneath the outer shelf and upper continental slope the southwestern side of Navarin basin is bordered by Navarin ridge and a narrow, intervening down-faulted trough filled with more than 2 km of sediment (Figs. 3 and 15).

Navarin ridge, a northwestward-trending basement high, is buried beneath Cenozoic sediment 0.5 to 1.0 km thick. The southeastern extent of Navarin basin is poorly known, but the basin may connect with Zhemchug basin underlying the head of Zhemchug canyon (Fig. 3). Also because of data limitations, the northwestern limit of Navarin basin is unknown. A single reflection profile off Cape Navarin crosses northwest of the basin, however (Figs. 2, 3 and 15).

Because seismic reflection coverage over Navarin basin is poor, only a few faults (undoubtedly there are many more) are known (Fig. 3); all are extensional normal ruptures. Numerous offsets in the sedimentary deposits northwest of the basin were found close to Cape Navarin. Some of these probably are continuous or associated, with, northwest-striking faults cutting Mesozoic and Cenozoic rocks (of the Koryak Range) exposed in the vicinity of the cape (Figs. 2 and 3).

Northern Province. Nunivak arch dominates the northern province, rising above the surrounding shelf provinces as a platform-like basement high that was first described by Scholl and Hopkins (1969). They speculate that it is the offshore continuation of the folded Mesozoic rocks of the Yukon-Koyukuk geosyncline. Nunivak Island, a subaerial sector of Nunivak arch, is underlain by shallow marine rocks of Late Cretaceous age (Hoare and others, 1968). More recent seismic reflection data have allowed us to modify the original outline of Nunivak arch (Fig. 3) shown by Scholl and Hopkins (1969, Fig. 3); our boundary indicates that both St. Matthew and Nunivak Islands rise above the arch. However, there are insufficient data to define the northern and southeastern limits of Nunivak arch. It is not known, for example, if its northern boundary encompasses St. Lawrence Island (Fig. 3). Numerous small breaks, mostly normal faults, rupture the

sedimentary cover overlapping Nunivak arch (Fig. 3).

Two elongate basins, St. Matthew and Hall, occur within the northern province (Figs. 3 and 15). St. Matthew basin trends northeastwardly and is approximately 280 km long (Table 1). Hall basin, much smaller, lies perpendicular to this trend at the southwestern end of St. Matthew basin. Both basins are irregularly shaped and contain less than 1.5 km of presumed Cenozoic sediment overlying a downwarped basement of Mesozoic and possibly Paleozoic rock. The elongate St. Matthew basin lies on strike with the offshore projection of the Kaltag Fault, a major strike-slip fault in western Alaska (Fig. 3; Patton and Hoare, 1968; Scholl and others 1970c).

Bering Sea Shelf - Potential Field Data

Magnetic Data. High-amplitude (1000 gamma or greater) and high-frequency (wavelengths less than a kilometer) magnetic anomalies are characteristic of much of the Bering Sea shelf. In the Bristol Bay region, an east-west boundary separates a band of high-frequency, high-amplitude anomalies from an area of low-amplitude anomalies to the south (Fig. 16). The boundary, approximately along latitude 56^{o}N, extends westward from the Alaska Peninsula to the Pribilof Islands (Fig. 16; Pratt and others, Fig. 2, 1972). Pratt and others (1972) suggest that to the east the northern belt of high-intensity anomalies may swing north into southwestern Alaska, possibly reflecting the magnetic signature of intrusive bodies within the Gemuk series (mapped in the Kuskokwim River region by Hoare and Coonrad (1961)).

The southern limit of the high-intensity magnetic belt generally falls along the southern edge of Nunivak arch. Also, the southern

limit of the belt is generally coincident with the northern boundaries of the large outer shelf basins such as St. George and Navarin (Figs. 3, 15, and 16). However, in the vicinity of the Pribilof Islands, the belt may extend farther south to include Pribilof ridge. West of St. Matthew Island, the southern edge of the belt appears to turn northwestward toward the Chukotsk volcanic terrain of eastern Siberia. The northern limit of the anomaly belt cannot be drawn (owing to a lack of data) east of Nunivak Island. West of the island, the northern boundary is sharply defined as the anomalies in the vicinity of St. Matthew basin are of low amplitude. The boundary appears to swing in a northwestern arc towards the Gulf of Anadyr and the Chukchi volcanic belt (Figs. 3 and 16).

The southern area of low-amplitude magnetic anomalies generally underlies St. George and Navarin basins. The zone extends southwestward beyond the shelf edge to the base of the continental slope. However, local sharp anomalies occur over basement highs such as Pribilof and Navarin ridges and near Cape Navarin (Figs. 3 and 16).

Gravity Data. Large negative gravity anomalies (below - 100 m gals) along the Bering Sea margin are restricted to deep water areas such as those near Pribilof and Zhemchug Canyons (Fig. 17). Small, localized negative anomalies are associated with St. Matthew basin, and a broad, regional low occurs east of St. Matthew Island (Figs. 3, 15 and 17). Relative lows (not necessarily negative anomalies) are found over much of the shelf. Most of these are centered over and along areas of structurally depressed basement detected in the seismic data. However, a number of relative gravity lows are located over the flanks or crestal areas of broad basement highs or upwarps such as Nunivak arch, which are overlain by a flat-lying or gently

dipping sedimentary mantle. Seismic reflection records reveal that these lows are associated with possible intrabasement synclinal structures in the so-called acoustic basement. Our seismic data are insufficient to define these structures.

A number of relative gravity highs, many exceeding 100 mgals, are correlative with acoustic basement highs, for example, Navarin and Pribilof ridges (Figs. 3, 15 and 17). However, the southwestern flank of Nunivak arch is apparently not associated with a relative gravity high, and anomalies over the opposite northeastern flank of the arch are actually regionally depressed. A west-trending anomaly high in the Bristol Bay area is on strike with the offshore projection of anticlinal structures in Jurassic rocks exposed at the Black Hills, Alaska Peninsula (Figs. 3 and 17; Pratt and others, 1972, Fig. 3).

Geologic History of the Bering Sea Shelf and Margin

Mesozoic and Cenozoic Tectonic Setting

Reconstructions of relative plate motion indicate that the Kula plate extended into the area of the Bering Sea during Mesozoic time (Scholl and Buffington, 1970; Larson and Pitman, 1972; Larson and Chase, 1972; Scholl and others, 1975; Cooper and others 1976a, b). The relative motion of the Kula plate and Alaska (North America plate) is thought to have been more or less parallel to the Bering Sea margin but perpendicular to eastern Siberia. However, apparently there was some underthrusting of the Bering Sea margin by the Kula plate during the Mesozoic, although quantitatively

the amount of underthrusting was probably greater beneath the adjacent eastern Siberia region.

At the end of the Mesozoic or in the earliest Tertiary, the insular Aleutian arc began to form in the deep oceanic area along the curving projection of the Alaska Peninsula (Scholl and Buffington, 1970; Hopkins and Scholl, 1970; Marlow and others, 1973; Scholl and others, 1975). Formation of the arc trapped a piece of the Kula plate north of it, thereby forming the abyssal floor of the Bering Sea. Entrapment terminated underthrusting of the Kula plate beneath the Bering Sea margin. Thus, compressional deformation of the margin ceased in earliest Tertiary time. Since the early Tertiary the margin has been uplifted and extensionally deformed; subsequent subsidence in many areas has been over one kilometer.

Formation of Mesozoic Basement Rock

Underthrusting along the Bering Sea margin resulted in the formation and subsequent folding and intrusion of eugeosynclinal rocks along the outer edge of the margin. Terrigenous deposits of Mesozoic age probably accumulated within the forearc (i.e., arc-trench gap of Dickinson, 1974) basins and troughs of the margin. These beds were probably folded and accreted to the margin in a manner similar to that envisioned for the Mesozoic margin of western North and Central America by Bailey and Blake (1969), Hamilton (1969), Ernst (1970), Page (1970a, 1970b), Bailey and others (1970), Hsu (1971), and Seely and others (1974). However, we do not believe that trench deposits constitute a significant fraction of the folded rocks, which now form the basement complex underlying the outer half of the Bering Sea shelf (Fig. 18). These forearc beds were intruded

by ultramafic bodies that are locally exposed in the Pribilof Islands (Barth, 1956). Although undated, these intrusive rocks are probably Mesozoic in age (Scholl and others, 1975).

As a result of underthrusting beneath the Bering Sea margin, a Mesozoic orogen formed above a wide subduction zone, a tectonic process widely hypothesized for active plate margins (Dickinson, 1974). Orogenic activity culminated in the formation of coastal mountain ranges of uplifted eugeosynclinal rocks. Flanking the growing coastal ranges on the inner half of the margin, a wide magmatic arc formed during the Mesozoic and earliest Tertiary (Fig. 18). Remnants of this arc are exposed on St. Matthew and St. Lawrence Islands (Fig. 3), and these igneous rocks extend offshore as part of the basement rock beneath the central area of the Bering Sea shelf. Magmatic rocks exposed on these islands are Late Cretaceous and earliest Tertiary in age (see above; Patton and Csejtey, 1971; Csejtey and others, 1971; Csejtey and Patton, 1974; Patton and others, 1976).

After the cessation of underthrusting in latest Cretaceous or earliest Tertiary time, both the eugeosynclinal coastal rocks of the forearc and the igneous rocks of the inner magmatic arc were uplifted and deeply eroded. Beveling of the central area of the shelf formed the bedrock platform of Nunivak arch (Figs. 3, 15). At the same time the compressional deformation that formed the bedrock of the outer part of the shelf and the adjacent margin changed to extensional rifting, thereby forming the outer subshelf basins. Extension and subsidence has continued during much of Cenozoic time (Figs. 11, 12 and 13).

Formation of Cenozoic Basins

Earlier work by Scholl and others (1966; 1968), Scholl and Hopkins (1969), and Hopkins and others (1969) provided evidence that the outer Bering shelf subsided differentially in the Cenozoic. This extensional deformation of the outer shelf differs dramatically from the earlier late Mesozoic and early Tertiary(?) compressional deformation of eugeosynclinal deposits along the margin, now the basement rocks underlying the outer Bering Sea shelf (forearc of Fig. 18). Differential collapse of this Mesozoic fold belt during the Cenozoic resulted in the formation of elongate basins and ridges that strike northwestward parallel to the margin and the structural grain of the fold belt (Fig. 3). Growth structures within the Cenozoic strata of these basins indicate that collapse, rifting, and sedimentation have been continuing processes (Figs. 3, 11, 12 and 13).

The lowest beds within some of the basins may be as old as Late Cretaceous(?), the time when the fold belt began to collapse and basins may have first formed. Because of the proximity of former coastal mountains to this belt, the lower units within the outer shelf basins could contain coarse clastic debris. Coarser lower units may in part explain the relative lack of coherent reflectors resolved acoustically within the lower section of seismic reflection records (Figs. 11, 12 and 13). Rates of shelf subsidence and sedimentation continued uniform until sometime in middle to late Tertiary time, when the ratio of subsidence to sedimentation changed dramatically. The resultant divergence in dips is most pronounced in basin areas beneath the shelf, such as St. George and Navarin basins, where the Cenozoic section is greatly thickened (more than 7 km, Figs. 3, 11, 12 and 13). Over much of the shelf the Cenozoic section

is commonly less than 2 km thick and the divergence is not readily evident. Regional geologic evidence suggests that the divergence formed in Miocene time.

The oldest Cenozoic beds that have been sampled from the upper part of the continental slope are marine deposits of middle Oligocene age. This early sedimentary conglomerate overlies denuded Mesozoic folds, indicating that subsidence of the outer shelf-upper slope area began prior to this time (Table 2, sample 7Q-B97-1S2; Hopkins and others, 1969; Scholl and others, 1975). Neogene deposits underlying the outer shelf include terrigenous strata and units rich in diatomaceous debris. Many or all of these beds are neritic deposits, thereby implying continuous subsidence of the outer shelf during Neogene time. The thicker basin deposits of the outer shelf have not been sampled thus we have no direct evidence as to when initial basin subsidence began. However, we speculate that the initial collapse of the margin probably began in latest Mesozoic or earliest Tertiary time in response to the end of underthrusting of the Kula plate beneath the Bering Sea margin. As noted earlier, the Kula plate had obliquely collided with the margin since at least early Mesozoic time. With formation of the Aleutian Ridge in the latest Cretaceous or earliest Tertiary, underthrusting shifted away from the margin to the ridge.

Isolation of the Bering Sea margin from underthrusting of the Kula plate would have relieved the compressive stresses along the margin. Isostatic rebound of previously subducted and relatively less dense sedimentary rock and upper crust beneath the margin may have initiated differential uplift and subsequent collapse of the outer shelf. Uplifted blocks

of the shelf would have been subject to rapid erosion thereby feeding coarse debris into the adjoining down-dropped basins.

During the Cenozoic the deep Aleutian Basin, underlain by a piece of trapped Kula plate west of and adjacent to the Bering Sea margin, received over 4 km of sedimentary debris. The oceanic crust beneath the Aleutian Basin has subsided about 3 km (Shor, 1964), apparently as an isostatic adjustment to the sedimentary loading. The depression of the crust beneath the abyssal basin may also have involved the adjacent Bering Sea margin, contributing to continued, regional subsidence of the outer shelf to the present.

Summary

The outer Bering Sea shelf is structurally underlain by a number of sediment-buried ridges and basins that are in turn underlain by deformed eugeosynclinal rocks of Mesozoic age. These structures are elongate and parallel to the margin. The sedimentary sections of two of the basins, St. George and Navarin basins, may be as much as 7-10 km thick. The combined area of these basins (90,000 km) and of the remaining outer shelf basins is over 100,000 km^2, an area roughly one-quarter the size of California. The cross-sectional configuration of most of the basins is asymmetric, i.e., that of a half graben.

The basement ridges of the outer shelf include folded sedimentary sequences that, like the ridges, probably strike parallel to the margin. In Pribilof Canyon the rocks of this nearly totally submerged foldbelt are mudstone, siltstone, and sandstone of Late Cretaceous age (Hopkins and others, 1969). At nearby St. George Island, presumed basement rock of

ultramafic composition is subaerially exposed (Barth, 1956; Cox and others, 1966). Folded Mesozoic rocks on the Alaska Peninsula trend toward the submerged foldbelt forming the basement complex of the outer shelf. The belt probably extends northwestward into the Koryak Range at Cape Navarin of eastern Siberia (Fig. 18). We envision the outer shelf foldbelt as an orogen of eugeosynclinal rocks tectonically accreted to the continent in a manner similar to that proposed for the Franciscan complex of western North America (Bailey and Blake, 1969; Hamilton, 1969; Ernst, 1970; Page, 1970a, 1970b; Bailey and others, 1970; and Hsu, 1971). However, we do not believe that the foldbelt consists of offscraped trench or abyssal plain deposits (Scholl and Marlow, 1974).

Sedimentary rocks within the basins are thought to be terrigenous and diatomaceous deposits of mainly Cenozoic age, although Cretaceous beds may form the basal units of the larger basins. The basin fill, informally termed the main layered sequence by Scholl and others (1968; 1975), consists of two units. The upper unit is virtually undeformed and typically composed of acoustically reflective strata. In contrast, the lower unit is slightly deformed and its beds appear to be less reflective (Figs. 11, 12 and 13). The lower unit dips more steeply towards the axis of the basin than the younger strata; the divergence in dip presumably indicates a change in the ratio of subsidence to basin filling and may be Miocene in age. Beneath the lower unit a major unconformity separates the deformed eugeosynclinal rocks of Mesozoic age from the overlying Cenozoic deposits of the basin fill.

Most of the inner Bering Sea shelf is underlain by a broad basement

high, Nunivak arch (Scholl and Hopkins, 1969). Beneath the southwestern flank of the arch, the limbs of intrabasement folds generally dip southward, probably striking parallel to the margin. The arch's northern flank is associated with decreases in regional gravity anomalies and intensity of magnetic signatures. These changes may signify a change in deeper crustal structures, possibly from an intermediate crust formed over Mesozoic ocean floor in the south to thicker and much older continental crust in the north.

