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A PRELIMINARY SUMMARY OF REGIONAL GEOLOGY, PETROLEUM POTENTIAL, ENVIRONMENTAL GEOLOGY, AND TECHNOLOGY FOR EXPLORATION AND DEVELOPMENT FOR PROPOSED OCS LEASE SALE #75, NORTHERN ALEUTIAN SHELF, BERING SEA, ALASKA

by

Michael S. Marlow, Hugh McLean, Alan K. Cooper, T. L. Vallier,
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Menlo Park, California
January 1980

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SUMMARY

This report provides a preliminary assessment of the regional geology, petroleum potential, environmental geology, and technology for development of possible oil and gas in that section of the southeastern Bering Sea, known as the Northern Aleutian Shelf, and proposed as OCS Lease Sale area #75. This summary report is in response to a request by the Director, Bureau of Land Management.

Underlying a large portion of continental shelf, north of the Alaska peninsula is a sediment-filled structural depression known as the Bristol Bay basin. The sedimentary deposits of part of the basin fill are exposed on the northern fringe of the Alaska Peninsula. This basin trends northeastward from the Alaskan peninsula and about four-fifths of it lies offshore beneath the flat Bering Sea shelf. This elongate structural sag is approximately 760 km by 320 km (475 x 200 mi.) and encompasses an area of about 246,050 sq. km (95,000 sq. mi). The basin is asymmetrical in cross section; the basement rock of the northwest flank dips gently toward the basin axis, but the southeast flank of folded Jurassic rock is steeply inclined, probably faulted, and crops out in the northern foothills of the Alaska Peninsula. The basin's sedimentary section, more than 6000 m (20,000 ft) thick, is composed chiefly of Cenozoic deposits; they are thickest in the southeast portion of the basin.

The northeast end of Bristol Bay basin is bounded by exposures of highly deformed, locally intruded, metamorphosed Paleozoic and Mesozoic rocks. To the southwest, the basin is delineated by the offshore extension of the Black

Hills, an anticlinal structure composed of Jurassic sedimentary rocks. South of the the basin, economic basement consists mainly of Mesozoic and Cenozoic volcanic and plutonic units that form the core of the Alaska Peninsula. To the north, beneath the Bering shelf, "acoustic" basement (as resolved on geophysical records) flooring the basin probably comprises Mesozoic sedimentary, volcanic, metamorphic and crystalline rocks.

The basin probably began to form in late Mesozoic time and the formed in part by the subsidence of basement rocks of Mesozoic and older age that were part of a volcanic-plutonic arc complex that extended from southern Alaska into the Bering Sea shelf and margin. The basin continued to subside and fill with sediment throughout the Cenozoic.

Nine wells have been drilled on the Alaska Peninsula adjacent to the axis of Bristol Bay basin. Although all the wells are effectively dry holes, a number of oil and gas shows were reported. Data from these wells suggest that the most prospective area for hydrocarbons is the southwestern, offshore portion of Bristol Bay basin between Port Moller and Amak Island. No wells have been drilled offshore. The southeastern half of the basin also contains the thickest Cenozoic sediment; the section here may have the greatest potential for prospective source and reservoir rocks. Some of the Mesozoic basement rocks beneath the basin may also be petroleum source or reservoir rocks.

Structural and stratigraphic traps associated with the faulted, southeastern edge of Bristol Bay basin are possible targets for exploration. These traps are mainly anticlinal structures in the Cenozoic sequence that formed by draping and differential compaction of strata over erosional and block-faulted highs developed within the basement complex. Stratigraphic pinch-outs may have developed within marine and nonmarine transgressive

sequences in the central area of the basin.

A preliminary resource appraisal suggests that there is a 5% probability that 2.3 billion bbl of oil and 5.8 trillion cu. ft. of gas and a 95% probability that <.1 bbl and <.1 trillion cu. ft. of gas may be present in the basin. However, it is unknown at this time whether hydrocarbon deposits of commercial size occur in the basin.

Major potential geo-environmental hazards in the Northern Aleutian Shelf area include faulting and earthquakes, sea floor instability due to sediment erosion, transport, and deposition, volcanic activity, and ice. Tidal effects in some bays and estuaries may be hazardous. Great earthquakes (magnitude greater than 8 on the Richter scale) have occurred along the nearby Aleutian arc and Alaska Peninsula south of the basin. Smaller earthquakes occur west of the basin between the peninsula and the Pribilof Islands. The magnitude of ground motion generated by these shocks is unknown.

Tsunami (earthquake)-, tide-, and storm-induced waves affect sediment movement in the area. The physical properties (stability, etc.) of the surficial sediment are unknown, at present and their role as possible hazards to man-made structures has not been evaluated.

The Northern Aleutian Shelf is bounded on the south by the volcanically active Alaska Peninsula and the eastern Aleutian Islands. Hazards from volcanic activity are associated with the eruption of lava and ash (explosive activity) and attendant earthquakes. These forces, including ground motion from earthquakes, may affect man-made structures as well as disturbing pre-existing, unstable sediment deposits.

During the colder months the region is in part covered with ice; the average thickness of this sea ice is 1 to 1.5 m. Most of the ice is mobile, although stationary ice, in sheets 1-2 m thick and as wide as 80 km, forms

along the shoreline of the Bay. Man-made structures could be affected by ice-ramming and bottom scouring.

INTRODUCTION

Location of OCS Area

The area with which this report is concerned lies north of the Alaska Peninsula and south of a line between Cape Newenham and the Pribilof Islands (Figs. 1 and 2), from Kvichak Bay, it extends southwestward along the northern side of the Alaska Peninsula toward the edge of the continental shelf. The area of the basin is approximately 246,050 sq. km. (Figs. 1 and 2; Hatten, 1971). The basement morphology of the basin is asymmetrical in cross section. The flanks of the basin are defined by a basement surface that dips gently northwestward and a steeply inclined southeastern flank that crops out in the northern foothills of the Alaska Peninsula (Burk, 1965; Hatten, 1971; Brockway and others, 1975). Approximately 80% of the basin lies offshore in water depths generally less than 60 m.

Available Data

During the last ten years there has been a great deal of exploration activity within the eastern Bering Sea. The bulk of the resulting data are proprietary and not publicly available. Since 1965 the U. S. Geological Survey has collected more than 6000 km of geophysical data from the southern Bering Sea shelf (Fig. 3) 860 km of 24 channel seismic-reflection profiles recorded in 1976 across the offshore portion of the basin.

Other public data include 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,

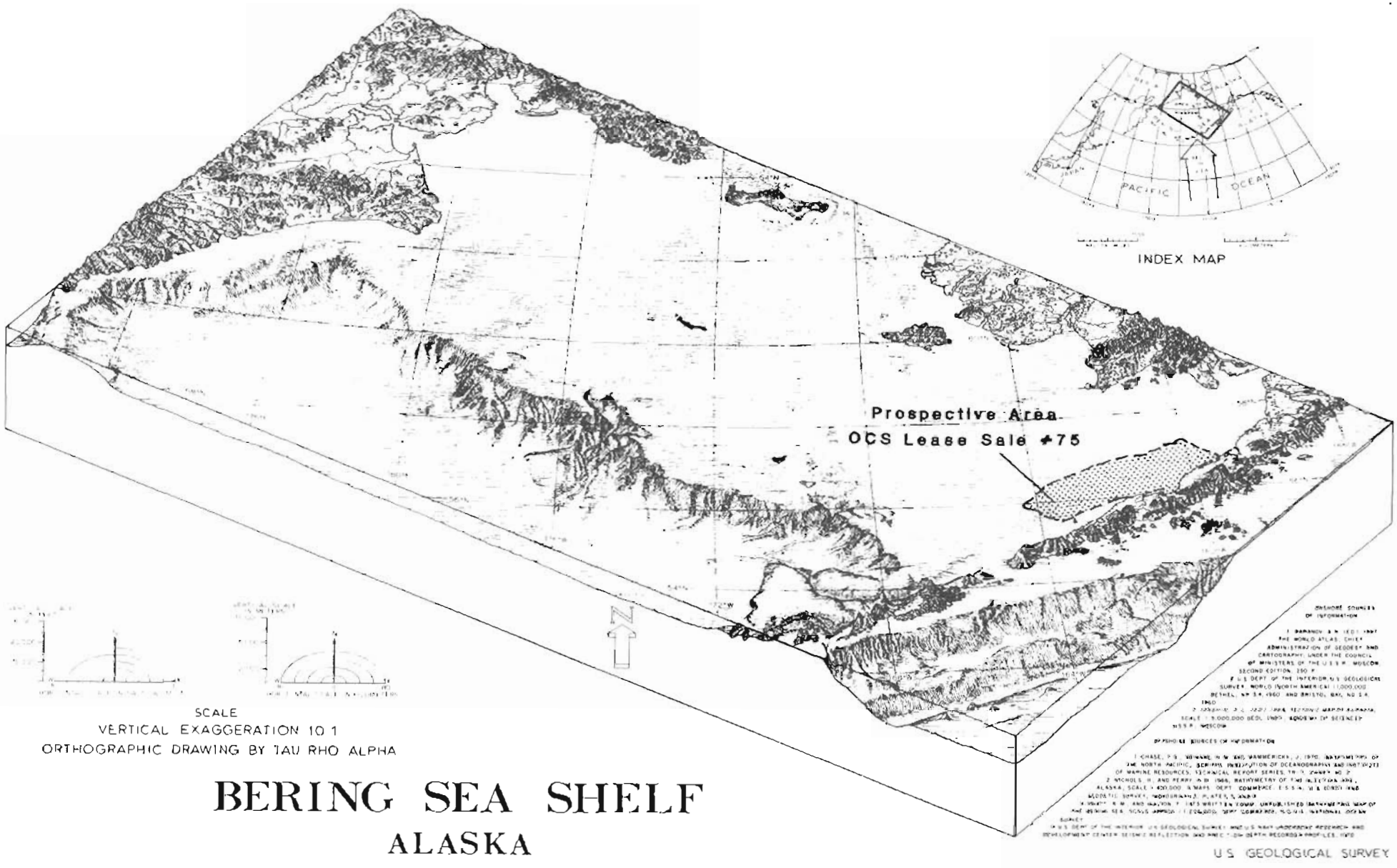


Figure 1. Physiographic diagram of the Bering Sea shelf and margin showing prospective area for OCS lease sale #75. Drawing by Tau Rho Alpha. From Marlow and others (1975).