St. Matthew basin, which cuts across the northern flank of Nunivak arch, is possibly the offshore expression of the Kaltag fault, a major right-lateral fault in western Alaska. Hall basin, and a ridge separating this basin from St. Matthew basin, lie athwart the southwestern terminus of St. Matthew basin, perhaps marking the southwesternmost extent of the fault. Deformed strata in the basal part of the sedimentary sequence of St. Matthew basin suggest that significant offset along this fault probably did not take place after the early Tertiary. No distal offshore extension of the Denali fault, a parallel right-lateral shear in southwestern Alaska, has been identified over the southern or outer Bering Sea shelf. This fault may terminate well north of the Pribilof Islands-St. George basin area toward which it strikes.

An arcuate zone of high amplitude magnetic anomalies occupies most of the central shelf area. We speculate that the magnetic anomaly belt is the signature of a mostly submerged Mesozoic magmatic arc, now part of the shelf's basement structure, that extends from southern Alaska through the Bering Sea shelf to eastern Siberia (Fig. 18).

The Mesozoic fold belt of the outer shelf and the magmatic arc of the inner shelf may have formed in response to oblique convergence between the Kula(?) and North American plates prior to the formation of the Aleutian arc in latest Cretaceous or earliest Tertiary time. The eugeosynclinal rocks that formed seaward of the magmatic arc probably accumulated on oceanic crust; the arc most likely formed above transitional or continental crust. In the latest Cretaceous or earliest Tertiary the deformed eugeosynclinal assemblage was uplifted and eroded, subsequently collapsing at least by the middle Oligocene to form the present basement ridge and basic complex of the outer Bering Sea shelf. Subsidence and extensional rifting took place after the formation of an Aleutian arc, which marked the cessation of underthrusting between the now entrapped Kula(?) plate in the deep Bering Sea and the adjacent North America plate. The boundary between the two plates is complex due to the southward growth of the Mesozoic Bering Sea continental margin caused by the tectonic accretion of eugeosynclinal masses to the North America block. The northernmost location of the former plate boundary may be beneath the southern flank of Nunivak arch, perhaps where the Kaltag and Denali faults probably terminate. If these faults are simple wrench-type shears resulting from an oroclinal bending of Alaska (Grantz, 1966), then displacement may be confined to the continental block of Alaska. Unlike the San Andreas fault, which is a major plate boundary, the Denali and Kaltag faults are probably not major plate boundaries and regional stresses along these faults may not be transmitted across the transitional crustal structures of the outer Bering Sea shelf.

PETROLEUM GEOLOGY

Alaska Peninsula and Bristol Bay Basin

Drilling History

As noted, since 1959 nine onshore wells have been drilled along the northern coastal lowland area of the Alaska Peninsula. No wells have been drilled offshore in this marine part of Bristol Bay basin. For descriptive purposes, the wells are divided here into a northern group of four wells, that bottomed in volcanic or granitic rocks, and a 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. 19). 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. 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 flatlying Tertiary sedimentary rocks in the Gulf Port Heiden and Great Basins Ugashik wells range from 33 $\pm$ 1.5 to 42 $\pm$ 4 m.y. (Oligocene to late Eocene, Berggren, 1969; Brockway and others, 1975). No significant shows 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 1790 and 1940 m. Oil and gas shows were also encountered in the basal sandstone beds of the

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 overlying Bear Lake Formation. The possibility of oil and gas migration from older sedimentary formations renders the offshore area between Port Moller and Amak Island 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-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 Bristol Bay 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. 19; 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.

Reservoir Beds and Seals

The rocks that have the greatest reservoir potential for oil and gas in the offshore area of Bristol Bay basin are probably the sandstone units of the Bear Lake Formation that are middle to late Miocene in age. 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 offshore Bristol Bay 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 Bristol Bay basin. Most structures appear to decrease in amplitude upward through the Cenozoic section, and the Pliocene and Pleistocene strata are 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.

Summary

The petroleum potential of the southwest portion of the offshore Bristol Bay basin between Ilnik and Amak Island is probably greater than that of the area to the northeast. The total thickness of Cenozoic sedimentary rocks is greater in the southwest portion and there may be petroleum prospects in the underlying Mesozoic strata. The petroleum potential is also higher for the southwest portion of the basin because shows of oil and gas occurred in three or possibly four of the wells drilled on the adjacent Alaska Peninsula. This is in contrast to the four northern wells where no hydrocarbon shows were reported.

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. 6). 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. No significant hydrocarbon shows were reported in the well. However, 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 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 on 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.

Eastern Siberia and Anadyr Basin

Drilling History

As of 1972, nine wells had been drilled into the onshore portion of the Anadyr basin, six were stratigraphic tests and three were exploratory attempts. The first exploratory well was drilled in 1969. Two later wells were drilled within 13 km of the first well in the central portion of the basin (Fig. 10). A Neogene section 1537 m thick was drilled in the Vostochno-Ozero #1 well (Fig. 20), producing excellent initial shows of 95% methane gas. Eight sandstone beds were encountered in the Miocene section between 903-1467 m that had effective porosities of 20-24% and gas permeabilities of 90 to 500 mds (Fig. 20) (Agapitov and others, 1970).

Initial testing of the Vostochno-Ozero gas zones produced 7,000 to 10,000 mcfd; continued testing, however, led to sharp drops in pressure and volume (Meyerhoff, 1972 a,b). Tests on the Zapadno-Ozero structure 13 km west were less productive (Agapitov and others, 1971).

Further oil and gas exploration in the older Paleogene section has indicated possible oil and gas shows in strata of Oligocene and Eocene age (Grigorenko and others, written comm., 1974). Details on testing of the older rocks are not yet available. Discoveries in the Paleogene rocks could stimulate exploration of Stepovak and Tolstoi strata of similar age and stratigraphic position on the Alaska Peninsula (Fig. 5).

Summary of Oil and Gas Potential of Neogene Strata in Anadyr Basin

Prospective petroleum structures in Anadyr basin include circular and oval anticlines that exhibit low amplitude closure over large areas. Structures in the central basin formed by block faulting within the basement rocks. As a result, the degree of folding diminishes upward through the Neogene section,

and the Pliocene deposits are nearly flat-lying. Along the southern edge of the basin, linear anticlinal structures formed by compressional folding.

Effective porosity values as high as 24% and gas permeability values up to 500 mds for some sandstone beds in the Miocene section of Anadyr basin indicate the presence of adequate reservoir rocks. The aggregate thickness of the sand units may be as much as 80 m. A rapid drop of gas pressure and volume during open-hole tests and abrupt lateral changes in stratigraphy suggest that the sandstone beds are lenticular and that each lens contains a relatively small volume of highly pressured gas and/or gas condensate.

Both structural and stratigraphic traps may occur within the onshore and offshore portions of the Anadyr basin Miocene section. Anticlinal flexures as well as sand pinch-outs are possible trapping mechanisms. Truncation of the folded, underlying Paleogene sandstone reservoirs by Neogene shales may also form possible traps.

Sandstone reservoirs appear to be sealed by abundant interbedded shale units. Sand lenses may be completely sealed within a shale or mudstone envelope. Soviet geologists consider the absence of an evaporite-type seal to be a potential problem. However, a number of Cenozoic basins in the United States (Cook Inlet, Ventura, and Los Angeles basins, for example) have produced hydrocarbons without evaporite seals.

There are at least two possible sources for the gas and gas condensate in the Miocene section of Anadyr basin. Hydrocarbons may have formed by maturation of organic material within the Miocene shales and mudstones interbedded with sandstone reservoirs, or the hydrocarbons may be migrating upward from older, truncated clastic rocks.

Drilling results from Anadyr basin are somewhat similar to those of the

onshore portion of Bristol Bay basin along the Alaska Peninsula. In each area fewer than 10 wells have been drilled into the Neogene section with disappointing results. In both areas, the hydrocarbon potential offshore may be greater than onshore because the offshore section could thicken and contain more marine source rocks as well as cleaner and more widespread reservoir sandstone beds.

Outer Bering Sea Shelf Basins

Offshore oil and gas seeps have not been reported in the outer shelf basins (Fig. 3). Hydrocarbon "sniffers" towed by industry boats may have detected submarine seeps, but these data are not available for public evaluation. There is, therefore, no (known) direct evidence that petroleum products have been generated in the outer shelf basins. However, inferences based on collected offshore data and regional geologic mapping suggest that adequate source and reservoir beds are present. Also, reflection profiles reveal structures large enough to have trapped significant quantities of migrating hydrocarbon fluids.

Source Beds

Siltstone beds of late Tertiary age that crop out on the continental slope commonly contain more than 0.25 per cent organic carbon (Marlow and others, 1976). However, these outcrops, few of which could be regarded as good source beds, can only be generally indicative of the type of deposits that form the upper or reflective sequence of the sedimentary section filling outer shelf basins (Figs. 5, 11, 12, and 13).

Important source beds of Miocene age may occur near the base of the upper sequence, or at the top of the underlying weakly reflected sedimentary section. This inference is based on the regional occurrence of organic-rich mudstone of middle Miocene and early late Miocene age in the deep-water areas of the Bering Sea. In part characterized by weak internal reflectivity, these fine-grained deposits were found at DSDP drilling sites (Deep Sea Drilling Project) at subbottom depths generally deeper than 600 m and typically beneath coarser

diatomaceous and terrigenous units (Creager, Scholl and others, 1973). Conceivably, coeval, although probably somewhat coarser, source beds underlie some of the outer shelf basin areas.

The probability that important source rocks occurring in lower Tertiary beds, which form much of the basins' poorly reflecting basal sequence, is equally speculative. Little is known about these rocks because they appear to pinch or wedge out against the lower flanks of the basin and correlative outcrops are virtually unknown on the nearby continental slope (Figs. 12 and 13).

Sedimentary rocks dredged from the folded Mesozoic section underlying the outer Bering Shelf contain as much as 1.0 per cent organic carbon. Thus the rocks of the so-called Mesozoic "basement" (of the Bering Sea shelf) may themselves be source beds for petroleum products--products that could either have been trapped within Mesozoic structures or in overlying Cenozoic ones.

Reservoir Beds

Many of the Miocene and Pliocene rocks dredged from the Bering Sea marginal continental slope are porous sandstones and siltstones (Hopkins and others, 1969; Marlow and others, 1976). The porosity of richly diatomaceous siltstone units exceeds 50 percent. If the textures and lithologies of these outcrops are partly representative of age equivalent units underlying the outer shelf basins, then adequate reservoir beds may occur in the upper sequence of highly reflective deposits beneath the shelf.

Reasoning on more general grounds, it can be argued that porous clastic units should be common within this upper sequence. For example, this sequence of nearly flat-lying deposits must have accumulated at a rate closely matching

that of basin subsidence, which, since the middle Miocene, has probably averaged between 150 and 300 m/10^6 years. The area of rapid accumulation is near the outfalls of major Alaskan rivers (e.g. Yukon and Kuskokwim), and, during the Neogene, the outer Bering Sea shelf was periodically swept by marine transgressions and regressions (Hopkins, 1967; Hopkins and Scholl, 1970). These factors argue for the deposition of coarse clastics and the likely occurrence of reservoir beds in the Neogene section of the outer shelf basin areas.

Reservoir beds are also likely to occur in the lower Tertiary rocks of St. George and Amak Basins. This inference is based on the recovery of early Tertiary(?) or possibly Cretaceous sandstone from the continental slope northwest of Zhemchug Canyon (Fig. 2; Marlow and others, 1976); and, from the canyon walls, sedimentary breccia of middle Oligocene age. The present porosity of these rocks is between 20 and 30 percent; much of the primary porosity having been lost through secondary calcareous cementation. Stratigraphically equivalent beds in adjacent sub-shelf basins may still retain much of their depositional porosity.

Again, reasoning on general grounds, it can be inferred that beds of lower Tertiary sandstone and possibly conglomerate should occur near the base of some of the outer shelf basins. This interpretation is based on the concept that in the early Tertiary the forming Bering shelf basins were flanked by coastal mountains, islands, and peninsulas. These subsiding, relative highlands of deformed and intruded Mesozoic rocks probably contributed coarse clastic debris to the adjacent basins. Sediment contribution should have continued until submergence of the outer Bering Sea shelf was virtually complete, probably in Oligocene time.

Traps

Published or publicly available seismic reflection profiles are insufficient in number and quality to resolve more than the general aspects of possible hydrocarbon traps in the outer shelf basins. However, both stratigraphic and structural traps include broad anticlinal closures and tighter folds associated with normal faults. Closure and fault offset increase with stratigraphic depth; hence, growth-type structural traps formed continuously along with basin filling.

Potential stratigraphic traps are recognizable in the thinning and edging of the beds of the older stratigraphic sequence toward the flanks of some of the shelf basins (Fig. 6 and 7). These beds dip toward the axis of the basin, hence up-dip migrating fluids would in part be trapped against the much denser and less permeable rocks of the Mesozoic basement. The basin's lower stratigraphic sequence is discordantly overlapped (especially to the north) 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 the outer shelf basins, shows and limited production of oil and gas in associated basins suggest this likelihood. The separate implications of the rocks sampled at submerged outcrops, the structure and reflective characteristics of the basin fill, which is thicker than 6.5 km, and regional geologic studies combine to indicate that the outer shelf basins may be a potential oil and gas province.

ENVIRONMENTAL HAZARDS

Introduction

Major potential geologic hazards in the southern Bering Sea include faulting and earthquakes, sea floor instability due to erosion and slumping, volcanic activity, and ice. Unfortunately, public data now available are not of sufficient quality or quantity for a thorough analysis of the Bering Sea Shelf and margin. Most data consist of low-energy seismic reflection records, sediment analyses from scattered localities, and various interpretations of these data. This part of the report is based mainly on Lisitsyn (1966), Askren (1972), Nelson and others (1974) and Sharma (1974).

Despite poor data, some geologic hazards can be broadly delineated and assessed. Faulting and sea floor instability are probably the greatest potential hazards in the region, although other hazards may be important locally. We will discuss each of the above hazards in a general way, realizing that additional data are needed to properly evaluate them.

Seismicity and Faulting

Earthquakes of greater than magnitude 8 on the Richter scale have been recorded from the extreme southern part of the Bering Sea along the Aleutian arc (Sykes, 1971). We know very little about associated ground motion due to earthquakes, in the area but it probably decreases north of the Aleutian arc. Most epicenters in the southern Bering Sea lie just north of the Alaska Peninsula-Aleutian Island chain. The deeper hypocenters (>150 km) are associated with lithospheric underthrusting along the Benioff zone and are confined to the arc. However, shallow earthquake hypocenters (<70 km) occur as far north as St. George Island.

Along the Bering Sea shelf and margin the distribution of faults their age and relative movement are not well known. Faults in the St. George basin are generally trend northwest, parallel to the shelf-slope break and to the long axis of the basin, the majority of the offsets are normal faults and bound numerous grabens of halfgrabens beneath the outer shelf (Fig. 3). Deeper beds within the St. George basin are increasingly offset with depth along these faults, implying that the faults are growth-type structures. Some faults rupture the sea floor, suggesting that they are Holocene in age and probably presently active.

Sea Floor Instability

Massive movements on submarine slopes are probably distinct geologic hazards along the entire continental margin of Alaska. Along the Bering Sea margin, however, submarine slumping and slope movement are largely undocumented. We suspect that some areas of hummocky topography along the continental slope as well as in the heads of submarine canyons are probably the result of massive slumping. At present, the causes, nature, or amounts of slumping are not known. The greatest potential for slumping occurs along the shelf-slope edge at depths of about 200 m, on the adjacent deeper slope and also near the heads and sides of submarine canyons, such as Probilof and Zhemchug Canyons (Fig. 2).

Sediment Deposition and Erosion

Surficial sediment distribution across the southern Bering Sea shelf and margin is described by Lisitsyn (1966), Askren (1972) and Sharma (1974). Sediment size in the vicinity of Bristol Bay grades from coarse sand along the inner shelf to fine silt near the outer shelf, although grain size is somewhat coarser at the shelf break. Data concerning the physical properties of these sediments are unavailable, and consequently the potential for slumping and slope instability is not known.

Tsunami-, tide-, and wind-induced waves do affect sediment movement in the southern Bering Sea according to Lisitsyn (1966, p. 96-98). Earthquakes and associated tsunamis can affect shallow water sedimentary deposits. Tides also have a strong effect in shallow water, particularly in funnel-shaped estuaries such as Kuskokwim Estuary, where the tide ranges up to 8 meters and current velocities can excees 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. Wave-generated forces can redistribute large volumes of sediment in a relatively short time and thereby may be hazards to man-made structures on the sea floor.

Volcanic Activity

The Bering Sea shelf and margin is 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 euption, 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 man-made structures and also shake loose pre-existing, unstable, and undercompacted sediment bodies.

Ice

Parts of the southern Bering Sea continental margin and shelf have ice cover during 0 to 50% of the year. Ice development is at its maximum in March and April when average ice thicknesses range from 1 to 1.5 m (Lisitsyn, 1966, p. 99). Both stationary and migration ice can occur. Stationary ice forms 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; man-made structures, pipelines and ports may be affected by ice-ramming and bottom scouring.

ESTIMATES OF UNDISCOVERED RECOVERABLE OIL AND GAS RESOURCES

Introduction

Estimates of undiscovered recoverable hydrocarbon resources for the Bering Sea shelf were derived by aggregating individual estimates for the four major provinces of the shelf: Navarin, St. Matthew-Hall, Bristol basins, and the Zhemchug-St. George basin complex. The combined basinal area of the Bering Sea shelf south of St. Lawrence Island comprises approximately (367,780 km^2) 142,000 square miles and contains in excess of (683,552 km^3) 164,000 cubic miles of prospective sedimentary rock. The appraisal of these provinces is based on a study by Miller and others (1975), and utilizes volumetric and analog methods.

It is statistically estimated that the mean undiscovered recoverable resources of oil beneath the Bering Sea shelf is 2.4 billion barrels; the 95 and 5 percent probability estimates range from 0[1/] to 6.2 billion barrels respectively. The estimate of the mean undiscovered recoverable resources of natural gas is 6.0 trillion cubic feet, and the same probability range is 0[1/] to 15.5 trillion cubic feet.

Areal Limit of Appraisals

The greater part of the Bering Sea shelf lies in water depths of less than 200 meters, with the exception of the shelf-edge portion of Navarin and Zhemchug-St. George provinces.

1/ '0': with marginal probability assigned.

Only those areas of the Navarin and Zhemchug-St. George basins that lie within the 200 meter water depth limit are appraised in this report. In addition, appraisal calculations for Navarin basin province exclude the U.S.S.R. portion of that province west of the 1867 U.S.-U.S.S.R. Convention Line (Figure 21). Portions of the Bering Sea shelf that are underlain by thin sedimentar sections (less than 500 meters) are also excluded because they are considered to be non-prospective for oil and gas.

Appraisal Procedures

The procedures for estimating undiscovered recoverable resources are provided in detail in Circular 725 (Miller and others, 1975, pages 20-26) and include:

1. Volumetric techniques using geologic analogs and setting upper and lower hydrocarbon yield limits through comparisons with a number of known areas.
2. Volumetric estimates with an arbitrary general yield factor applied in cases where direct analogs are unknown.
3. Application of Hendricks' (1965) potential-area categories.
4. Comparison of all published and documented resource estimates to estimate values generated by the above methods.

The Resource Appraisal Group (U. S. Geological Survey, Denver, Colorado) after reviewing the available geologic and appraisal data, made estimates of undiscovered recoverable resources, both individually and in group session. After review, these estimates resulted in a final consensus "raw" set of estimates of undiscovered recoverable oil and gas. The appraisal was made by a subjective probability technique involving an initial set of estimates, assuming the existence of commercial oil and gas in each of the provinces. The technique is as follows:

1. A low resource estimate corresponding to a 95 percent probability (19 in 20 chance) that there is at least that amount present.
2. A high resource estimate with a 5 percent probability (1 in 20 chance) that there is at least that amount present.
3. A modal estimate of the resource amount that the estimator ascertains as most probable.

In addition to the foregoing, a corollary probability assessment was also made regarding the assumption, or condition, that commercial oil and/or gas does exist in the appraisal area. In the initial appraisal, the assumption is made that oil and gas do exist in commercial quantities. This assumption cannot be made with certainty, however, in frontier areas such as the Bering Sea shelf, where no hydrocarbons have been discovered. It was therefore necessary to assign a marginal probability[1/] to the event, "commercial oil found" and the event, "commercial gas found". The probability of finding oil and/or gas in commercial quantities beneath the Bering Sea shelf south of St. Lawrence Island is estimated at 80 percent (See Fig. 22 and note that the oil and gas lognormal curves are initiated at the 80 percent probability level).

Geologic and volumetric yield analogs were applied to the four provinces of the Bering Sea shelf in order to provide approximate values of hydrocarbon yield. Analogs are limited to the United States and Canada and include Salinas,

1/ For detailed discussion in marginal probability, see Miller and others (1975, p. 23-25).

Ventura, MacKenzie, Cook Inlet and Norton basins (Norton basin has not been drilled). Several of these analog areas are not directly comparable to the Bering Sea shelf and thus the analog calculations are considered highly uncertain.

The potential-area categories 2, 3 and 4 of Hendricks (1965, Table 5) were also applied to the provinces of the Bering Sea shelf in order to develop a range of values. In addition, all published and documented resource estimates were compared to the estimate values generated by both the volumetric-analog and the potential area method. Values derived by the Resource Appraisal Group for the Bering Sea shelf were limited to between 5 and 95 percent of the probability range as well as the modal (most likely) estimate for undiscovered recoverable oil and gas resources. These values of low (95 percent), high (5 percent), modal estimate, and marginal probability are the "raw" data that were subsequently statistically analyzed.

A lognormal distribution was fitted by computer to the high, low and modal value of the raw estimates to compute the probability distribution for each province (Kaufman, 1962). These estimates were aggregated through a Monte Carlo computer procedure to yield the probability distribution curves for the Bering Sea shelf and include the associated marginal probability.

The curves of total oil and total gas potential for the Bering Sea shelf include the full range of probability values and are shown in Fig. 22. The curves can be used to provide estimates of undiscovered recoverable resources at any chosen probability. For example, the estimate of undiscovered recoverable oil at the one percent probability is approximately 7.7 billion barrels, the 95 percent probability is zero, and the 5 percent probability is 6.2 billion barrels.

Summary of Oil and Gas Resource Estimates

Estimates of undiscovered recoverable oil and gas resources for the Bering Sea shelf, exclusive of the Norton Basin, are shown in Figure 22 and are summarized in the following table:

Table 3. Estimates of undiscovered recoverable resources in the Bering Sea shelf south of St. Lawrence Island, Alaska.

	Aggregate Totals		
	95% Prob	5% Prob	Stat Mean
Oil (billions of barrels)	0	6.2	2.4
Gas (trillions of cubic feet)	0	15.5	6.0

At present there have been no oil or gas discoveries beneath the Bering Sea shelf. The marginal probability of finding oil and/or gas in commercial quantities in this frontier area is approximately 80 percent, corresponding to a 20 percent probability of finding no oil or gas in commercial quantities.

FIGURE CAPTIONS

Figure 1. Physiographic diagram of the Bering Sea shelf and margin. Drawing by Tau Rho Alpha. From and Marlow and others (1975).

Figure 2. Trackline chart of surveys across the Bering Sea margin. Heavy tracklines with hour ticks are the lines of profiles shown in Figures 12, 13, and 14. Base map is from Scholl and others (1974).

Figure 3. Generalized geologic map of western Alaska, the Alaska Peninsula, and eastern Siberia. Onshore geology is modified from Burk (1965), Beikman (1974), and Yanshin (1966). Offshore outlines of the subshelf basins, ridges, and Nunivak arch from Figure 16. The offshore extension of the Kaltag fault is diagrammatic in that the expression of the fault beneath the shelf may include all of St. Matthew basin.

Figure 4. Alaska Peninsula index map from locations of wells drilled into the Bristol Bay basin.

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

Figure 6. 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).

Figure 7. Composite columnar section of the Nushagak lowlands, from Mertie (1938).

Figure 8. Generalized regional cross-section across the Bethel and Nushagak lowlands, the Alaska Peninsula, Shelikof Straits, and Kodiak Island. Based on geology in Beikman (1974), Burk (1965), Hoare (1961), Hoare and Coonrad (1961), and Mertie (1938). Lithologic symbols after Beikman (1974).

Figure 9. Stratigraphic section of the central part of the Anadyr basin, U.S.S.R., based on seismic interpretations by Dolzhanskyi and others (1966).

Figure 10. Index map showing location of Anadyr basin, U.S.S.R., as well as a structure contour map of Anadyr basin showing local uplifts and locations of exploratory wells.

Figure 11. Interpretative drawing of seismic reflection profile S-16 across the southern Bering shelf. For location of the profile see Fig. 2. Travel time, in seconds, is two - way time. Kilometer scale is for water depths only, based on an assumed velocity of sound in seawater of 1.5 km/sec.

Figure 12. Interpretative drawing of seismic reflection profile S-5 across the central Bering shelf. For location of the profile see Figure 2 and for explanation see Figure 11.

Figure 13. Interpretative drawing of seismic reflection profile B-92 across the northwestern Bering shelf. For location of the profile see Figure 2 and for explanation see Figure 11.

Figure 14. Curve of total sediment thickness versus one-way travel time of sound in sediment for the Bering shelf.

Figure 15. Structure contour map of acoustic basement. Derived in part from Scholl and others (1968) and Scholl and Hopkins (1969). Some of the control lines are shown in Figure 2 but other lines not shown are from M. Holmes of the University of Washington (written commun., 1974).

Figure 16. Profile map of total field magnetic anomalies over the Bering shelf south of 63^{o}N. Data in western Bristol Bay are from Pratt and others (1972) and unpublished NOAA (U.S. Dept. of Commerce) profiles. Some lines are from Kienle (1971) and unpublished profiles of the Geological Survey of Canada. The earth's regional magnetic field has been removed using the standard IGRF programs (IAGA Commission, 1969). No corrections were made for magnetic storms or diurnal effects.

Figure 17. Profile map of free-air gravity anomalies over the Bering shelf south of 63^{o}N. Positive anomalies are shaded. Sources of data are as for Figure 16.

Figure 18. Speculative outlines of Mesozoic and earliest Tertiary structural elements of the Alaska Peninsula, Bering Sea margin, and eastern Siberia. Magmatic arc is though to consist of calc-alkalic volcanic and plutonic rocks. Both now form the basement rocks beneath the outer Bering shelf. Outlines drawn north of St. Matthew Island are from Patton and others (1976), those on and near the Alaska Peninsula are from Burk (1965, 1972), Pratt and others (1972), and Moore (1974); the boundaries over the central outer shelf are from this study.

Figure 19. Generalized stratigraphic cross-section of Bristol Bay basin along the Alaska Peninsula. Modified from Brockway and others (1975). See Fig. 5 for columnar section of Bristol Bay and Alaska Peninsula regions.

Figure 20. Columnar section of Vostochno-Ozero No. 1 well drilled in Anadyr basin, U.S.S.R., showing gas zones, porosities and permeabilities.

Figure 21. Index map of Alaska showing boundaries of major onshore and offshore petroleum provinces and the area of the Bering Sea shelf appraised in this report (hachured) and Miller and others (1975).

Figure 22. Lognormal probability distribution of total undiscovered recoverable oil and gas resources for the Bering Sea shelf south of St. Lawrence Island.

TABLE 1. SEDIMENTARY BA [illegible] HE BERING SHELF

BASIN NAME	LOCATION	LENGTH km (mi)	WIDTH km (mi)	AREA km^2 (mi^2)	DEFINING CONTOUR FOR AREA km (Feet)	VOLUME km^3 (mi^3)	DEPTH TO DEEPEST PART km (Feet)	PERCENT OF BASIN WITH WATER DEPTH LESS THAN 200 m
Navarin	60.0°N 177.0°W	400 (250)	190 (120)	80,000 (31,000)	2.0 (6,500)	400,000 (96,000)	>6.5 (>21,000)	85
St. George	56.0°N 167.0°W	300 (190)	50 (31)	12,000 (4,700)	3.0 (9,800)	56,000 (13,400)	>6.5 (>21,000)	100
St. Matthew	62.0°N 169.0°W	280 (174)	40 (25)	9,200 (3,500)	1.0 (3,200)	4,600 (1,100)	1.34 (4,400)	100
Zhemchug	58.0°N 174.5°W	100 (60)	30 (20)	2,500 (1,000)	2.0 (6,500)	860 (200)	2.75 (9,000)	20
Inner	58.0°N 171.5°W	130 (80)	15 (9)	1,600 (600)	1.5 (5,000)	1,200 (300)	1.7 (5,500)	100
Pribilof	56.2°N 170.0°W	100 (60)	20 (12)	1,200 (500)	2.0 (6,500)	1,200 (300)	4.0 (13,000)	75
Walrus	58.2°N 173.0°W	100 (60)	10 (6)	700 (300)	1.5 (5,000)	520 (120)	2.0 (6,500)	100
Otter	57.8°N 171.5°W	90 (56)	10 (6)	600 (230)	1.5 (5,000)	460 (110)	1.7 (5,500)	100
Hall	61.4°N 171.2°W	70 (44)	10 (6)	450 (170)	1.0 (3,200)	220 (50)	1.2 (3,900)	100
Dalnoi	56.8°N 173.0°W	40 (25)	10 (6)	400 (150)	1.5 (5,000)	300 (70)	1.8 (5,900)	100
Garden	56.7°N 170.5°W	20 (12)	10 (6)	130 (50)	1.5 (5,000)	100 (20)	1.5 (4,900)	100

Table 2. Dredge Samples from t[illegible] Bering Sea Continental Slope

Sample	Location	Latitude Longitude	Depth (m)	Dominant Rock Type	Age	Porosity (%)	Bulk Density (gm/cc)	Organic Carbon as % C	Comments
TT-1	Inner gorge of Pribilof Canyon		1600	Diatomaceous mudstone (acoustic basement)	Cretaceous (Campanian)	--	--	0.62	Hopkins and others, 1969 Fossil control
70-B101-1S1	South of Zhemchug Canyon	58°14.5'N 174°01.1'W	900-1000	Calcareous diatomaceous mudstone	Late Pleistocene	--	--	--	Fossil control
70-B101-1S2	South of Zhemchug Canyon	58°14.5'N 174°01.1'W	900-1000	Calcareous diatomaceous mudstone	Late Miocene	59	1.10	--	Fossil control
70-B97-1S1	South wall of Zhemchug Canyon	58°17.2'N 174°49.0'W	1300-1500	Diatomaceous siltstone	Middle or Late Miocene	57	1.04	--	Fossil control
70-B97-1S2	South wall of Zhemchug Canyon	58°17.2'N 174°49.0'W	1300-1500	Lithic (metasedimentary and volcanic rock fragments) pebbly conglomerate	Middle Oligocene	29	1.88	0.34	Fossil control
70-B93-3	Southwest of St. Matthew Island	59°09.2'N 178°27.2'W	450-650	Calcareous wacke	Pliocene-Pleistocene	14	2.28	0.29	Fossil control
70-B92-3S1	Near base of continental slope southwest of St. Matthew Island	59°33.1'N 178°54.7'W	2400-2600	Calcareous argillite	--	21	2.05	0.41	
70-B92-3S2	Near base of continental slope southwest of St. Matthew Island	59°33.1'N 178°54.7'W	2400-2600	Calcareous lithic wacke	--	21	2.06	0.22	
70-B92-3S3	Near base of continental slope southwest of St. Matthew Island	59°33.1'N 178°54.7'W	2400-2600	Diatomaceous siltstone	Middle Pliocene	--	--	--	Fossil control
70-B92-3S5	Near base of continental slope southwest of St. Matthew Island	59°33.1'N 178°54.7'W	2400-2600	Calcareous lithic pebbly wacke	--	17	2.18	0.25	
70-B92-3S7	Near base of continental slope southwest of St. Matthew Island	59°33.1'N 178°54.7'W	2400-2600	Calcareous lithic (metasedimentary and volcanic rock fragments) calcareous wacke	--	--	--	<0.10	