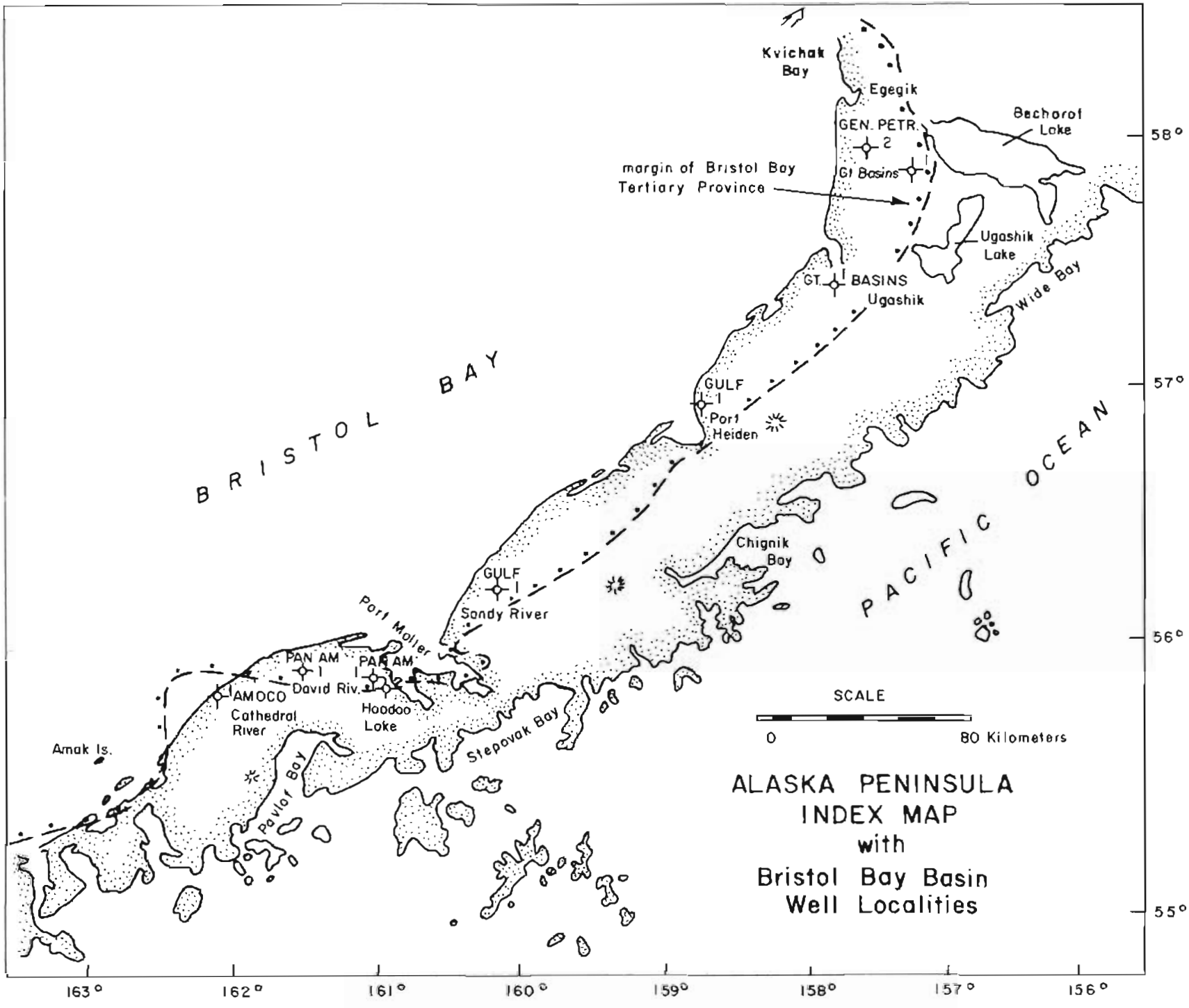


Figure 2. Index map of the Alaska Peninsula showing sites of wells drilled on the peninsula.

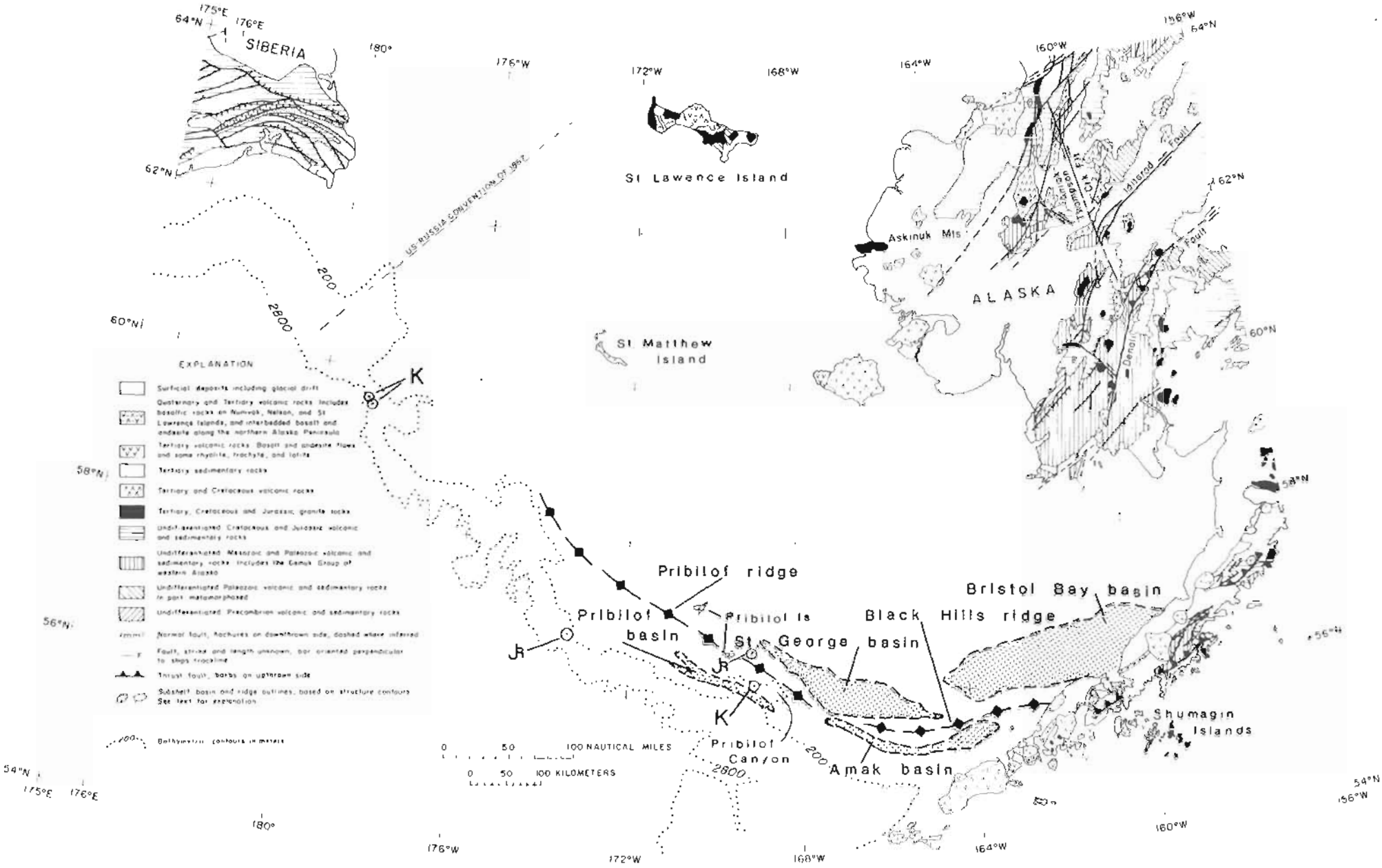


Figure 4. Generalized geology of western Alaska, Alaska Peninsula, and eastern Siberia. Onshore geology is modified from Burk (1965), Yanshin (1966), and Beikman (1974). Off shore outlines of subshelf ridges and basins are derived from Figure 9. Dotted open circles indicate sites where Jurassic (Jr) and Cretaceous (K) sedimentary rocks were dredged from the continental slop (Marlow and others, 1979b, Vallier and others, 1980a). Albers equal-area projection.

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. 4). These shallow water rocks strike west toward the southern Bering shelf area and are paralleled to the north by a belt of Jurassic granitic rocks (Fig. 4; Burk, 1965).

Cretaceous and older Mesozoic geosynclinal rocks of southwest Alaska trend southwestward toward the southern Bering Sea shelf (Fig. 4; Payne, 1955; Hoare, 1961; Gates and Gryc, 1963; Patton, 1973). These complex allochthonous terranes are composed of diverse sedimentary and igneous belts that are thought to have been accreted as "microplates" to nuclear Alaska during Mesozoic and earliest Cenozoic time (Jones, 1978; Jones and Silberling, 1979).

Further, deformed deep water sedimentary rocks of Cretaceous age are exposed south of the Alaska Peninsula in the Shumagin Islands and are thought to be uplifted former trench and slope deposits accreted to the southern Alaskan margin by late Mesozoic or earliest Tertiary time (Fig. 4; Moore, 1972, 1973a, b, 1974). Earlier hypotheses for the evolution of the southern Bering Sea margin included speculations that these deformed rocks extend to the northwest beneath the southern Bering Sea margin (Burk, 1965; Moore, 1972, 1973a, b, 1974; Patton and others, 1974, 1976; Scholl and others, 1975; and Marlow and others, 1976a, 1977).

Thus, the southeastern Bering Sea shelf is a focal area for a number of diverse structural trends that converge on the region. Unraveling these trends and determining whether they merge or terminate beneath this section of the shelf may be an exceedingly difficult task, but one that is critical to our understanding of the evolution of the Bering Sea.

Geologic Setting

Mesozoic Rocks

The oldest rocks exposed in the vicinity of St. George, Amak, and outer Bristol Bay basins are Upper Jurassic siltstone and sandstone of the Naknek Formation, which crop out in the Black Hills of the western end of the Alaska Peninsula (Figs. 4, 5; Burk, 1965). The Cathedral River Unit 1 well spudded into the Black Hills and drilled to a total depth of 4,359 m (14,301 ft.); the well reportedly penetrated Triassic strata (McLean, 1979). Rocks recently dredged from the outer shelf near the Pribilof Islands and from the continental slope west of the islands include fossiliferous, gray-green volcanic sandstone of Late Jurassic age (Fig. 4; Vallier and others, 1980; Marlow and others, 1979a, b, 1980).

Lithified mudstone, siltstone, and sandstone of Late Cretaceous age were dredged from acoustic basement exposed in Pribilof Canyon along the outer Bering Sea margin (Fig. 4; Scholl and others, 1966; Hopkins and others, 1969). To the northwest near Siberia, argillaceous limestone and sandy siltstone interbedded with volcanic sandstone were dredged from the continental slope along the Beringian margin. Both the limestone and the siltstone contain Campanian or Maestrichtian (Late Cretaceous) pollen and spore assemblages (Marlow and others, 1980).

Ultramafic basement rocks are subaerially exposed on St. George Island in the Pribilof Islands (Barth, 1956). These ultramafic bodies consist of serpentized peridotites that are intruded by a grandodiorite dike that has been dated radiometrically and has a minimum age of 50 to 57 m.y. (Hopkins and Silberman, 1978). We suspect that the peridotites are Mesozoic in age and that they either intrude the Jurassic basement rocks beneath the Pribilof Islands or that they may be allochthonous blocks within the basement

COMPOSITE COLUMNAR SECTION

BRISTOL BAY AND ALASKA PENINSULA REGIONS, ALASKA

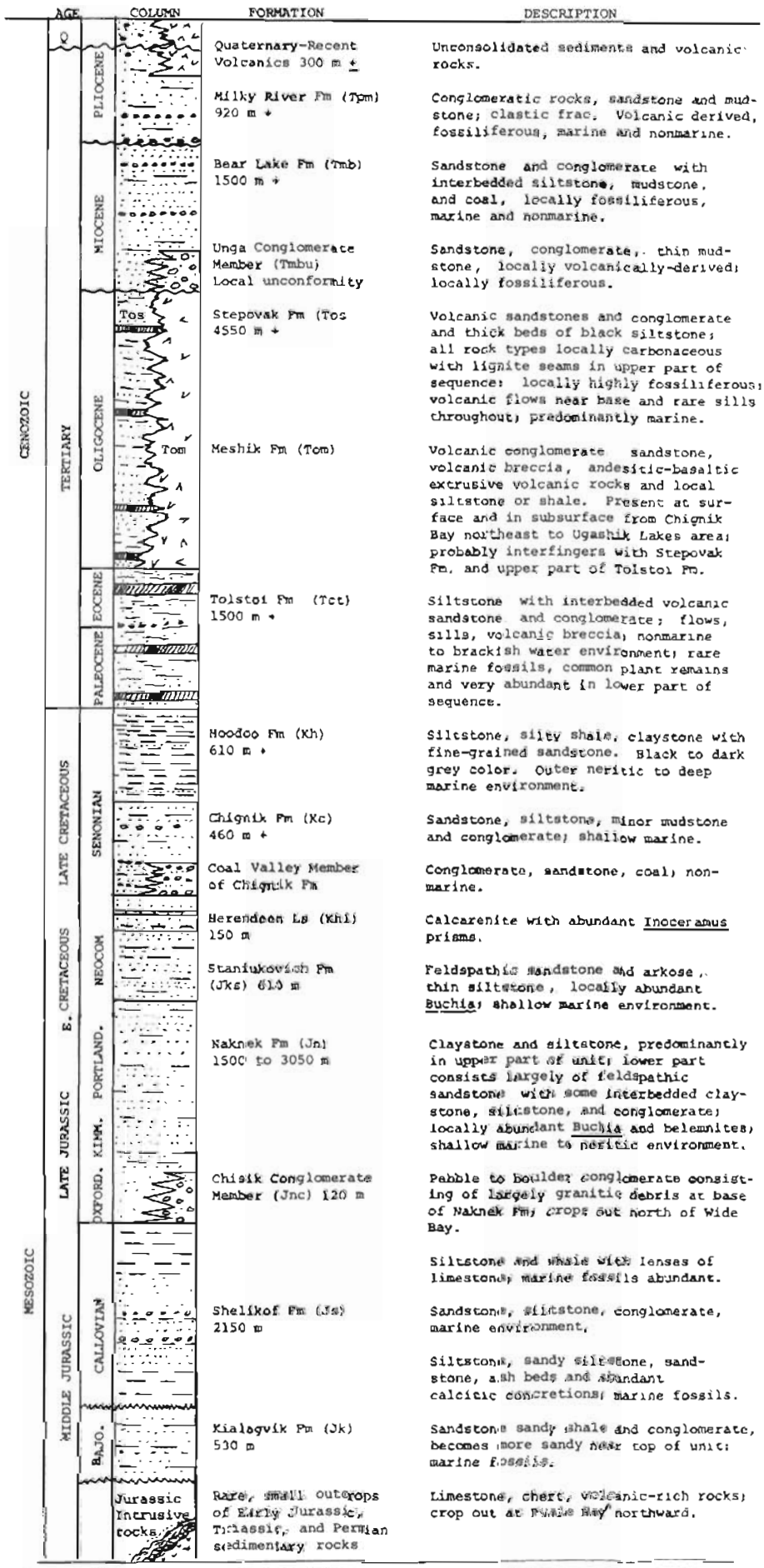


Figure 5. Composite columnar section of strata in the area of proposed lease sale #75 and the Alaska Peninsula. Derived from Burk (1965) and Brockway and others (1975).

complex. In this paper we will assume that the seismically-resolved acoustic basement beneath the southern outer Bering Sea margin that flanks the western end of the basin consists mainly of indurated sedimentary rocks of Mesozoic age.

In the vicinity of Port Moller along the western end of the Alaska Peninsula, the Upper Jurassic to Lower Cretaceous Naknek and Staniukovich Formations are unconformably overlain by Upper Cretaceous rocks of the Chignik and Hoodoo Formations (Fig. 12, Burk, 1965). Middle Cretaceous strata are missing, probably as a result of deformation and uplift along the Alaska Peninsula in Middle to Late Cretaceous time (Burk, 1965).

Cenozoic Rocks

Cenozoic rocks exposed on the Alaska Peninsula include assemblages representing all the Tertiary epochs (Figs. 4, 5, 6; Burk, 1965). The only parts of the Tertiary that may be missing include the Oligocene-Miocene transition and the early Paleocene. According to Burk, these were periods of uplift, deformation, and erosion on the Alaska Peninsula, although the major uplift and formation of the peninsula took place during Pliocene time.

Paleogene rocks on the Alaska Peninsula are composed almost entirely of volcaniclastic debris, containing principally andesitic and basaltic volcanic components (Burk, 1965; McLean, 1979). These rocks, up to 9100m (30,000 ft.) thick, are both marine and non-marine; their volcanic content, which includes both detrital material as well as interbedded flows, indicates that volcanism was ubiquitous throughout the peninsula in the early Tertiary. Paleocene and Eocene rocks overlie Upper Cretaceous strata with only slight discordance and, locally, lower Tertiary units rest on rocks as old as the Late Jurassic (Burk, 1965). Major Paleogene formations exposed on the Alaska Peninsula include the Tolstoi (Paleocene or Eocene), the Stepovak (Eocene(?) and Oligocene), the Meshik (Oligocene), and the Belkofski (Oligocene) Formations (Burk, 1965;

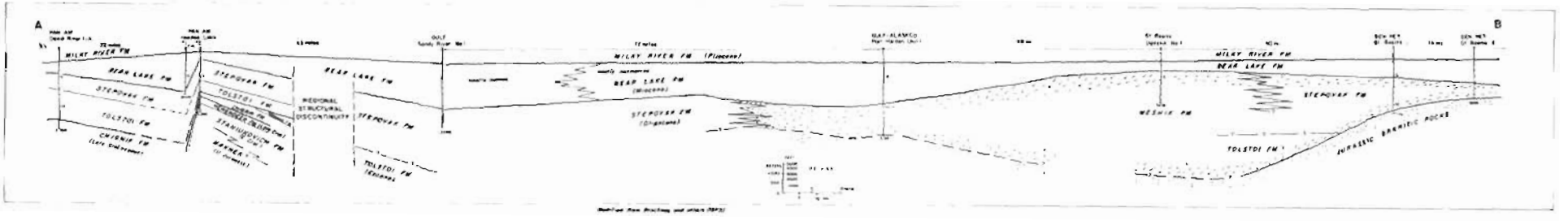


Figure 6. Generalized statigraphic cross section along the northern side of the Alaska Peninsula. Modified from Brockway and others (1975).

McLean, 1979).