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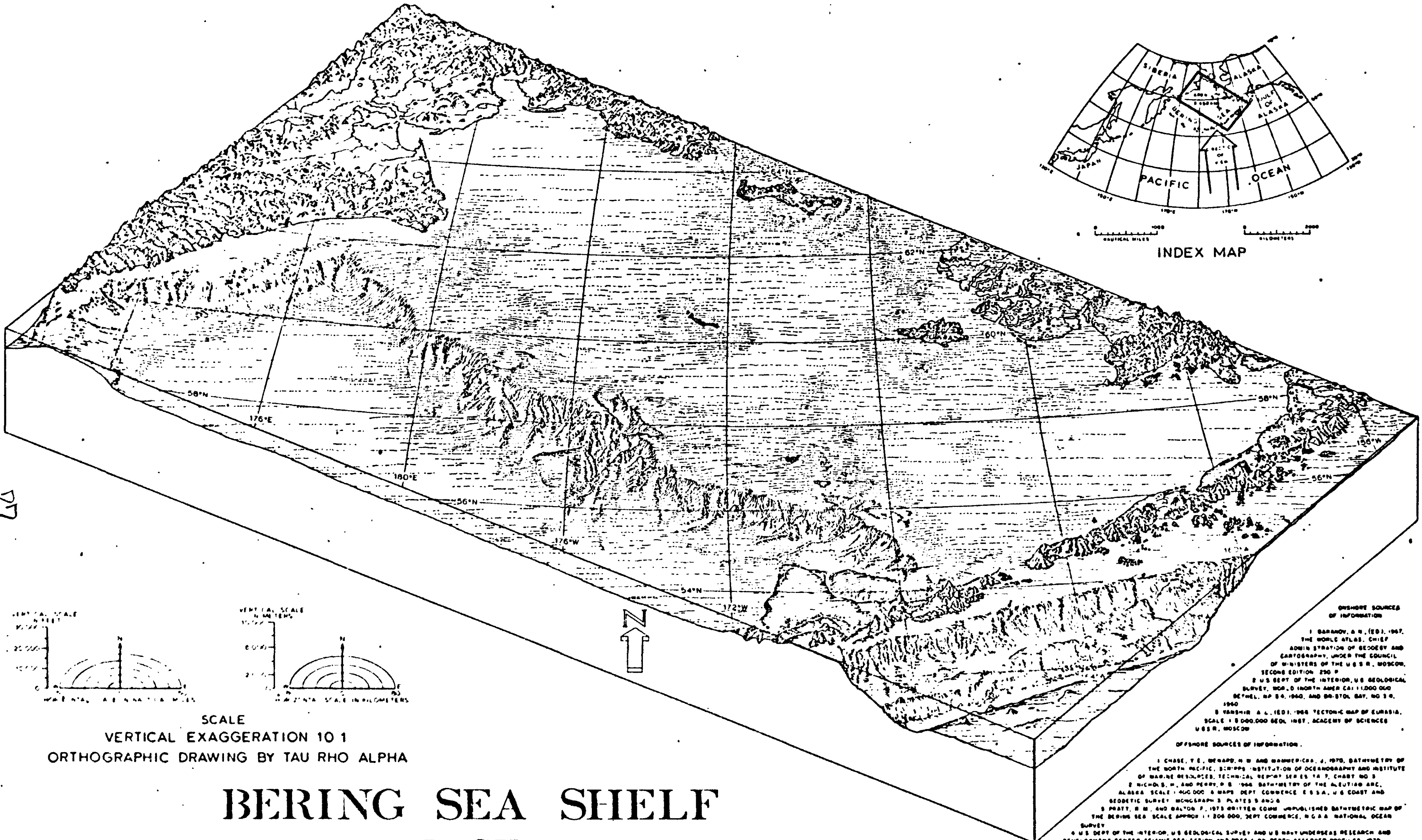

SCALE

VERTICAL EXAGGERATION 10 1

ORTHOGRAPHIC DRAWING BY TAU RHO ALPHA

BERING SEA SHELF

ALASKA

ONSHORE SOURCES OF INFORMATION

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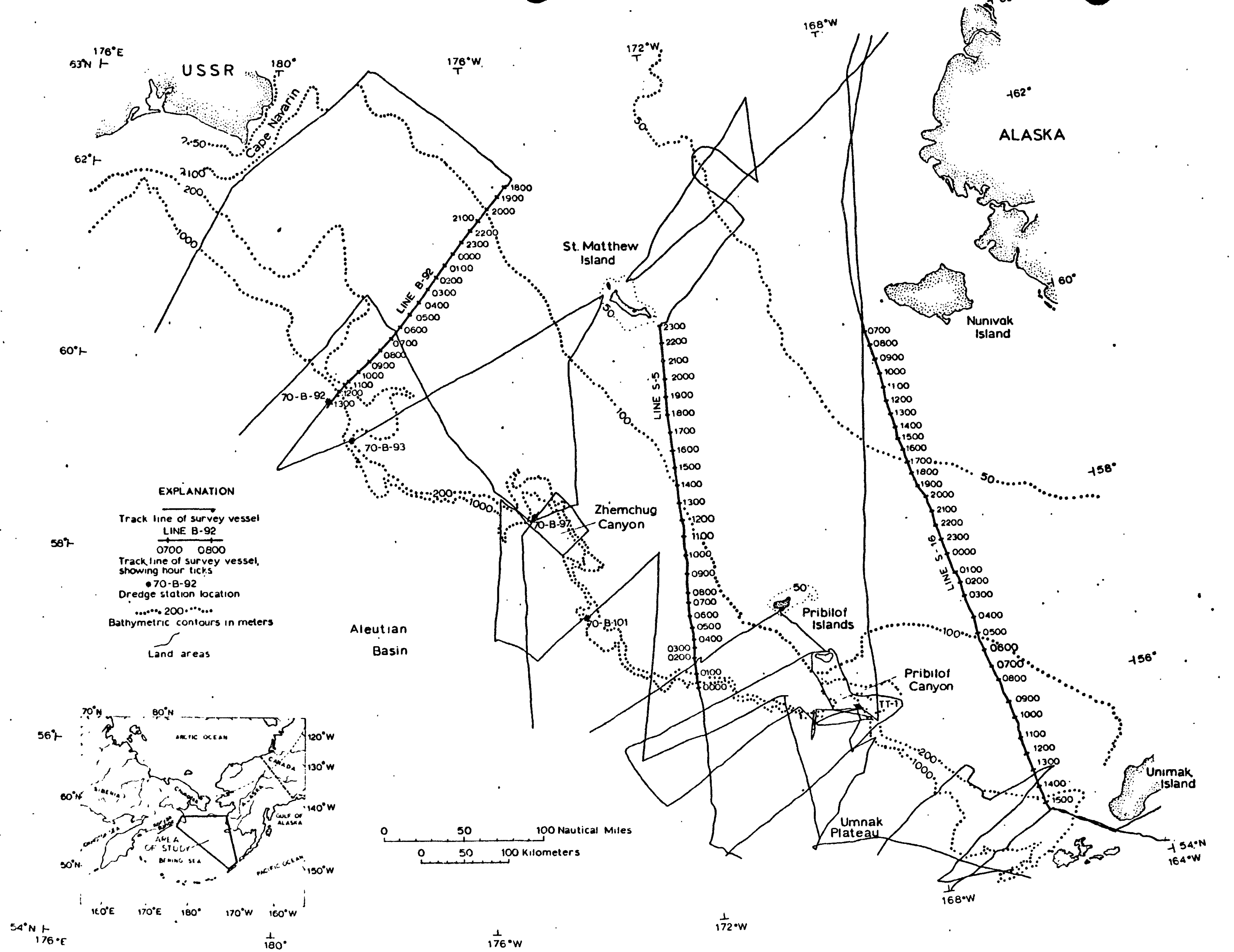
4 U S DEPT OF THE INTERIOR, U S GEOLOGICAL SURVEY AND U S NAVY UNDERSEAS RESEARCH AND DEVELOPMENT CENTER SEISMIC REFLECTION AND PRECISION DEPTH RECORDER PROFILES, 1970

U S GEOLOGICAL SURVEY


USSR
Cape Navarin
ALASKA
Nunivak Island
St. Matthew Island
Pribilof Islands
Pribilof Canyon
Zhemchug Canyon
Umnak Plateau
Unimak Island
Aleutian Basin
LINE B-92
LINE S-5
LINE S-16
70-B-92
70-B-93
70-B-97
70-B-101
TT-1
EXPLANATION
Track line of survey vessel
LINE B-92
0700 0800
Track line of survey vessel, showing hour ticks
70-B-92
Dredge station location
200
Bathymetric contours in meters
Land areas
0 50 100 Nautical Miles
0 50 100 Kilometers
ARCTIC OCEAN
CANADA
SIBERIA
GULF OF ALASKA
AREA OF STUDY
BERING SEA
PACIFIC OCEAN
70°N
80°N
60°N
50°N
120°W
130°W
140°W
150°W
160°E
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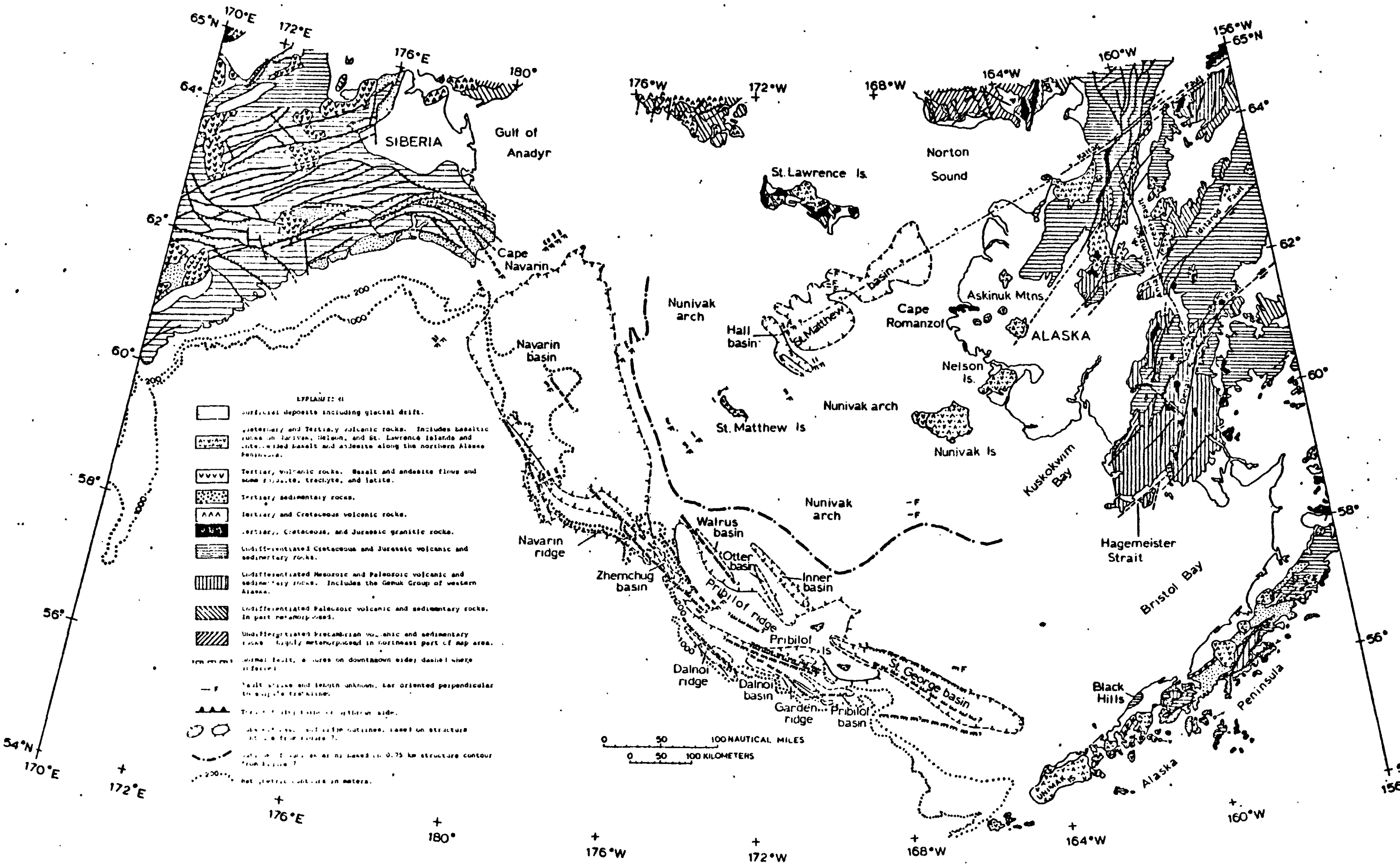

65°N
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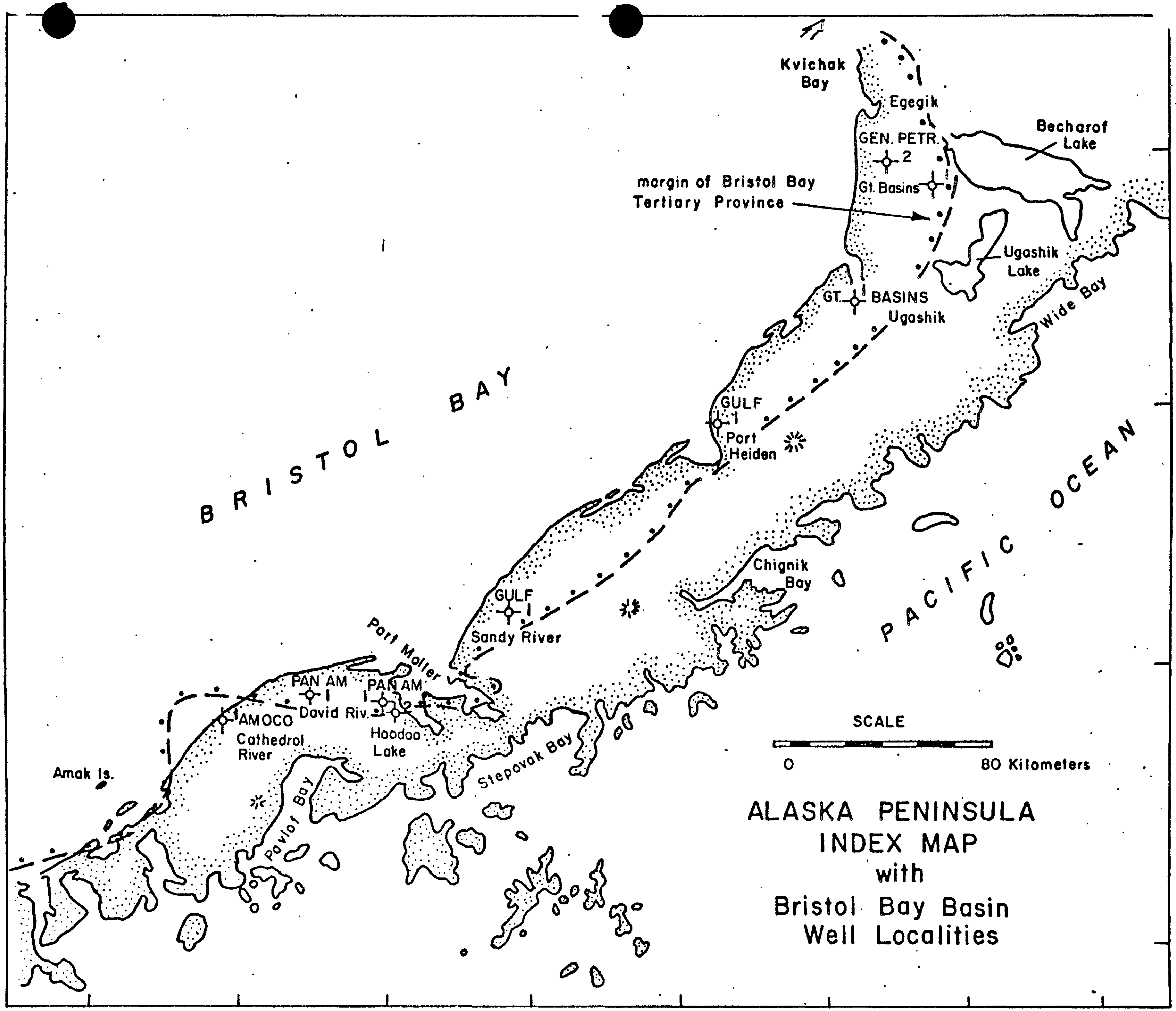
180°
176°W
172°W
168°W
164°W
160°W
156°W
65°N
SIBERIA
Gulf of Anadyr
Cape Navarin
Navarin basin
Navarin ridge
Zhemchug basin
Walrus basin
Otter basin
Inner basin
Pribilof ridge
Pribilof Is
St George basin
Dalnoi ridge
Dalnoi basin
Garden ridge
Pribilof basin
Nunivak arch
Hall basin
St. Matthew basin
St. Matthew Is
St. Lawrence Is.
Norton Sound
Cape Romanzof
Askinuk Mtns.
ALASKA
Nelson Is.
Nunivak Is
Kuskokwim Bay
Hagemeister Strait
Bristol Bay
Black Hills
Alaska Peninsula
Unimak Is.
200
1000
0 50 100 NAUTICAL MILES
0 50 100 KILOMETERS