Neogene rocks exposed on the Alaska Peninsula include marine and nonmarine volcaniclastic rocks, volcanic flows, and breccias. The thickest Neogene formation on the peninsula, the Bear Lake Formation, consists of 1500 m (5000 ft) of porous sandstones and conglomerates that are interbedded with siltstone, mudstone, and coal of middle and late Miocene age (Burk, 1965; Brockway and others, 1975; McLean, 1979). Unconformably overlying the Bear Lake Formation are up to 500 m (1500 ft) of shallow marine to nonmarine sandstone, pebbly mudstone, and carbonaceous mudstone of the Talchilni Formation, which is late Miocene to Pliocene in age (Burk, 1965); the Talchilni Formation has been mapped only in the southwestern area of the Alaska Peninsula in the vicinity of Cold Bay (Burk, 1965; McLean, 1979). Brockway and others, (1975), in a composite stratigraphic section of the peninsula and Bristol Bay, indicate that the Bear Lake Formation is overlain unconformably by the Milky River Formation, which consists of more than 1000 m (3000+') of conglomerate, sandstone, and mudstone that were deposited in a shallow marine environment (Fig. 5). Much of the Alaska Peninsula is capped by a relatively flat-lying section of nonmarine clastic rocks that are poorly consolidated and interbedded with volcanic flows and breccias of Pleistocene and Holocene age (McLean, 1979).

Cenozoic rocks exposed on the Alaska Peninsula are probably equivalent to strata that are buried beneath the adjacent Bering Sea shelf within Bristol Bay basin (Burk, 1965; Hatten, 1971) and St. George basin (Marlow and others, 1976a, 1977).

STRUCTURAL FRAMEWORK AND EVOLUTION OF THE NORTHEN ALEUTIAN SHELF

Seismic-Reflection Data

Profile AB

A 24-channel seismic-reflection profile shown in Figures 7 and 8 illustrates the spatial relationship of several large subshelf features near the Alaska Peninsula, namely the positions of Amak basin, the Black Hills ridge, and Bristol Bay basin (for location, see Fig. 3). Near the center of the profile, at a subbottom depth of about 1.0 sec, moderately-dipping strata are resolved within the core of a basement ridge, informally named the Black Hills ridge after similar-deformed rocks exposed nearby in the Black Hills of the Alaska Peninsula. Offshore, the equivalent strata within the Black Hills ridge are cut by a major unconformity shown by heavy line in Figure 7. The cutting of this unconformity may be Cretaceous in age because middle Cretaceous rocks are missing on the nearby Alaska Peninsula due to uplift and erosion (Burk, 1965). The unconformity can be traced along the section to the east into Bristol Bay basin, where the surface of the unconformity appears to grade into a depositional contact with parallel reflectors above and below it (Figs. 7 and 8). If this reflector is indeed Cretaceous in age, then the layered strata beneath this horizon could be of the same age or older. Hence, the initial formation and filling of the basin could have begun by late Mesozoic time. The same argument can be made for the dipping strata near the bottom of Amak basin along the western end of the same profile (Fig. 7). We originally speculated that, because of the enormous thickness of sedimentary fill (> 10 km) in a number of basins beneath the Bering Sea shelf, the initial formation of these basins may have occurred by the end of the Mesozoic (Marlow and others, 1976a, 1977).

As revealed by the northeastern half of profile AB, Bristol Bay basin in

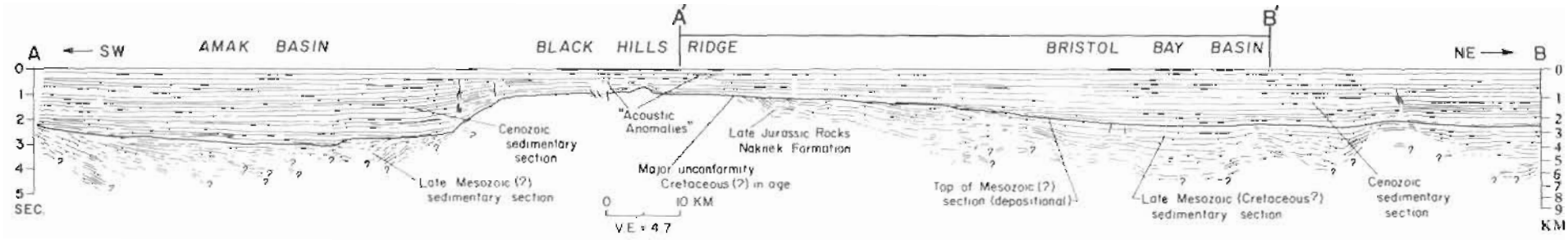


Figure 7. Interpretative drawing of 24 channel seismic-reflection profile across the southern Bering Sea shelf. For location of profile see Figure 3. Two-way travel time in seconds. Kilometer scale is derived from velocity function explained in Figure 10. Detailed segment A'B' is shown in Figure 8.

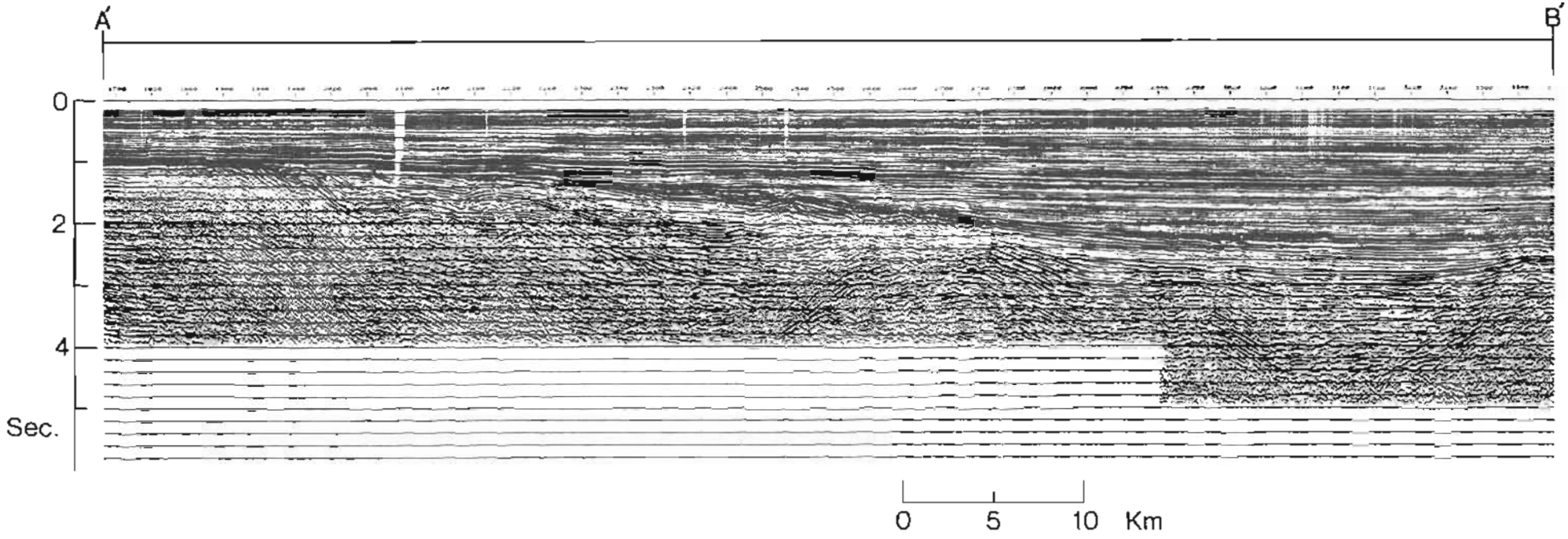


Figure 8. Twenty-four channel seismic-reflection record used in constructing part of the interpretative drawing shown in Figure 7.

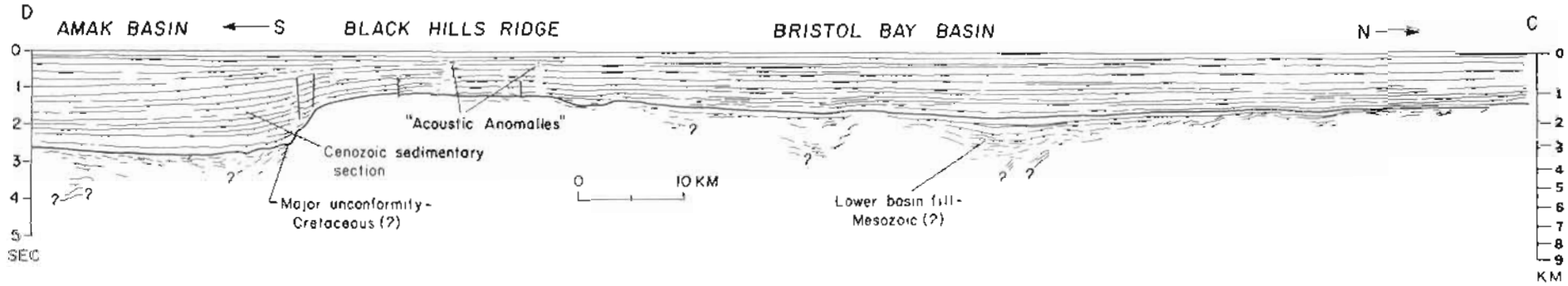


Figure 9. Interpretative drawing of 24 channel seismic-feflection profile CD across Amak and Bristol Bay basins. For location of profile see Figure 3, and for explanation see Figure 7.