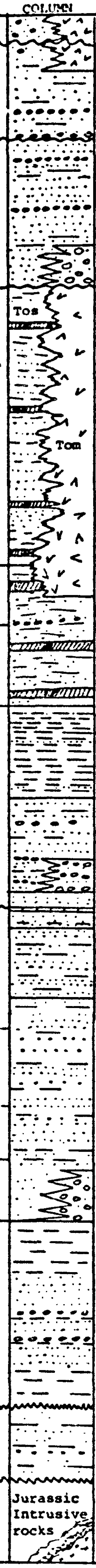


ALASKA PENINSULA
INDEX MAP
with
Bristol Bay Basin
Well Localities
SCALE
0
80 Kilometers
BRISTOL BAY
PACIFIC OCEAN
Kvichak Bay
Egegik
Becharof Lake
GEN. PETR. 2
Gt. Basins
margin of Bristol Bay Tertiary Province
Ugashik Lake
GT. BASINS
Ugashik
Wide Bay
GULF 1
Port Heiden
Chignik Bay
GULF 1
Sandy River
Port Moller
PAN AM 1
David Riv.
PAN AM 1
2
Hoodoo Lake
AMOCO
Cathedral River
Amak Is.
Pavlof Bay
Stepovak Bay
58°
57°
56°
55°
163°
162°
161°
160°
159°
158°
157°
156°

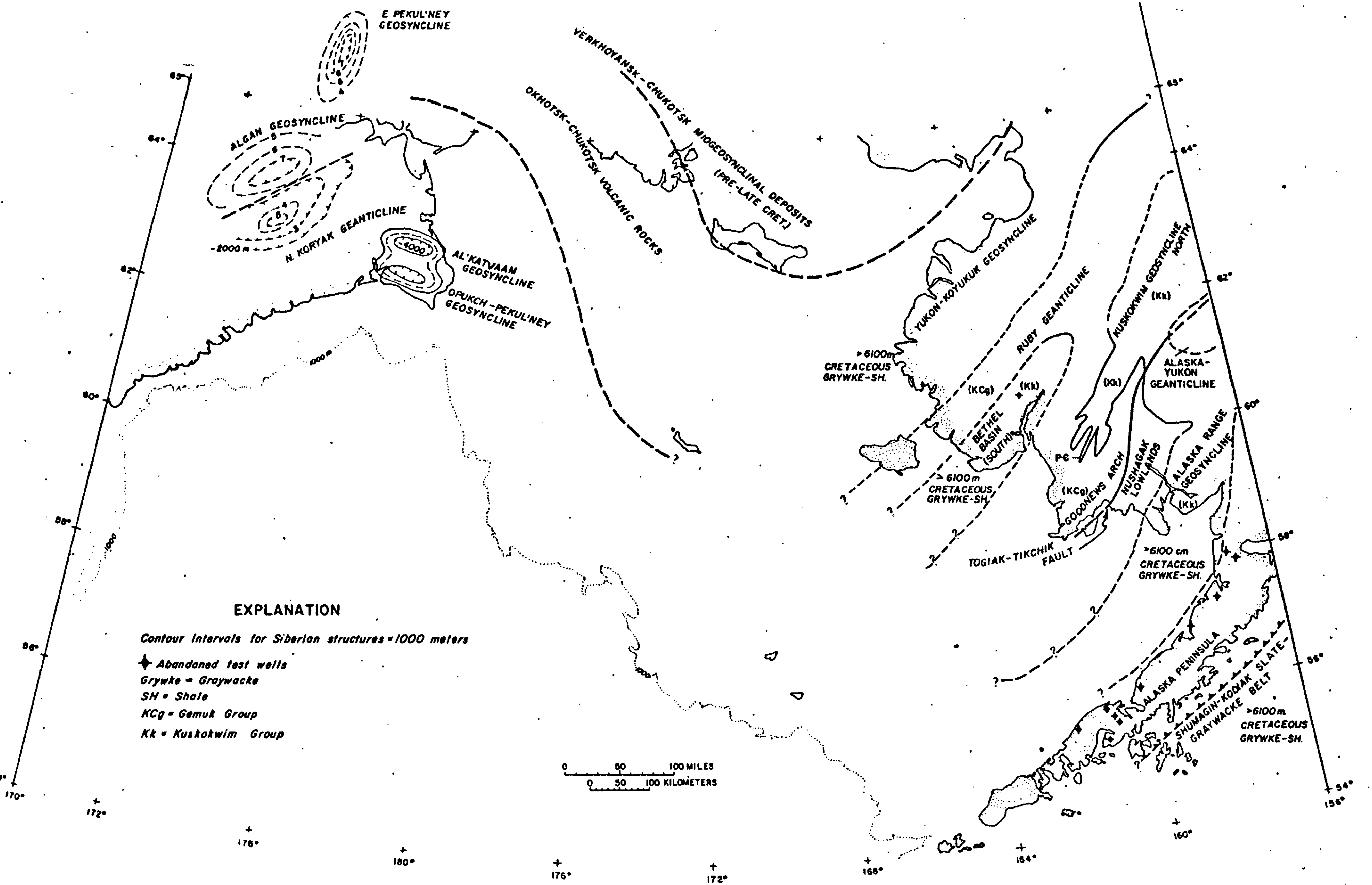
Figure 4

COMPOSITE COLUMNAR SECTION

BRISTOL BAY AND ALASKA PENINSULA REGIONS, ALASKA*



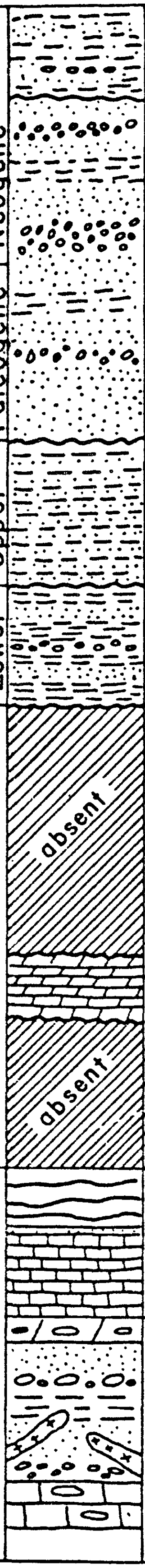
Era	Period	Epoch / Stage	Formation	Description
	Q		Quaternary-Recent Volcanics 300 m ±	Unconsolidated sediments and volcanic rocks.
CENOZOIC	TERTIARY	PLIOCENE	Milky River Fm (Tpm) 920 m +	Conglomeratic rocks, sandstone and mudstone; clastic frac. Volcanic derived, fossiliferous, marine and nonmarine.
		MIOCENE	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.
		OLIGOCENE	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.
		EOCENE / PALEOCENE	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.
MESOZOIC	LATE CRETACEOUS	SENONIAN	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.
	E. CRETACEOUS	NEOCOM	Herendeen Ls (Khl) 150 m	Calcarenite with abundant Inoceramus prisms.
			Staniukovich Fm (Jks) 610 m	Feldspathic sandstone and arkose, thin siltstone, locally abundant Buchia; shallow marine environment.
	LATE JURASSIC	PORTLAND. / KIMM.	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 Buchia and belemnites; shallow marine to neritic environment.
		OXFORD.	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.
	MIDDLE JURASSIC	CALLOVIAN		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.
		BAJO.	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.



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

Figure 6

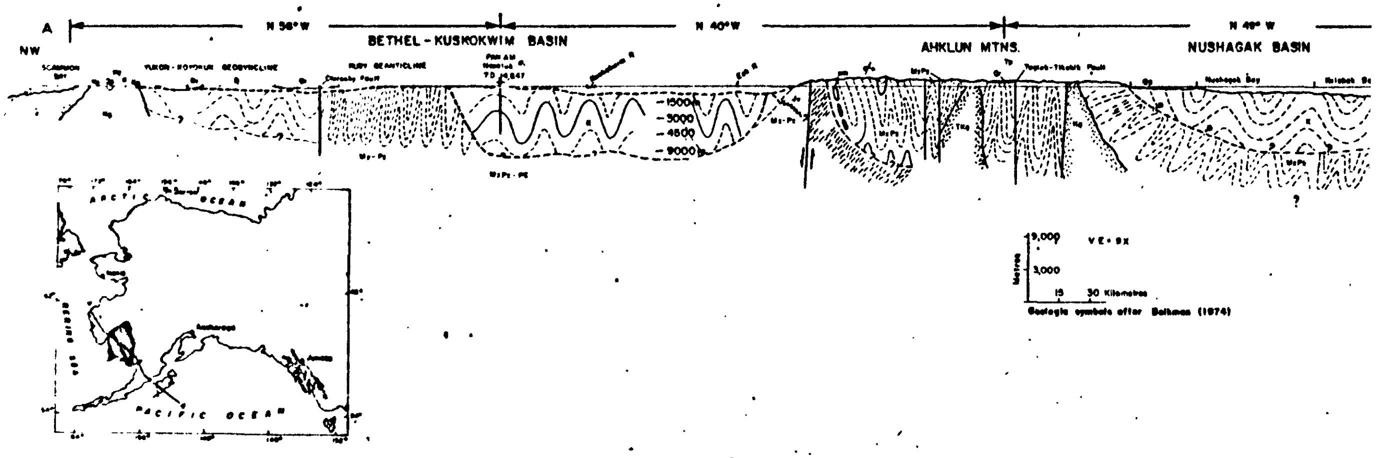
COMPOSITE COLUMNAR SECTION NUSHAGAK LOWLANDS, ALASKA



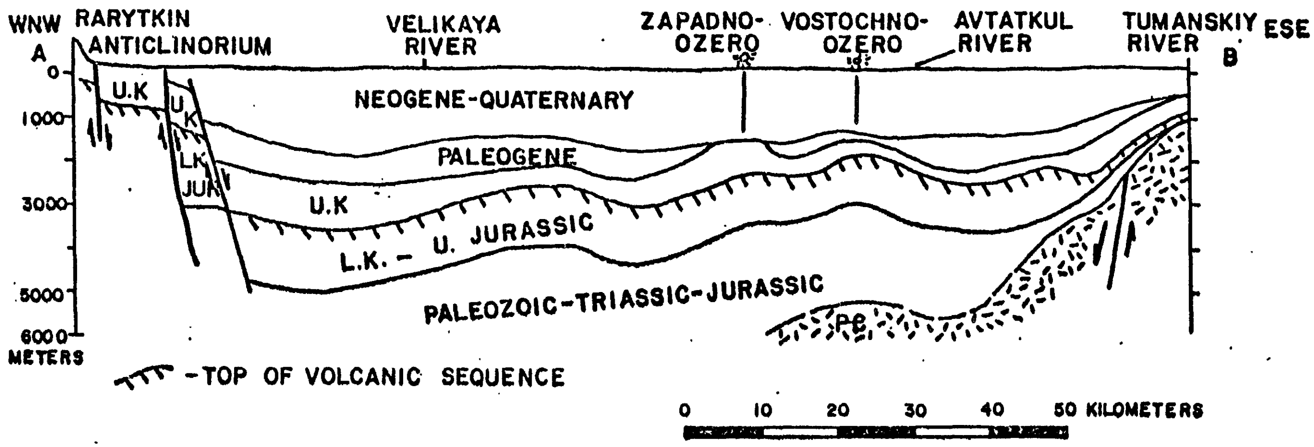
AGE			FORMATION	DESCRIPTION
CENOZOIC	Q.		Holocene Quaternary	Unconsolidated glacial and post-glacial sand and gravel.
CENOZOIC	Tertiary	Neogene / Paleogene	Nushagak Fm. Spurr (1900) (thickness unknown)	Stratified gravel, coarse sandstone, arkose, and clay. Locally cross bedded and folded; nearshore marine-nonmarine 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			
MESOZOIC	Triassic		(thickness unknown) Noric Stage	Unnamed-thoroughly recrystallized white to cream colored limestone and limestone conglomerate. Contains pseudomonotis, myochoncha, placites.
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).

From Mertie (1938)

Figure 7


A
NW
N 56°W
BETHEL - KUSKOKWIM BASIN
RUBY GEANTICLINE
N 40°W
AHKLUN MTNS.
N 49° W
NUSHAGAK BASIN
Nushagak Bay
Togiak-Tikchik Fault
-1500
-3000
-4600
-9000
9,000
3,000
Metres
VE = 9X
15
30 Kilometres
Geologic symbols after Beikman (1974)
ARCTIC OCEAN
BERING SEA
PACIFIC OCEAN

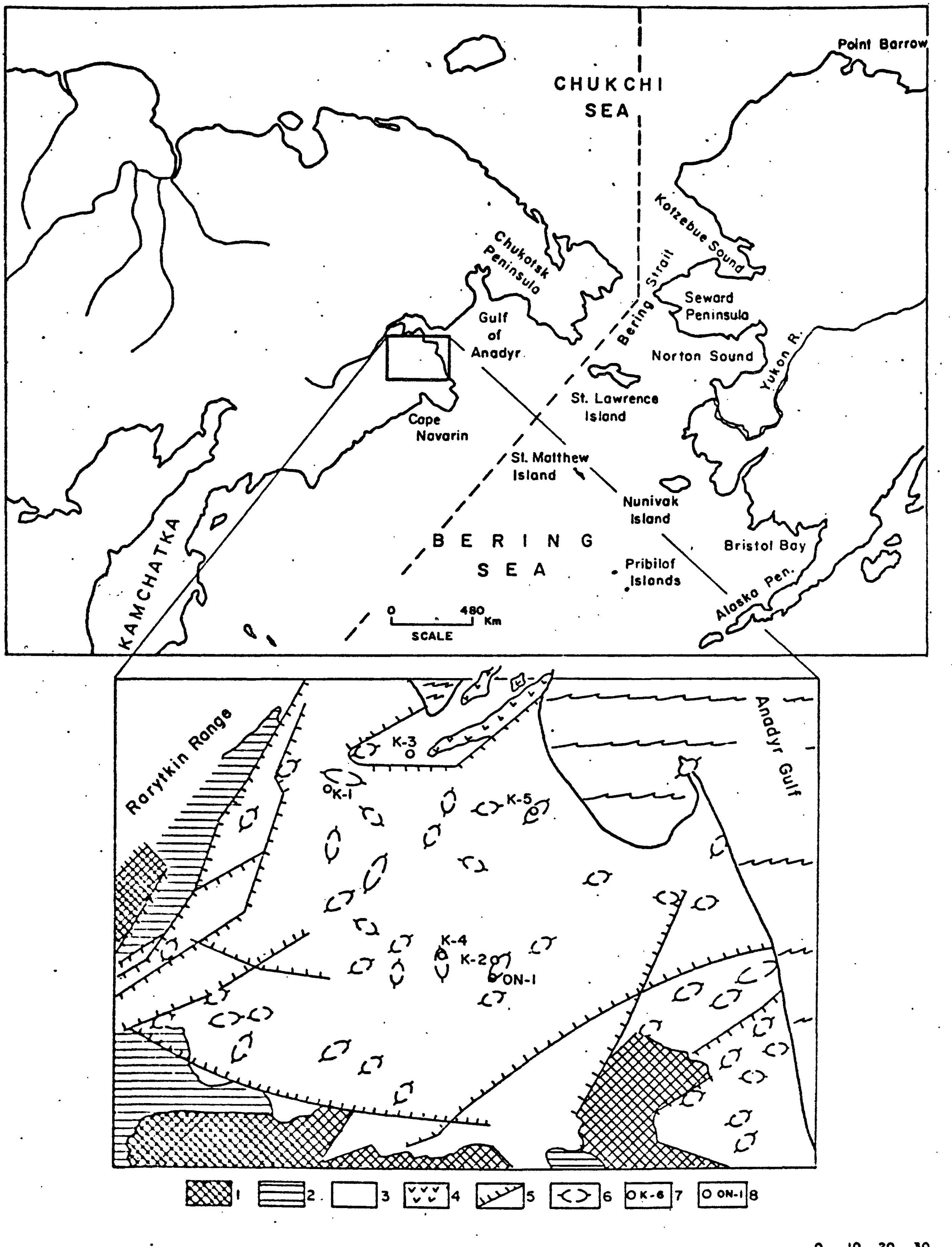
F8



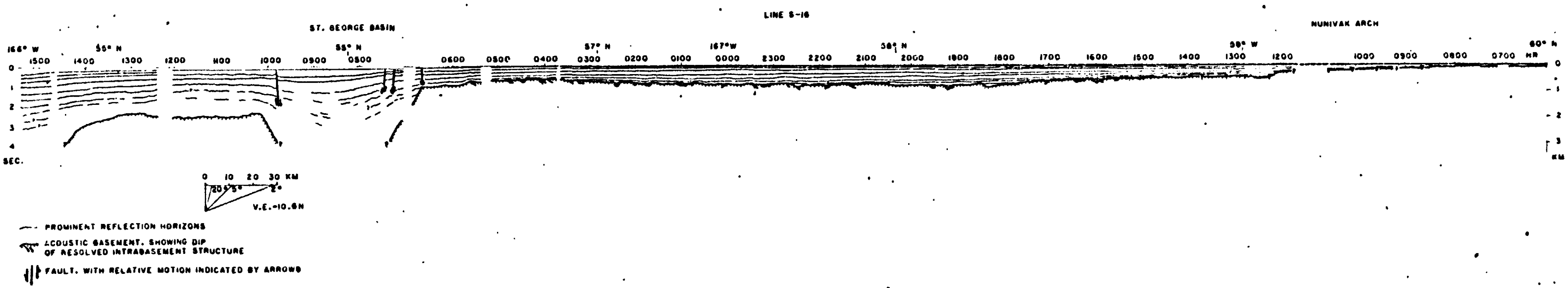
SEISMIC CROSS SECTION, ANADYR BASIN
From Dolzhanskii and others (1966)
and
Meyerhoff (1972[b])

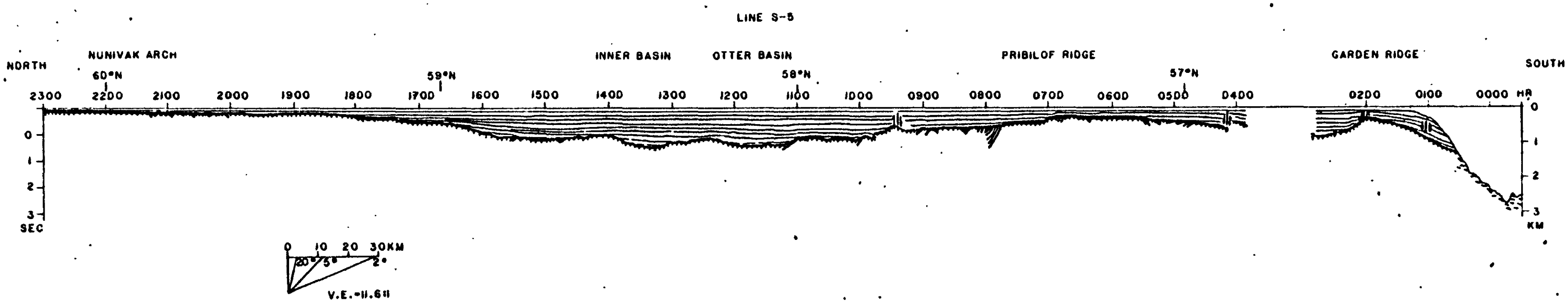
Figure 7

INDEX MAP AND GEOLOGY ANADYR BASIN

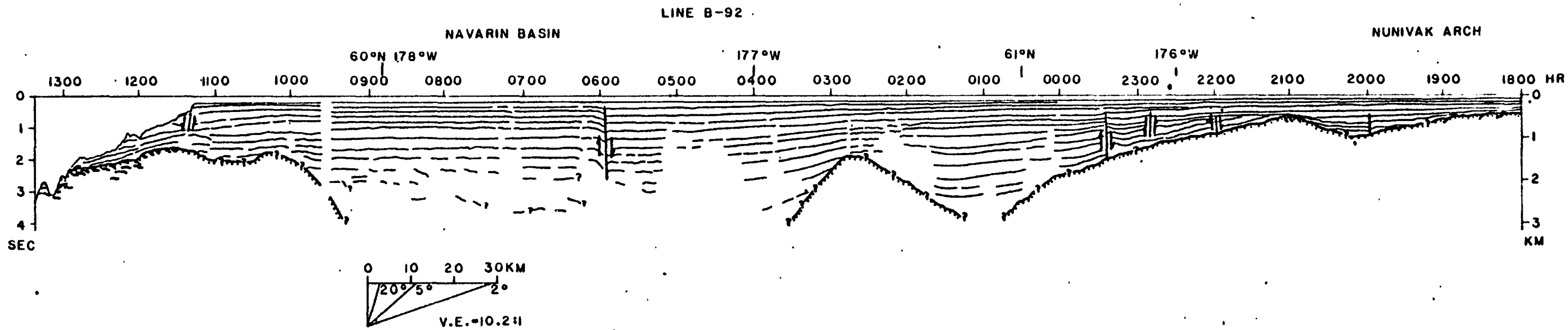


1- Late Mesozoic
2- Albian-Senonian
3- Cenozoic-Late Senonian
4- Cenozoic volcanics
5- Faults
6- Local uplifts
7- Structural wells
8- Stratigraphic Well No. 1 (Exploratory)


LINE S-16
ST. GEORGE BASIN
NUNIVAK ARCH
166° W
55° N
56° N
57° N
167°W
58° N
59° W
60° N
HR
SEC.
KM
0 10 20 30 KM
V.E.=10.6X
PROMINENT REFLECTION HORIZONS
ACOUSTIC BASEMENT, SHOWING DIP OF RESOLVED INTRABASEMENT STRUCTURE
FAULT, WITH RELATIVE MOTION INDICATED BY ARROWS


LINE S-5
NORTH
SOUTH
NUNIVAK ARCH
INNER BASIN
OTTER BASIN
PRIBILOF RIDGE
GARDEN RIDGE
60°N
59°N
58°N
57°N
2300 2200 2100 2000 1900 1800 1700 1600 1500 1400 1300 1200 1100 1000 0900 0800 0700 0600 0500 0400 0200 0100 0000 HR
0 1 2 3 SEC
0 1 2 3 KM
0 10 20 30KM
20° 5° 2°
V.E.=11.6:1

12


LINE B-92
NAVARIN BASIN
NUNIVAK ARCH
60°N 178°W
177°W
61°N
176°W
1300 1200 1100 1000 0900 0800 0700 0600 0500 0400 0300 0200 0100 0000 2300 2200 2100 2000 1900 1800 HR
0 1 2 3 4 SEC
0 1 2 3 KM
0 10 20 30KM
20° 5° 2°
V.E.=10.2:1

Preliminary Report on the Regional Geology, Oil and Gas Potential and Environmental Hazards of the Bering Sea Shelf South of St. Lawrence Island, Alaska

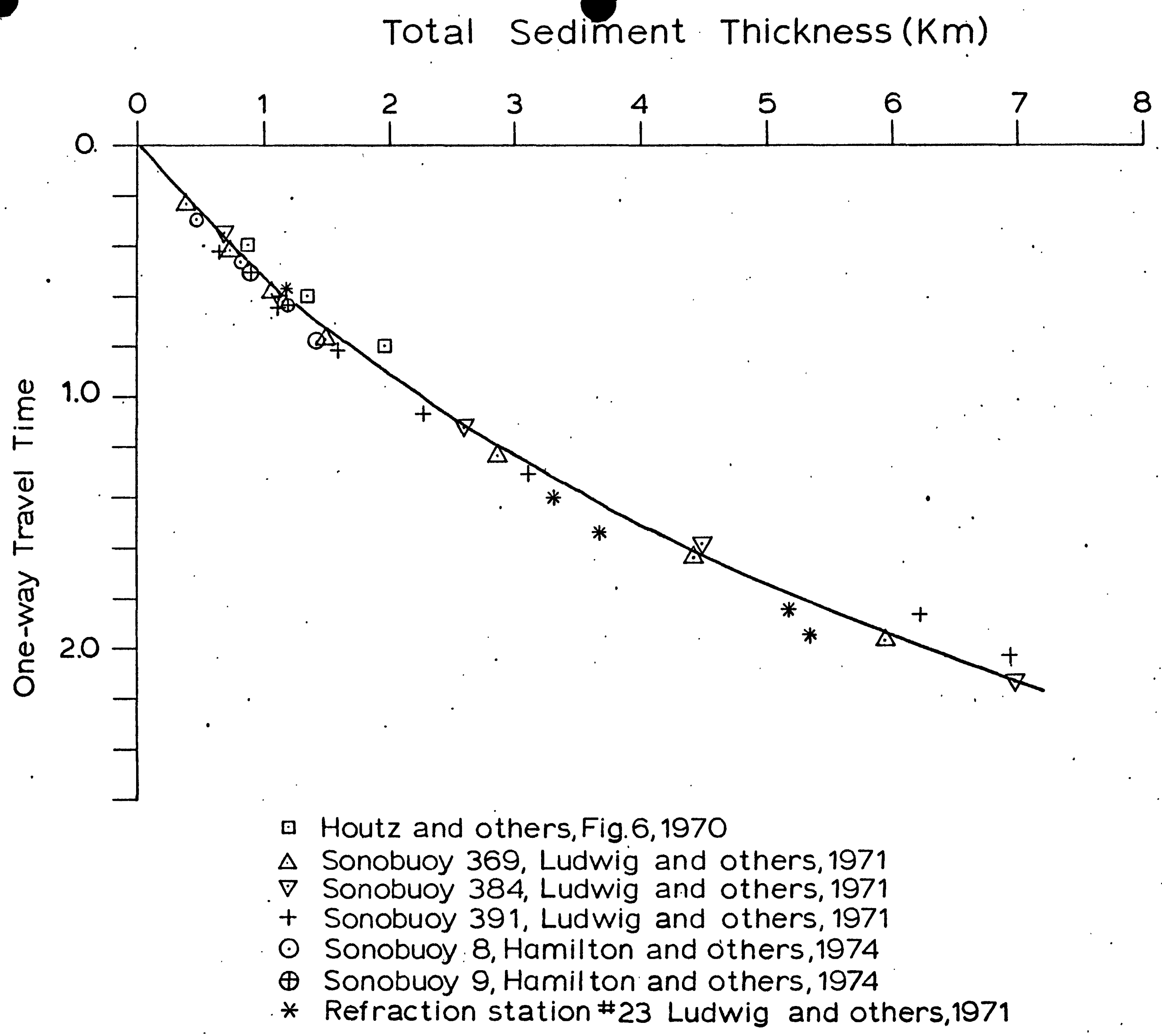
by

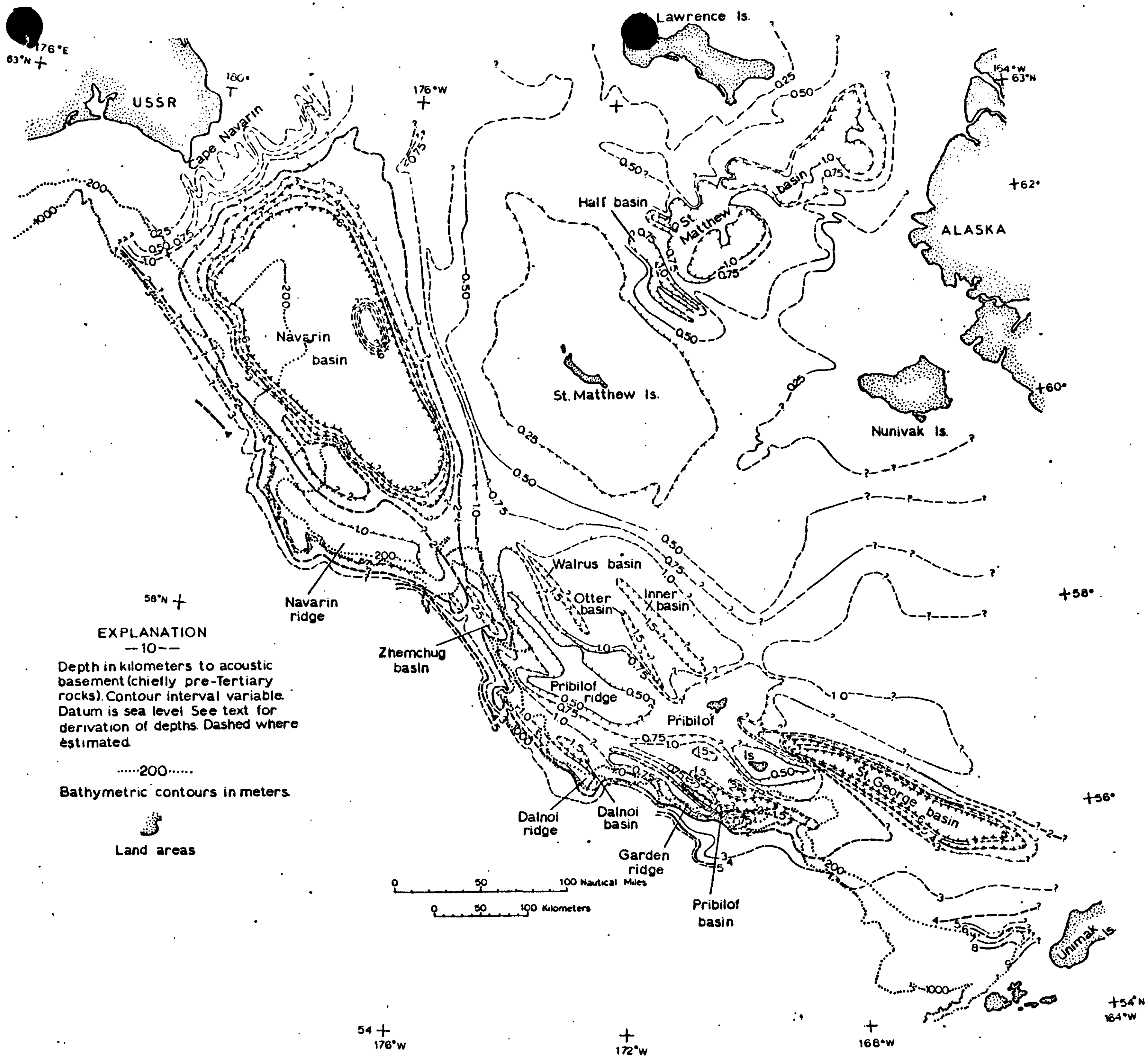
Michael S. Marlow, Hugh McLean, Tracy L. Vallier, David W. Scholl
James V. Gardner and Richard B. Powers