See reverse for figure

Figure 10. Structure-contour map of acoustic basement. Derived in part from Scholl and others (1968), Scholl and Hopkins (1969), and Marlow and others (1976a, 1977). To convert two-way traveltime on the seismic-reflection records to depths in kilometers, generalized velocity function was used:

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

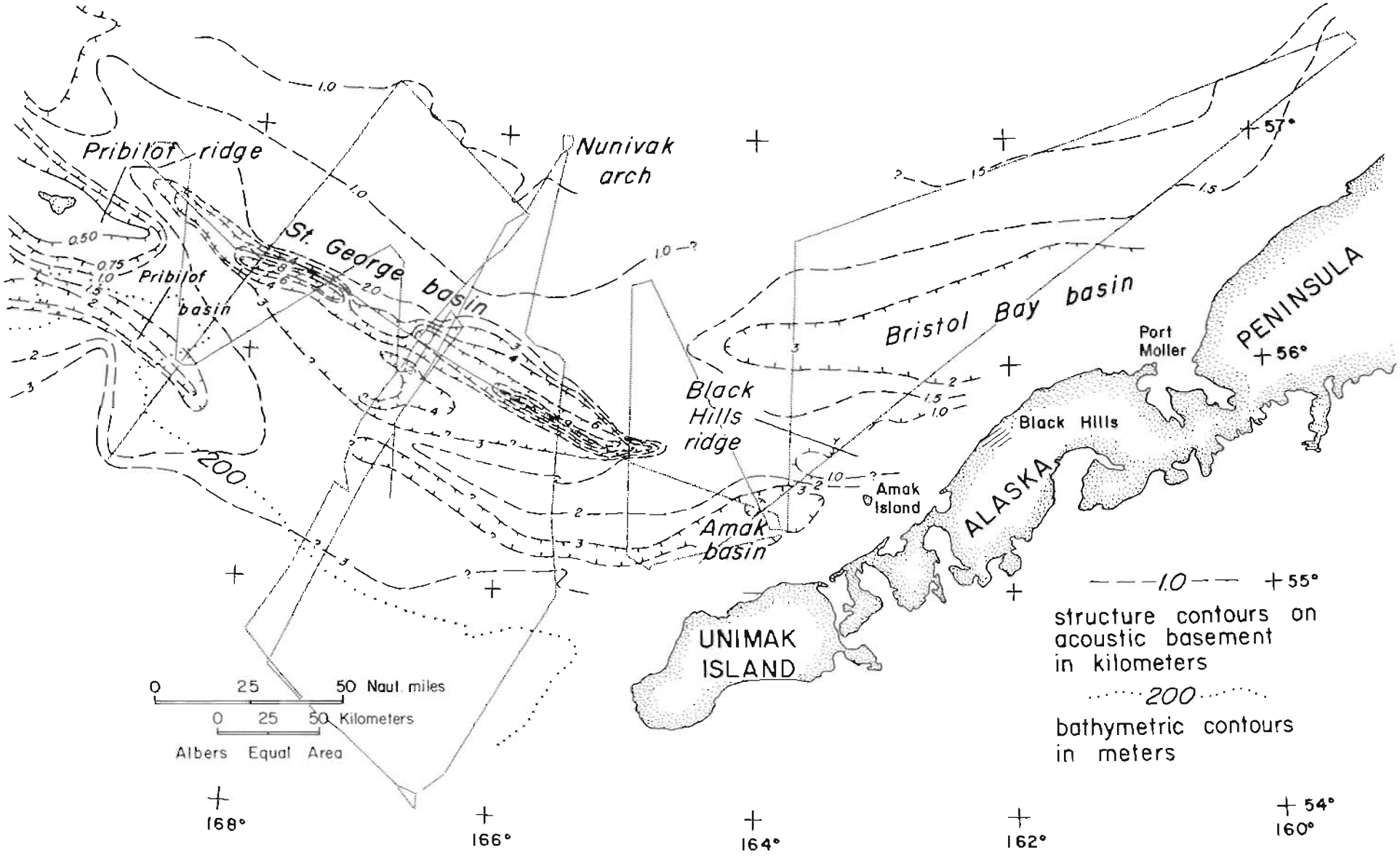
where:

D = Depth or thickness in kilometers

t = One-way traveltime.

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

Albers equal-area projection.


Pribilof ridge
Pribilof basin
St. George basin
Nunivak arch
Black Hills ridge
Amak basin
Amak Island
Bristol Bay basin
Port Moller
Black Hills
ALASKA
PENINSULA
UNIMAK ISLAND
200
0 25 50 Naut. miles
0 25 50 Kilometers
Albers Equal Area
168°
166°
164°
162°
160°
57°
56°
55°
54°
structure contours on acoustic basement in kilometers
200
bathymetric contours in meters

of the inner Bering Sea shelf (Fig. 10, Scholl and Hopkins, 1969; Marlow and others 1976a). Nunivak arch apparently extends as far east as 160°W, just north of Bristol Bay basin , although our seismic-reflection profiles are widely spaced east of 164°W (Fig. 3).

Bristol Bay basin underlies most of the northern side of the Alaska Peninsula, extends offshore beneath the adjacent Bering Sea lowlands, and encompasses a total area of more than 246,000 sq. km (Hatten, 1971). The offshore portion of the basin west of Port Moller, as defined by the 1.5 km structural contour, totals 18,900 sq. km (Fig. 10). A northeast-southwest seismic-reflection profile reveals that the thickest section filling the basin is in excess of 7 km in the vicinity of Port Moller, where a large embayment in the peninsula may reflect substantial basin subsidence and sediment infilling (Figs. 7, 8, and 10). Unlike St. George basin which is a graben, Bristol Bay basin is structurally a crustal sag or depression beneath the shelf. The upper sedimentary section in Bristol Bay basin is gently dipping to flat-lying, and the lower basin fill is only mildly folded and draped over basement blocks (Figs. 7 and 8).

Located just north of Unimak Island, Amak basin, like Bristol Bay basin, is a gentle crustal sag or depression beneath the flat southern shelf (Figs. 7, 9 and 10). The western part of the basin is an elongate, narrow, sediment-filled trough that is defined by the 3 km structural contour and that trends west parallel to the Black Hills ridge; however, the main depocenter of the basin is circular in shape and filled with slightly more than four kilometers of section. This sedimentary sequence is either flat-lying or dips very gently and is undeformed except where the strata are offset by folding or high angle faulting on the northeast side of the basin along flanks of the Black Hills ridge (Figs. 7 and 9). The entire basin sequence laps on to the Black

Hills ridge except for the upper few hundred meters of section, which are flat-lying and probably represent a period of rapid sediment flooding across the entire southern shelf during Pleistocene time.

Geologic History

Bristol Bay basin, as a distinct structural trough, probably began to form in late Mesozoic time and has continued to subside during most of Cenozoic time. On the basis of scant publicly available seismic-reflection data this basin is an elongate structural sag that is asymmetrical in cross section. The northern flank of Mesozoic basement rock dips gently to the south but the southern flank is steeply inclined and crops out in the northern foothills of the Alaska Peninsula.

The basin probably began to form in conjunction with the formation of the Aleutian Island arc and the "trapping" of a piece of Pacific oceanic crust in the adjacent abyssal Bering Sea at the end of the Mesozoic era or in earliest Tertiary time (Scholl and others, 1975; Marlow and others, 1976a, b). The rocks beneath the sediment fill in Bristol Bay basin have subsided during much of Cenozoic time and the basin now contains more than 6-8 km of sedimentary rock. The basin fill onshore includes volcanic rocks of Oligocene age.

Summary

The rate of subsidence of Bristol Bay basin has approximately equaled the rate of deposition since late Mesozoic time. The maximum thickness of sedimentary rock in the deepest part of the basin is not well known but probably exceeds 6 km and may be as thick as 8 km. The basin fill does not appear to be deformed except locally near the southern basin edge along the northern shore of the Alaska Peninsula.

Most of the upper Mesozoic and Cenozoic sedimentary rock units exposed onshore along the Alaska Peninsula probably exist offshore beneath the south-

eastern Bering Sea shelf. The position of the basin behind the Aleutian arc may have isolated it from the numerous episodes of volcanism and plutonism that substantially reduced the petroleum potential of the sedimentary sequences along the Alaska Peninsula (McLean, 1979).

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 Neogene sedimentary sequence generally overlies Jurassic granitic rocks although locally it covers volcanic rocks 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 enchance 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.

PETROLEUM GEOLOGY

Alaska Peninsula and Bristol Bay Basin

Drilling History

Since 1959, nine wells have been drilled along the northern coastal lowland area of the Alaska Peninsula. No wells have been drilled offshore in

the 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 Ugashik No. 1, and the Gulf-Alaskco Port Heiden No. 1 (Fig. 2). 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 1200 m to 3350 m and consists of interbedded nonmarine 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 flat-lying 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) according to Berggren (1969) and 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 Miocene Bear Lake Formation between 1790 and 1940 m. Oil and gas shows were also encountered in the basal sandstone beds of the Bear Lake Formation and in the Stepovak Formation (Brockway and others, 1975). Shows of oil and gas were reported from sandstone beds in the Stepovak and Tolstoi Formation in the Pan American Hoodoo Lake No. 2 well. However, no shows occurred in the Pan American Hoodoo Lake No. 1 well, which penetrated 2258 m of the Bear Lake Formation and 198 m of the Stepovak Formation. In the Pan American David River 1-A well, gas shows occurred in sandstone units of

the Bear Lake and Stepovak Formations. Additional shows of oil and gas were reported in the Tolstoi Formation. Drilling in the same well revealed one gas show in the Chignik Formation at a depth of approximately 4175 m.

The Amoco Cathedral River Unit 1 well was spudded into Jurassic rocks of the Naknek Formation in the Black Hills near the western tip of the Alaska Peninsula and reached a total depth of 4,359 m (McLean, 1979). Cuttings from the well, which reportedy bottomed in Triassic strata, were analyzed by McLean for organic carbon content. The samples have a total organic content of less than 1% and were contaminated below 2,621 m. Petrographic examinations of sandstone chips from the well show no visible porosity in any part of the section (McLean, 1979).

The thickness of the flat-lying Cenozoic sedimentary sequence and the lithology of the underlying basement rocks are the principal factors affecting the potential of offshore oil and gas accumulations in the adjacent Bristol Bay basin. Thickness is important in that source rocks must attain a burial depth where temperatures are high enough to generate substantial quantities of oil and gas. There apparently has not been sufficient burial of most of the Bear Lake Formation to generate petroleum liquids; only one oil show has been reported in all of the wells that have penetrated this formation. That oil show appeared at a depth of about 3050 m in the Gulf Sandy River well. However, in this well the oil encountered within the basal portion of the Bear Lake Formation may have been derived from source rocks within the underlying Stepovak Formation.

In offshore areas where the flat-lying Cenozoic sequence overlies older, folded and truncated sedimentary rocks, such as the Mesozoic strata of the Black Hills, oil may have migrated upward into the more porous sandstone beds of the 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 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 lower Tertiary or upper Mesozoic sedimentary rocks.

The flat-lying sequence of Cenozoic sedimentary rocks is locally folded and uplifted along the foothill belt of the Alaska Peninsula. Farther offshore, the strata may be depositionally draped over fault blocks within the acoustic basement (Hatten, 1971). The rocks considered to have the greatest petroleum potential in the offshore area 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

Drill cuttings from eight of the nine wells drilled along the Alaska Peninsula were analyzed by McLean (1977) for their organic geochemistry, lithology, and petroleum potential. Analyses of several of the wells indicate that Paleogene strata are rich in organic matter but are immature. However, coeval sedimentary sections offshore in the basin may be more deeply buried than those units on the peninsula and hence may be more mature. In general, fine-grained Neogene sedimentary rocks have a significantly lower carbon content than Paleogene strata, which suggests that the younger strata may have been deposited in brackish to nonmarine environments (McLean, 1979).

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. 6; 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 deeply enough to generate hydrocarbons. Marine shale of Late Jurassic and Late Cretaceous age might also be considered as potential source rocks where they are 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 portion of the 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, chert, and sedimentary lithic fragments. Most of the sandstones could be classified as lithic subgraywackes and others as lithic arenites (Burk, 1965). In the Gulf Sandy River No. 1 well, Bear Lake sandstone above 6,300 feet has porosity values as high as 36.5% and permeability as high as 1,268 mds. Below 6,300 feet, high values for porosity and permeability are 29% and 43 mds, respectively (McLean, 1977). 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 large in area but have a limited amount of closure. Structural traps in the offshore area may have formed during the early filling of Bristol Bay basin. Most structures 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 Port Moller 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 may also be 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.

POTENTIAL GEOLOGIC HAZARDS

The potential geologic hazards in the Bristol Bay region have not been fully evaluated. A general environmental analysis of the region is available in Buck and others, 1974. In the adjacent St. George basin region, potential geologic hazards have been outlined by Gardner and others (1979) who discussed faulting, potentially unstable sediments, and sedimentology of surface sediments.

For this preliminary analysis, therefore, we have relied on the data and analyses of others, specifically Lisitsyn (1966), Askren (1972), Nelson and others (1974), Sharma and others (1972), and Sharma (1974, 1975).

The major potential geologic hazards in the Bristol Bay region include earthquakes, tsunamis, faulting, seafloor instability caused by rapid sediment movement (erosion, transport, and deposition), volcanic activity, and sea ice represents an additional natural hazard. Tide-and storm-induced waves also can affect man-made structures.

Earthquakes and Faults

Earthquakes with magnitudes greater than 8 on the Richter scale have been recorded along the Alaska Peninsula (Sykes, 1972) and some with magnitudes between 7 and 8 on the Richter scale have been recorded in the southeastern Bering Sea (Dept. of Commerce, 1970). There is very little known, however, about associated ground motion and tsunamis caused by the earthquakes. The ground motion probably

decreases to the north across the shelf because of distance from the major epicenter belt. Most epicenters in the southern Bering Sea lie just north of the Alaska Peninsula-Aleutian Island chain. Shallow earthquake hypocenters (<70 km depth) occur as far north as St. George Island.

Faults are extensive in the St. George Basin region just west of Bristol Bay where they are classified as major, surface, and minor (Vallier and Gardner, 1977; Gardner and others, 1979). The faults are concentrated along and in the St. George Basin and some offset the seafloor implying that they are active. No data are available on the distribution, size, or types of faults in the Bristol Bay region.

Sediment Movement

The distribution of surface sediments across the continental shelf of the southern Bering Sea is described by Lisitsyn (1966), Ashnen (1972), Sharma and others (1972), and Sharma (1974, 1975). Based on their data sediment size in the vicinity of the southeastern Bering Shelf grades from coarse sand along the inner shelf to fine silt near the outer shelf, although grain size is somewhat coarser near the shelf break. Data concerning the other physical properties are not available, and consequently the potential for slumping and slope instability is not known.

Lisitsyn (1966, p. 96-98) does not believe that waves have much effect on sediment movement in the deeper parts of the southern Bering Sea. We do know, however, that waves (Tsunami-, tide-, and wind-induced) can greatly affect sediment movement in near-shore areas and probably are major agents for sediment movement along the north shore of the Alaska Peninsula. Tides can have a strong effect in shallow water, particularly in funnel-shaped estuaries such as Kuskokwim Estuary north of Bristol Bay, where the tidal range is as great as 8 meters and current velocities can exceed 200 cm/sec (Lisitsyn,

1966). Wind-induced waves can move sediment in depths of up to 100 meters in the Bering Sea. Storms are frequent, and the probability of storm waves several meters in height exceeds 20% during the year (Lisitsyn, 1966, p. 98). The strongest and most prolonged storms occur during the fall and early winter season. Wave-generated forces can redistribute large volumes of sediments in a relatively short time and thereby are potential hazards to man-made structures on the sea floor and in near-shore areas on land.

Volcanic Activity

The southeastern Bering Sea Shelf is bounded on the south by the Alaska Peninsula and the eastern Aleutian Islands where several volcanoes are active. Coats (1950) lists 25 active volcanoes in the Aleutian Islands and 11 on the Alaska Peninsula and mainland. Hazards from volcanic activity are associated with the eruption of lava and ash and the attendant earthquakes. The distribution of ash is dependent on the magma composition, eruption character, wind speed and direction at the time of eruption, height of eruption, volume of material, and specific properties of the pyroclastic debris. Eruptions from the large andesitic cones on the Alaska Peninsula and Aleutian Islands are mostly the explosive type and can spread pyroclastic material such as ash-flow tuffs or related pyroclastic avalanche deposits over large areas (Miller and Smith, 1977).

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 kmn from the source, averaging about 500 km, and thus could cover all of Bristol Bay basin if wind direction, eruption height, wind speed, volume and other factors were complementary.

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 have ice cover during 10 to 50% of the year (Fig. 11, McRoy and Goering, 1974). 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 are present. 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 near the shorelines where the ice is thickest; man-made structures and pipelines may be affected by ice-ramming and bottom scouring.

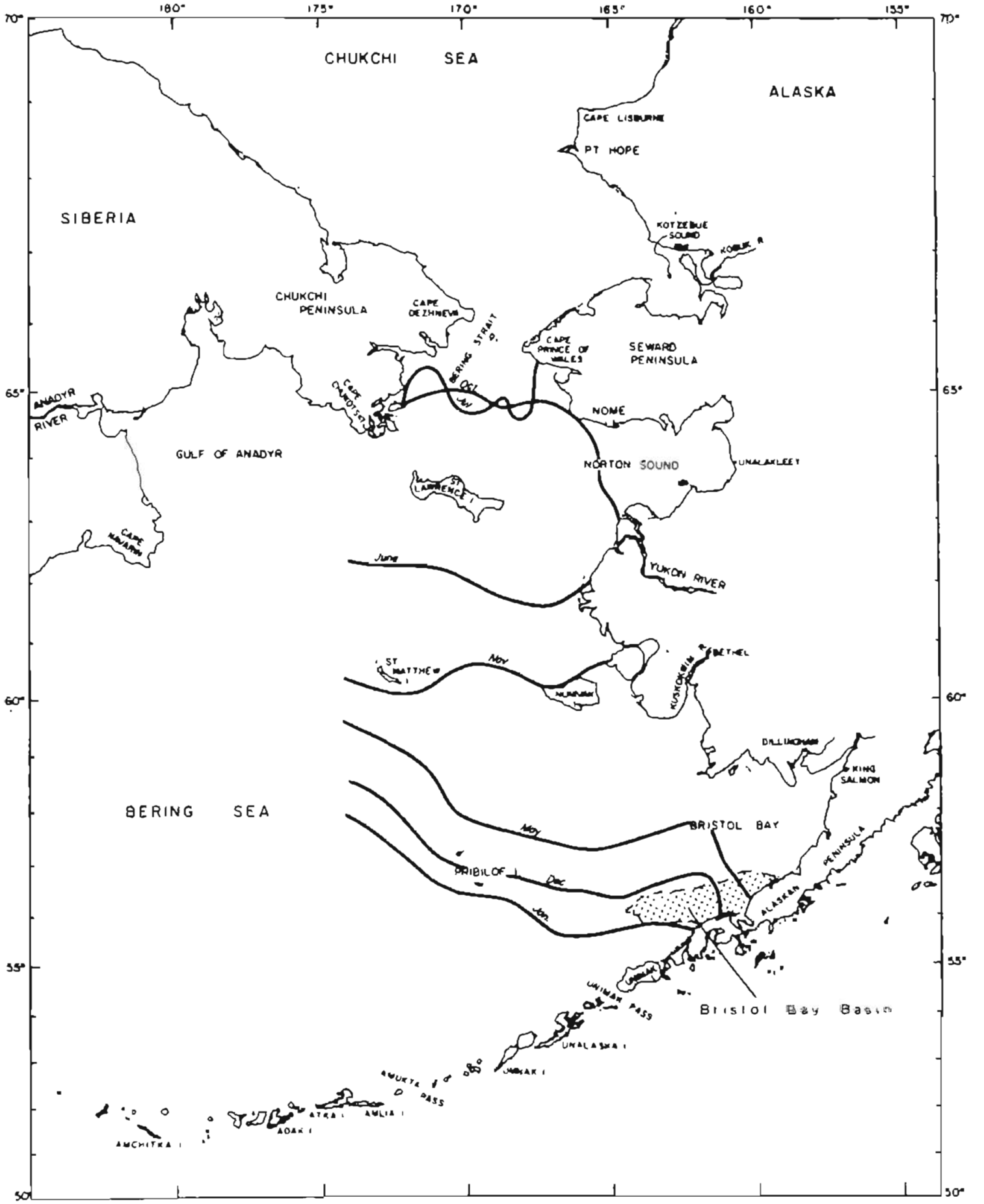
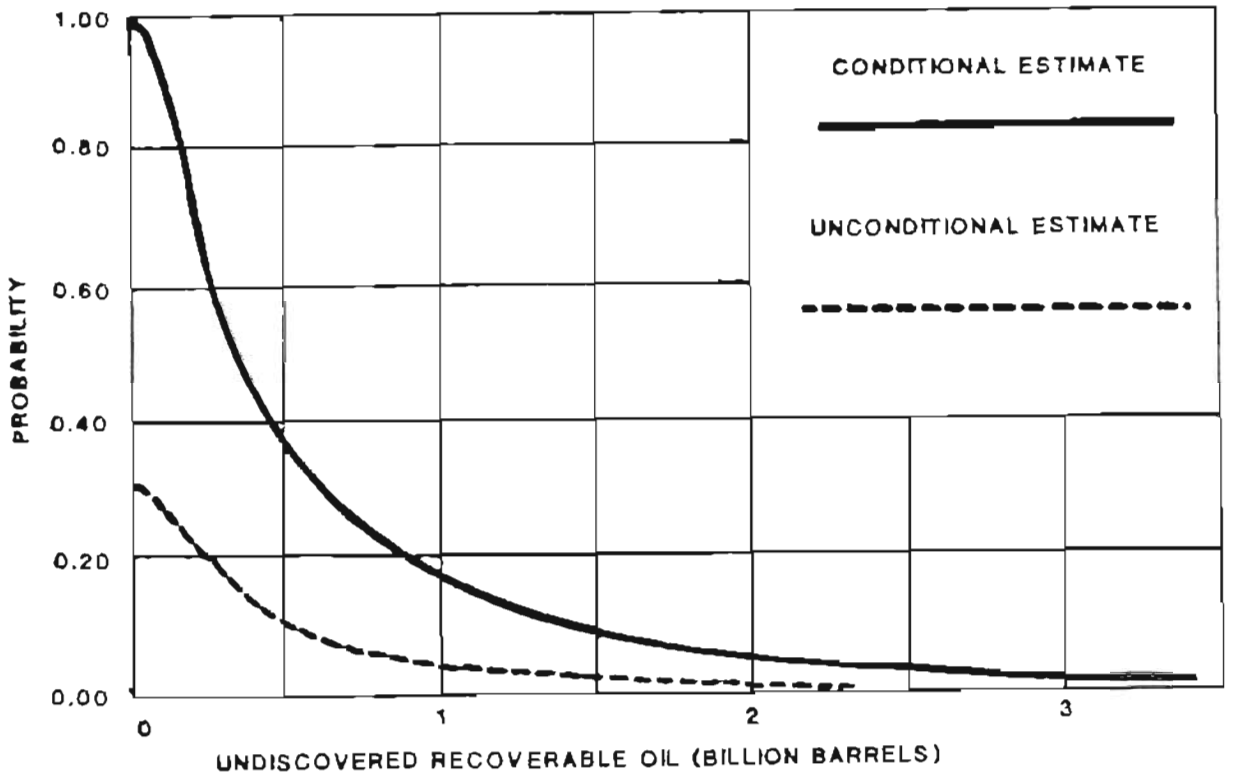