ABSTRACT

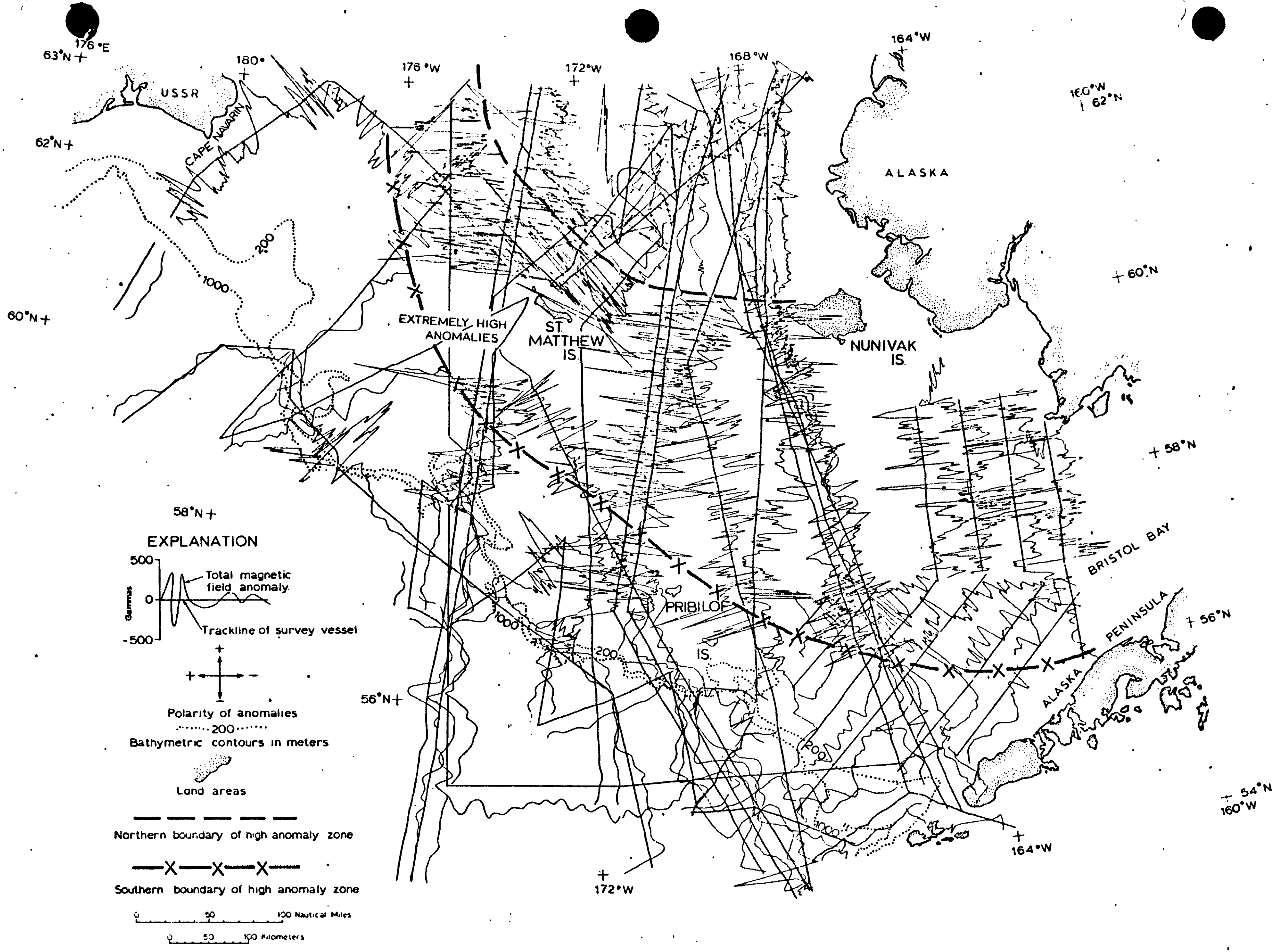
The Bering Sea shelf is underlain by at least 11 basins that are prospective sites for hydrocarbon accumulations. Ranging in areal size from 130 km^2 (50 mi^2) to 246,000 km^2 (95,000 mi^2) these basins encompass a combined area over 546,000 km^2 (211,000 mi^2), larger than the size of the state of California. The majority of the basins are either elongate graben half (asymmetric) grabens, or structural sags and lie beneath flat sea floor of the shelf. Geophysical data indicate that two of the basins, St. George and Navarin, contain more than 10 km (6.2 mi) of Upper Cretaceous(?) and Cenozoic sedimentary strata.

The inner shelf is underlain by a broad basement high, Nunivak arch, the western or seaward half of which is characterized by an arcuate belt of high-frequency and high-amplitude magnetic anomalies. This zone of intense magnetic anomalies along the shelf is probably the signature of a Mesozoic magmatic arc that extends from southwestern Alaska to eastern Siberia and consists of Jurassic to Cretaceous plutonic and volcanic rocks. We speculate that this magmatic arc resulted from oblique convergence and subduction in the Mesozoic between the Kula(?) and North America plates along the eastern Bering Sea margin. Folding and uplift

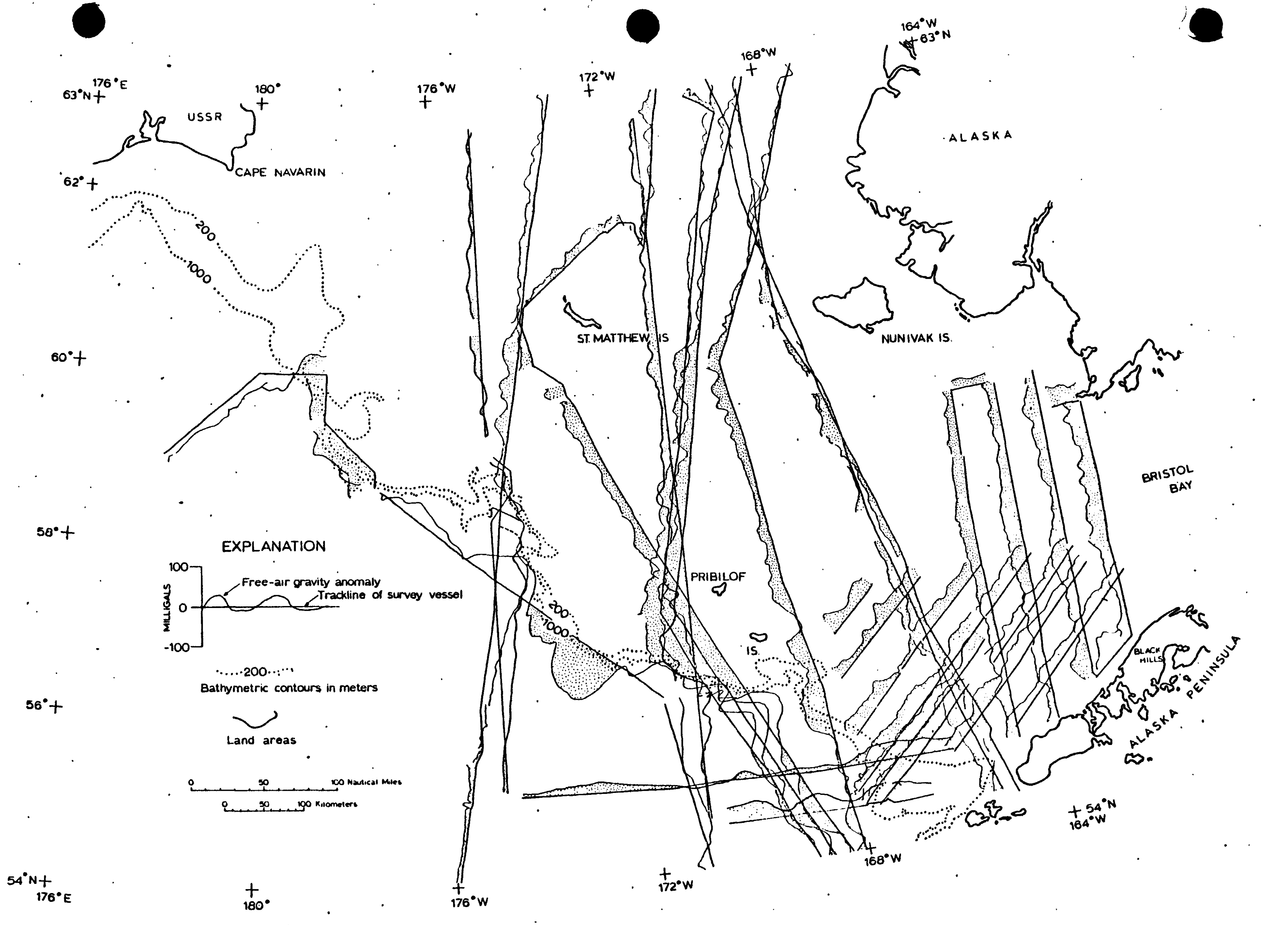

Total Sediment Thickness (Km)
0
1
2
3
4
5
6
7
8
0.
1.0
2.0
One-way Travel Time
Houtz and others, Fig. 6, 1970
Sonobuoy 369, Ludwig and others, 1971
Sonobuoy 384, Ludwig and others, 1971
Sonobuoy 391, Ludwig and others, 1971
Sonobuoy 8, Hamilton and others, 1974
Sonobuoy 9, Hamilton and others, 1974
Refraction station #23 Ludwig and others, 1971

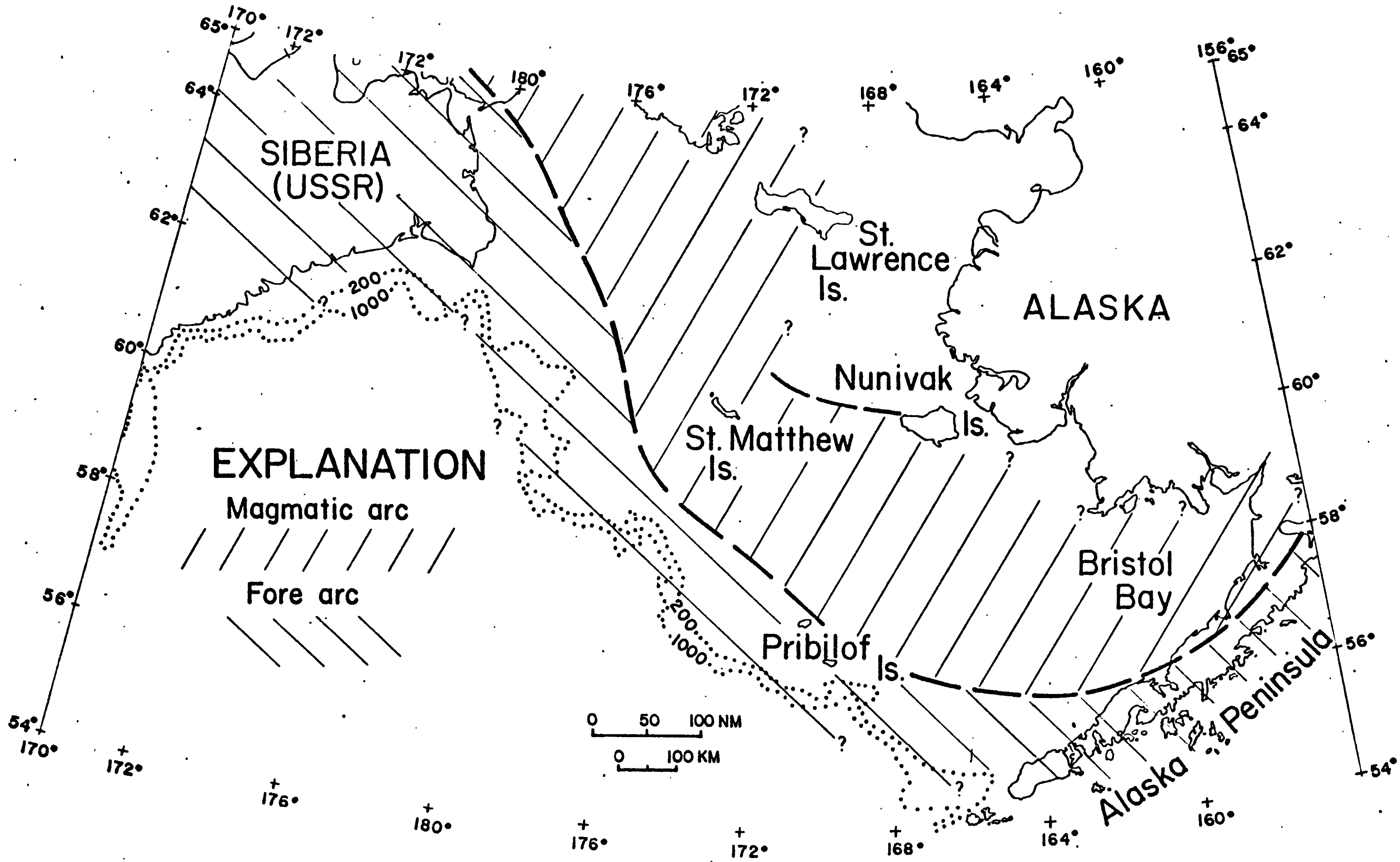

USSR
Cape Navarin
Lawrence Is.
ALASKA
Half basin
St. Matthew basin
St. Matthew Is.
Nunivak Is.
Navarin basin
Navarin ridge
Zhemchug basin
Walrus basin
Otter basin
Inner X basin
Pribilof ridge
Pribilof Is
St. George basin
Dalnoi ridge
Dalnoi basin
Garden ridge
Pribilof basin
Unimak Is.
EXPLANATION
—10—
Depth in kilometers to acoustic basement (chiefly pre-Tertiary rocks). Contour interval variable. Datum is sea level. See text for derivation of depths. Dashed where estimated.
·····200·····
Bathymetric contours in meters.
Land areas
0 50 100 Nautical Miles
0 50 100 Kilometers
176°E 63°N
180°
176°W
164°W 63°N
62°
60°
58°
56°
58°N
54°N 164°W
54 176°W
172°W
168°W