Figure 11. Extent of ice cover across the Bering Sea shelf for different months of the year. From McRoy and Goering (1974).

Figure 12a. Log normal probability distribution curves of total undiscovered recoverable oil and gas reserves in the area proposed for OCS Lease Sale #75.



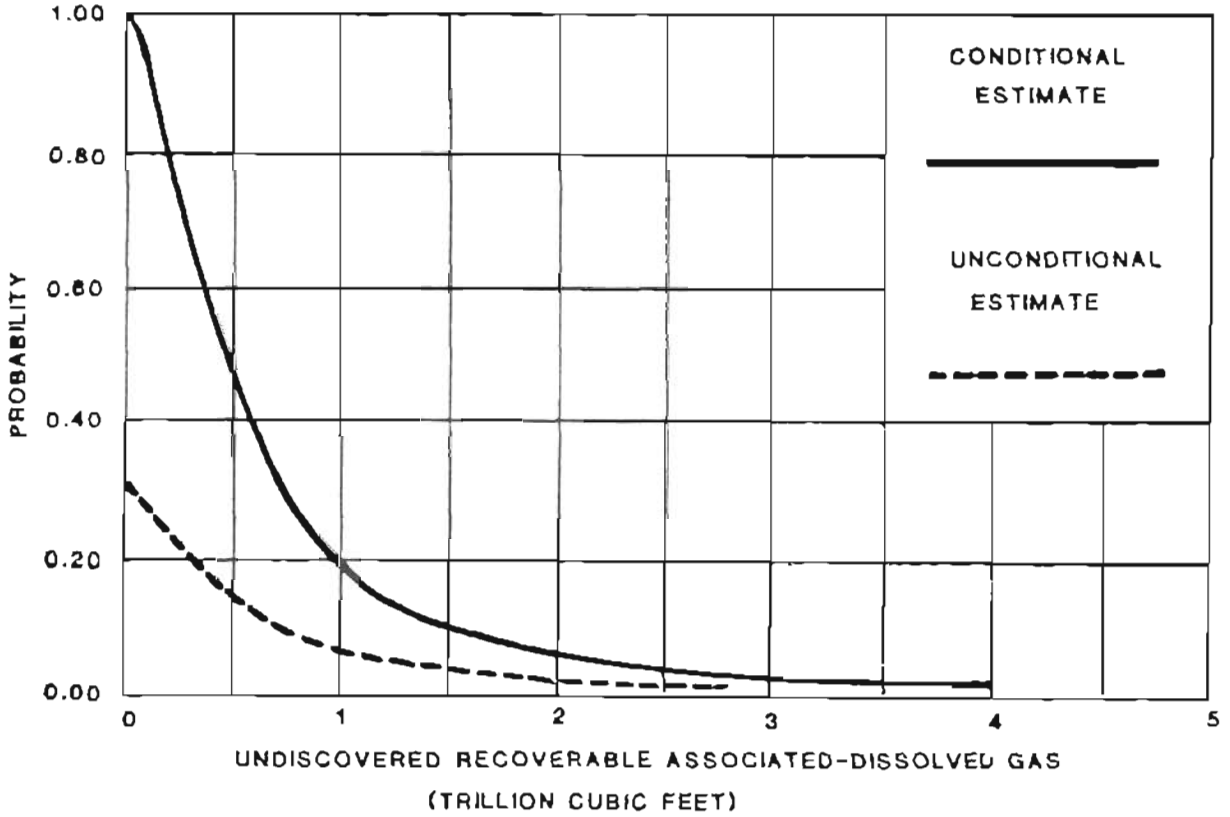
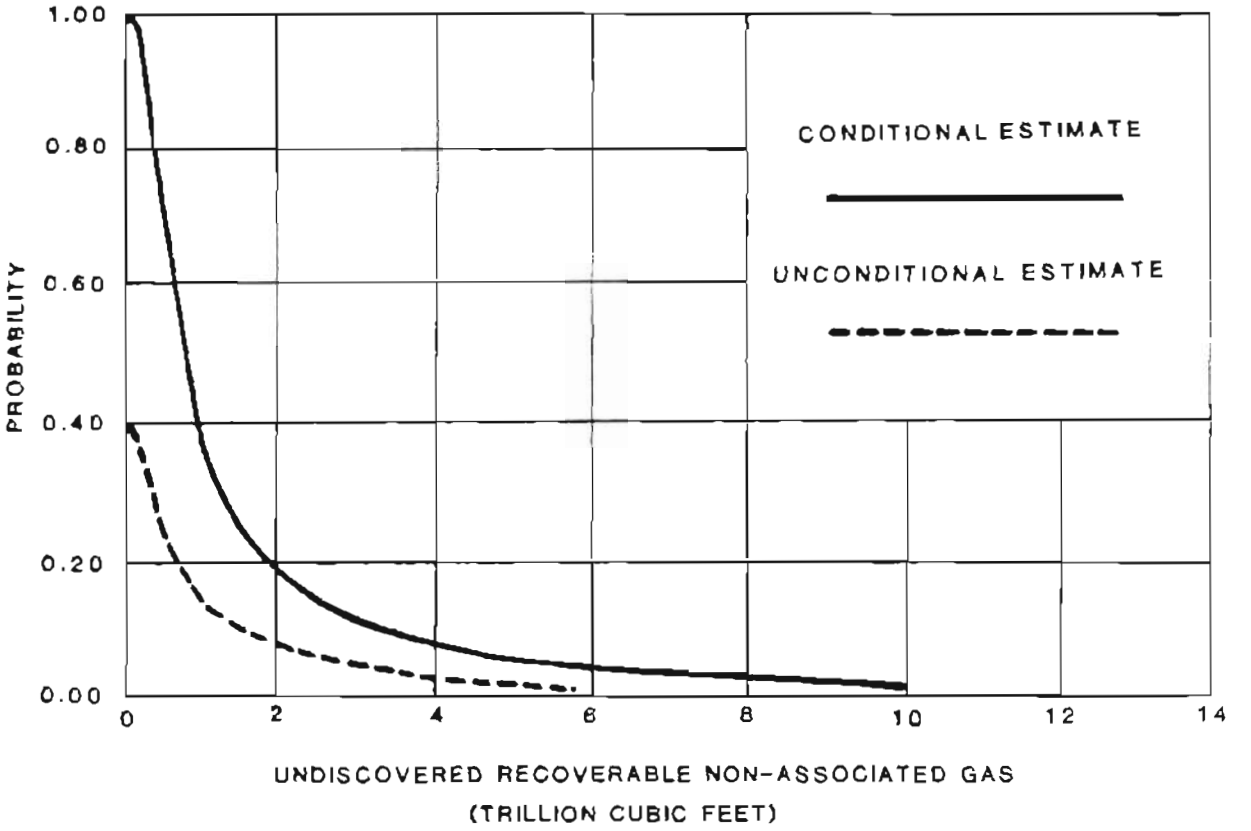


Fig. 12a

Figure 12 b. Log normal probability distribution curves of total undiscovered recoverable oil and gas reserves in the area proposed for OCS Lease Sale #75.