15

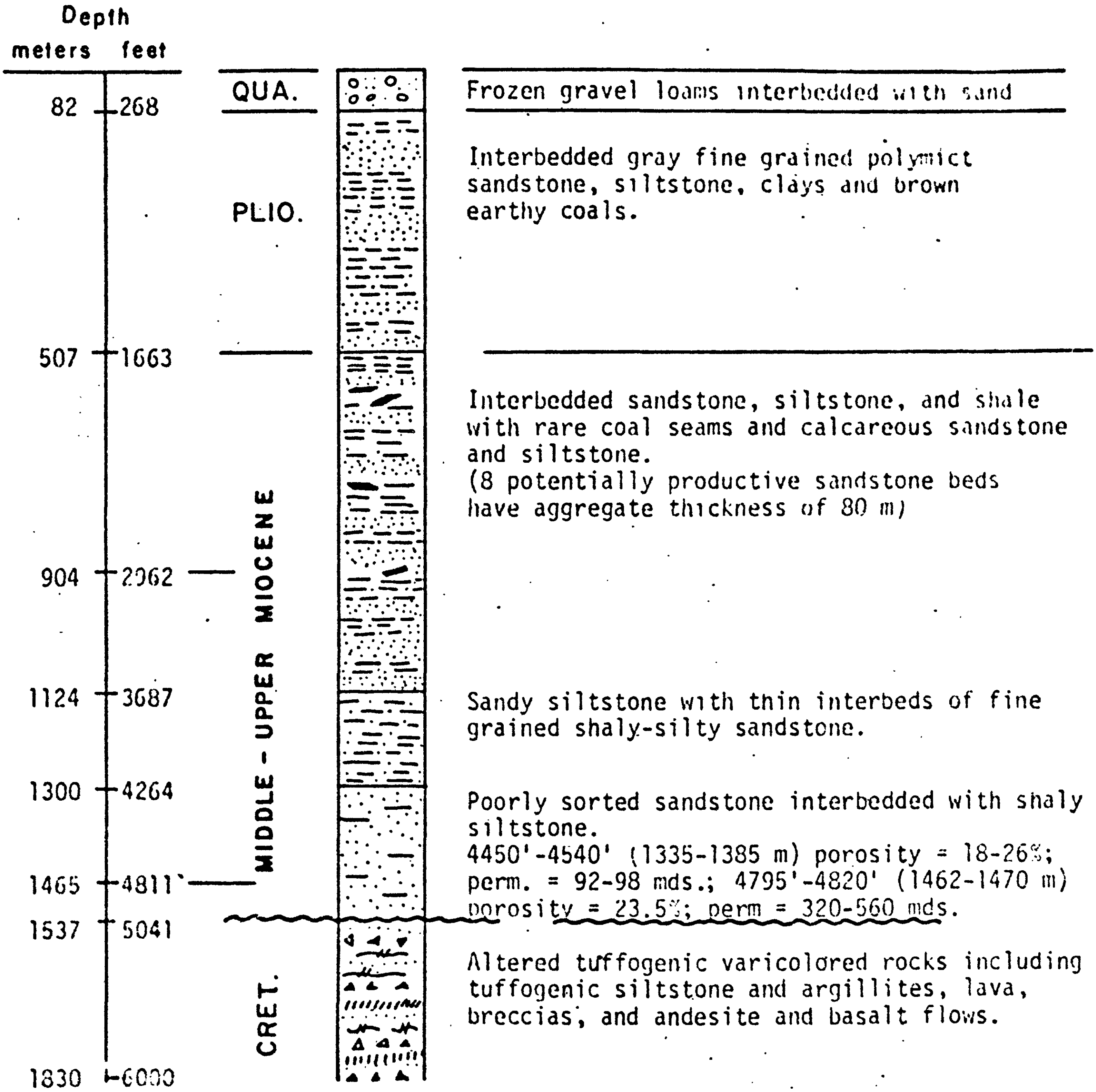

63°N 176°E
180°
176°W
172°W
168°W
164°W
160°W 62°N
USSR
CAPE NAVARIN
62°N
ALASKA
60°N
200
1000
EXTREMELY HIGH ANOMALIES
ST. MATTHEW IS.
NUNIVAK IS.
58°N
BRISTOL BAY
PRIBILOF IS.
56°N
ALASKA PENINSULA
54°N 160°W
164°W
172°W
EXPLANATION
500
0
-500
Gammas
Total magnetic field anomaly
Trackline of survey vessel
Polarity of anomalies
200
Bathymetric contours in meters
Land areas
Northern boundary of high anomaly zone
Southern boundary of high anomaly zone
0 50 100 Nautical Miles
0 50 100 Kilometers

16


63°N 176°E
180°
176°W
172°W
168°W
164°W 63°N
USSR
CAPE NAVARIN
ALASKA
62°
200
1000
60°
ST. MATTHEW IS.
NUNIVAK IS.
BRISTOL BAY
58°
EXPLANATION
100
0
-100
MILLIGALS
Free-air gravity anomaly
Trackline of survey vessel
PRIBILOF IS.
200
1000
BLACK HILLS
ALASKA PENINSULA
200
Bathymetric contours in meters
56°
Land areas
0 50 100 Nautical Miles
0 50 100 Kilometers
54°N 164°W
54°N 176°E
180°
176°W
172°W
168°W

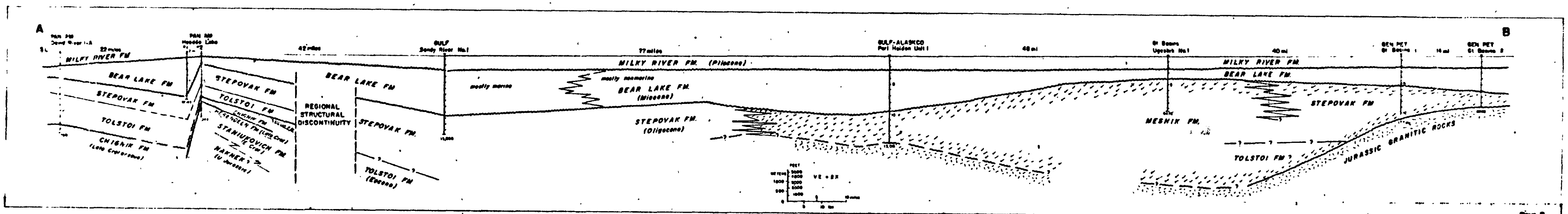

SIBERIA
(USSR)
ALASKA
St.
Lawrence
Is.
Nunivak
Is.
St. Matthew
Is.
Pribilof
Is.
Bristol
Bay
Alaska
Peninsula
EXPLANATION
Magmatic arc
Fore arc
200
1000
0 50 100 NM
0 100 KM

VOSTOCHNO-OZERO NO. 1
or
STRATIGRAPHIC WELL NO. 1



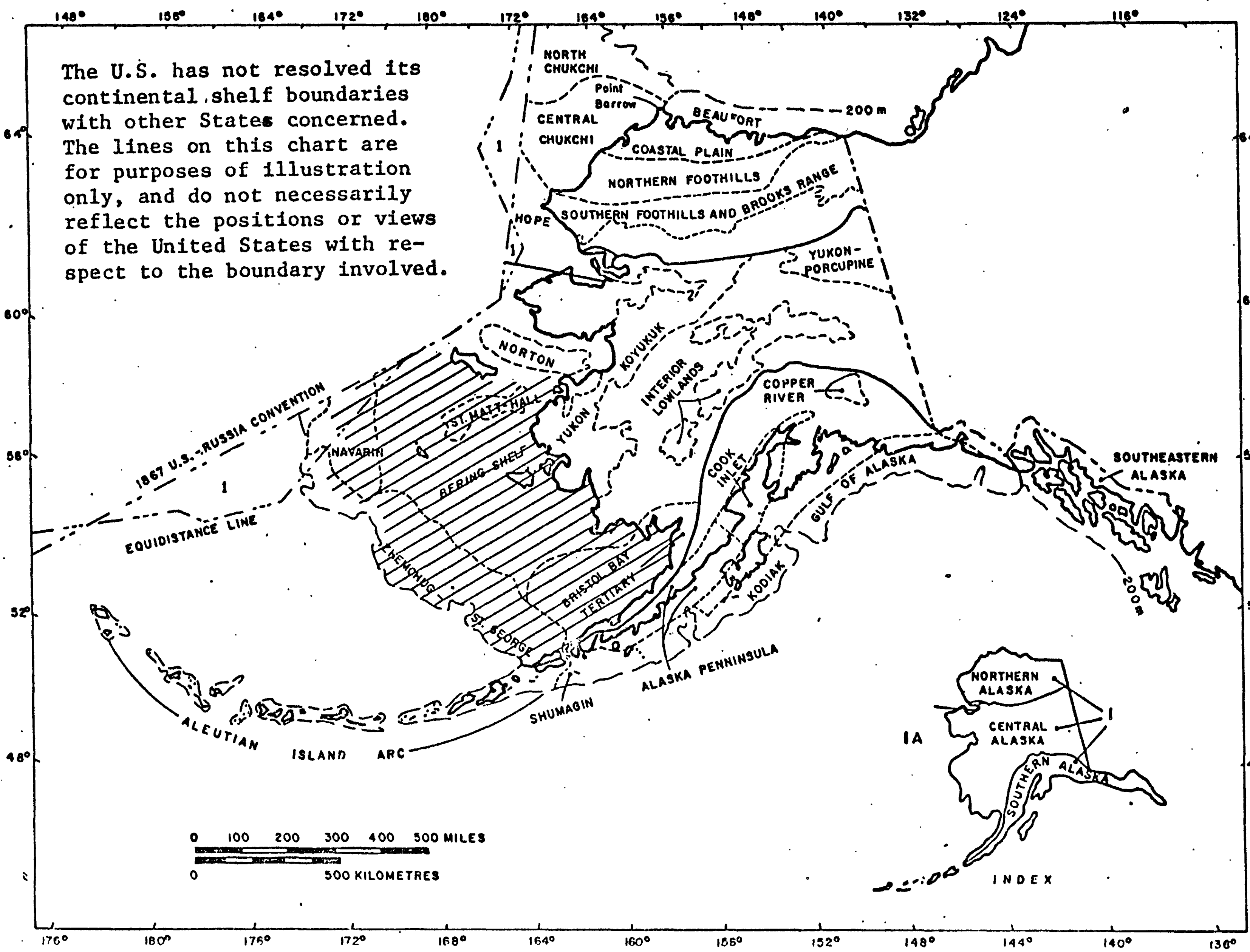
From Agapitov and others (1970)

Figure 20

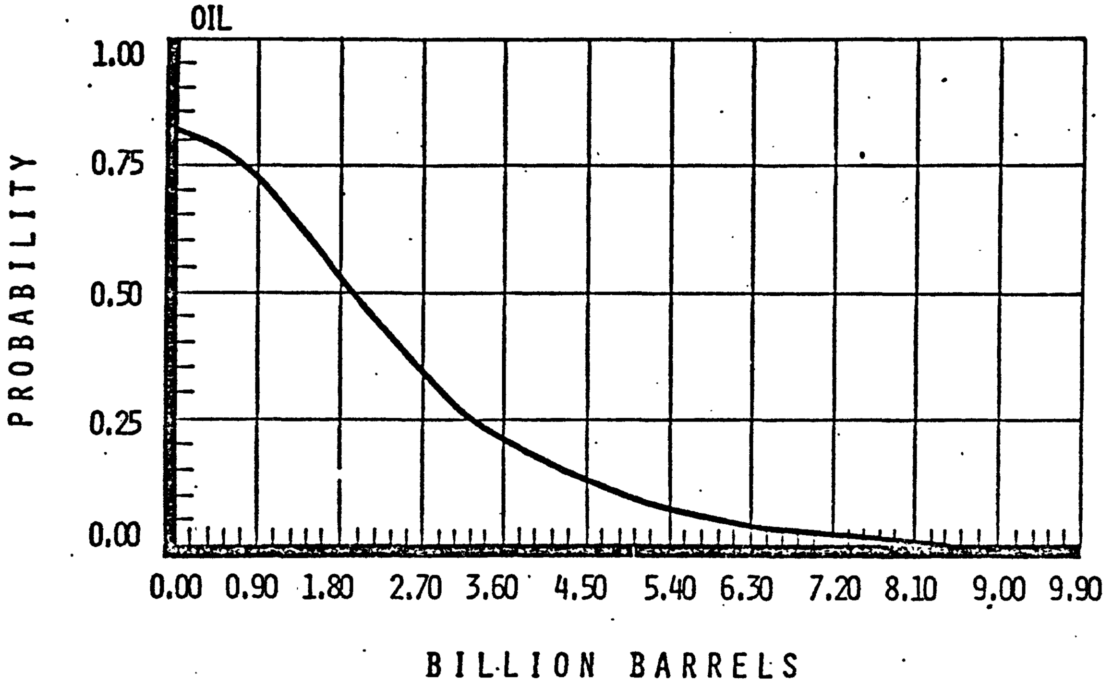


Modified from Brockway and others (1975)

Figure


The U.S. has not resolved its continental shelf boundaries with other States concerned. The lines on this chart are for purposes of illustration only, and do not necessarily reflect the positions or views of the United States with respect to the boundary involved.
NORTH CHUKCHI
Point Barrow
CENTRAL CHUKCHI
BEAUFORT
200 m
COASTAL PLAIN
NORTHERN FOOTHILLS
SOUTHERN FOOTHILLS AND BROOKS RANGE
HOPE
YUKON-PORCUPINE
NORTON
KOYUKUK
INTERIOR LOWLANDS
COPPER RIVER
YUKON
ST. MATT-HALL
NAVARIN
BERING SHELF
1867 U.S.-RUSSIA CONVENTION
EQUIDISTANCE LINE
COOK INLET
GULF OF ALASKA
SOUTHEASTERN ALASKA
KODIAK
BRISTOL BAY TERTIARY
ST. GEORGE
ALASKA PENNINSULA
SHUMAGIN
ALEUTIAN ISLAND ARC
0 100 200 300 400 500 MILES
0 500 KILOMETRES
NORTHERN ALASKA
CENTRAL ALASKA
SOUTHERN ALASKA
IA
INDEX

BERING SHELF -
SOUTH OF ST. LAWRENCE ISLAND



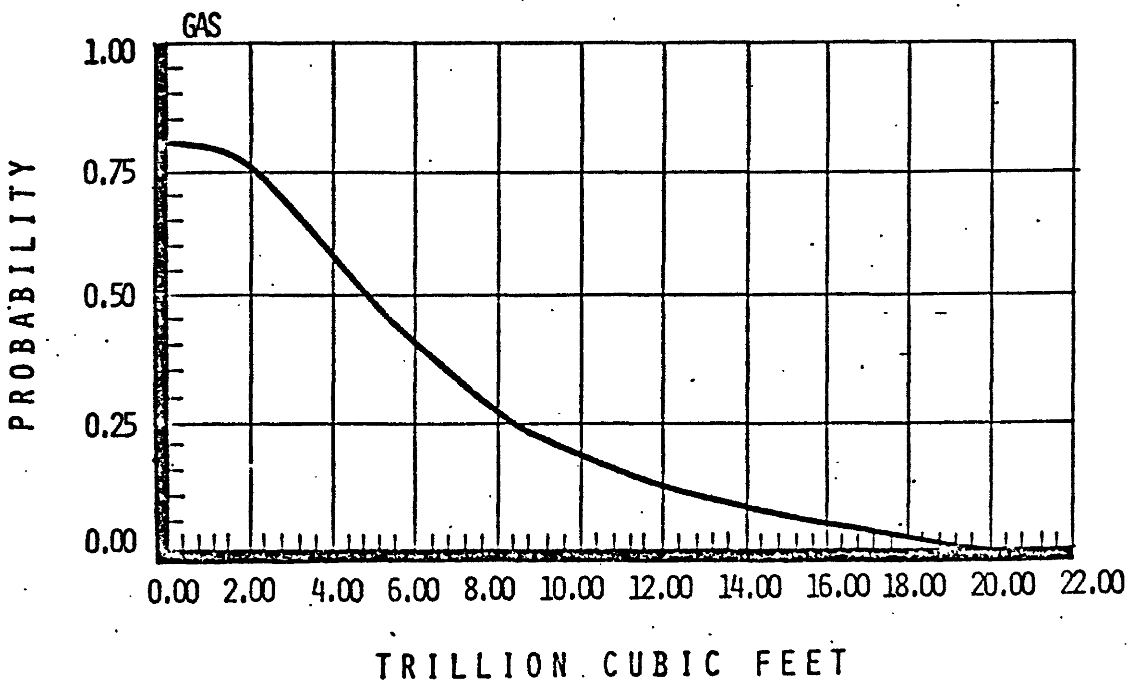


Fig 23