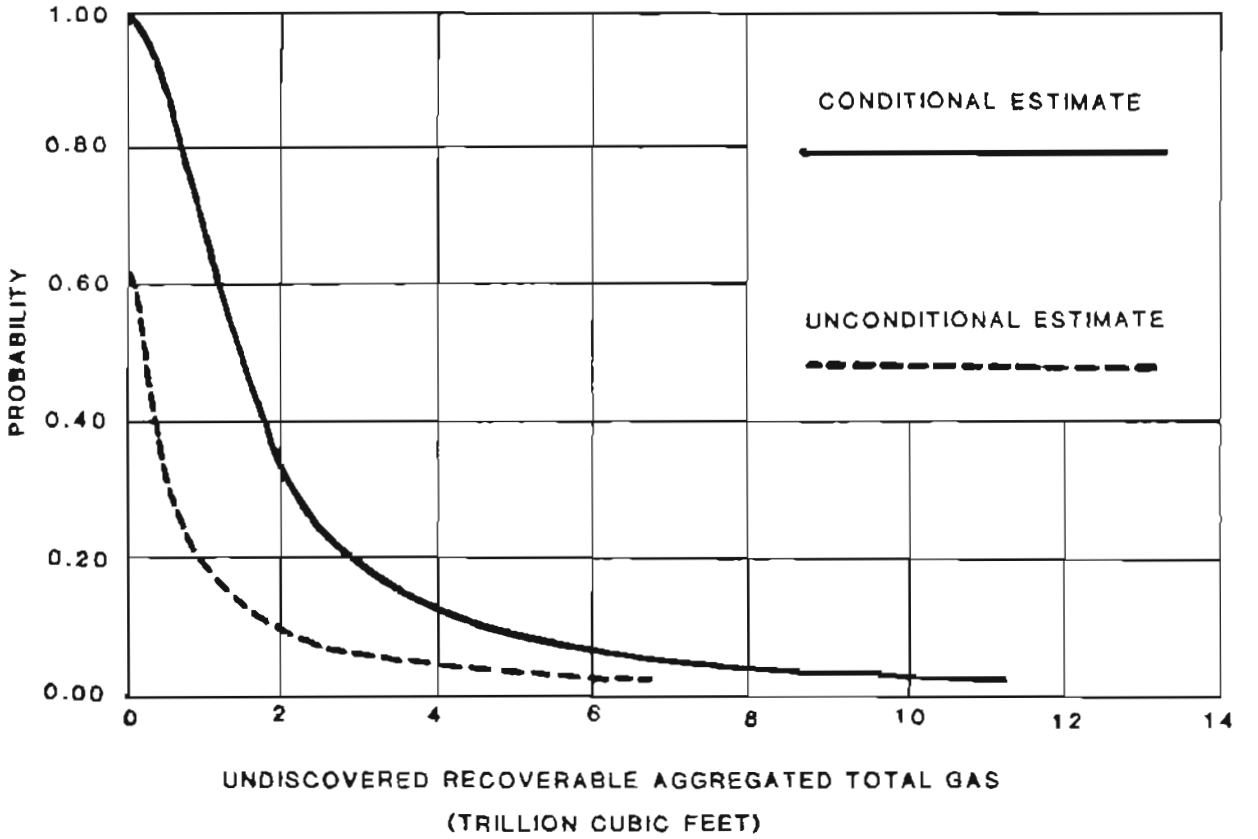


Fig.1~~8~~6

TABLE 1

	95% Probability	5% Probability	Statistical Mean	Marginal Probability
Oil (billions of barrels)				
Conditional	<.1	2.3	.7	.3
Unconditional	0	1.0	.2	-
Assoc./dissolved gas (TCF)				
Conditional	.1	2.5	.7	.3
Unconditional	0	1.3	.2	-
Non-assoc. gas (TCF)				
Conditional	<.1	5.8	1.5	.4
Unconditional	0	2.9	.6	-
Aggregated gas (TCF)				
Conditional	.26	7.2	2.24	.58
Unconditional	0	3.2	.82	-

TECHNOLOGY

Estimated development time table: Estimating development of hydrocarbon prospects in the northern Aleutian continental shelf is difficult. The weather here is comparable to that of the North Sea between England and Norway where successful petroleum production is now underway at about the same latitude. The adverse weather and sea conditions as well as the great distances from supply bases in the southern Bering Sea will probably cause delays in operations and increased costs.

Exploratory drilling would probably commence within two years after the lease sale. Assuming exploratory success, production platform installation would begin during the fifth or sixth year after the leases are issued and development drilling would be completed by the fifteenth year. Subsea completions may be included in this development phase. Peak oil production, as limited by marketing facilities, would occur about the eighth year after the lease sale. Individual fields would have a 26-year life and all platforms will be removed by the fortieth year after production beings.

Based on present arctic regional experience, it is estimated that giant-class fields of a minimum of 100 million barrels can be developed economically; however, the rapidly escalating price of oil and the feasibility of economical ship transport of oil and gas to the U. S. West Coast may justify development of smaller fields.

If 5 million barrels are recovered per well, then 40 wells per production platform yields the following figures for the daily production of oil and gas given the conditional or unrisked minimum, maximum, and most likely cases:

	95% Probability	5% Probability	Statistical Mean
Recoverable Oil BBbl.	0.1	2.3	0.7
Oil Fields (avg. 0.1 BBbl.)	1	23	7
Wells (including service)	30	290	210
Peak production MBD	41	945	288
Gas-oil ratio	1100	1000	1090
Peak gas production MMCFD	45	945	314

The number of service wells is based on North Sea experience, where there are about half as many service wells as there are production wells. The production figures assumes 15 percent production of recoverable reserves during the peak production year.

In the Bristol Bay basin a gas field not associated with oil production must contain about 2.5 trillion cubic feet of gas to be economically viable over a 20 year constant production life. The conditional or unrisked parameters for these minimum-sized gas fields are:

	95% Probability	5% Probability	Statistical Mean
Gas, TCF	0.1	5.8	1.5
Gas Fields	0	2	1
Gas MMCFD	0	795	205
Gas Wells	0	36	10

The number of gas wells required and daily production figures are based on average North Sea production experience. The 95 percent probability case and the mean case are too low to justify development except in conjunction with closely associated oil fields.

Gas not associated with oil that is found near oil-associated gas (gas cap and dissolved gas), could be economically shipped using the same pipelines used for oil transportation. During the early years of oil production, associated and nearby nonassociated gas are often injected into the oil reservoir to increase oil recovery. Depending on market conditions and engineering considerations, the demand on pipelines could be temporally spaced

to allow the use of a smaller, more economical system to transport both associated and nonassociated gas.

Estimated facilities: Exploration bases would probably be at Cold Bay, King Salmon, or Dillingham. All three have airports capable of handling medium-sized jet aircraft. These towns would require development of support facilities as they are small, and had populations in 1978 of 256, 202, and 914, respectively. Cold Bay and King Salmon are each U.S. Air Force bases. Port Heiden and Port Moller, sparsely populated areas on the Alaska Peninsula between Cold Bay and King Salmon, each have air strips large enough to handle smaller aircraft. These two areas would require extensive development to operate as exploration bases, but they are a centrally located for offshore exploration.

Cold Bay is large and can be entered by deep-draft vessels. In the bay there is a decaying dock and the adjacent water is 30 feet deep. King Salmon, 15 miles upstream from the mouth of the Naknek River, cannot be approached by ships. Vessels approaching Dillingham usually anchor offshore and transfer cargo to and from shore by smaller boats and barges. Vessels drawing 12 feet or less can moor at the cannery and fuel wharves only at high tide. Port Heiden and Port Moller do not have any docking facilities and cannot be closely approached by ships. Kodiak has three deep-draft municipal wharves and many private ones underlain by as much as 40 feet of water. Dutch Harbor has several deep water wharves and more are being built to support a rapidly expanding fishing industry.

Technology for successful drilling and production in northern offshore environments has been developed in Cook Inlet and in the North Sea. Secondary drilling platforms would probably be used in shallow water for exploratory drilling. Drill ships and semi-submersible vessels would be used for

Sea access to the proposed sale area is from the south via Unimak Pass around the western end of Unimak Island. Unimak Pass is 1,644 nautical miles from Seattle and about 4000 miles from Japan.

REFERENCES CITED

Askren, D. R., 1972, Holocene stratigraphic framework-southern Bering Sea continental shelf: Masters thesis, University of Washington.

Barth, T. W. F., 1956, Geology and petrology of the Pribilof Islands, Alaska: U. S. Geological Survey Bulletin 1028-F, p. 101-160.

Beikman, H., 1974, Preliminary geologic map of the southwest Quadrant of Alaska: U. S. Geological Survey Misc. Field Studies map MF-611, 2 sheets.

Berggren, W. A., 1969, Cenozoic chronostratigraphy, planktonic foraminiferal zonation and the radiometric time scale: Nature, v. 224, no. 5224, p. 1072-1075.

Brockway, R., Alexander, B., Day, P., Lyle, W., Hiles, R., Decker, W., Polski, W., and Reed, B., 1975, Bristol Bay region, "Stratigraphic correlation section", southwest Alaska: The Alaska Geological Society, P. O. Box 1288, Anchorage, AK 99510.

Buck, E. H. and others, 1974, The Bristol Bay environment, a background study of available knowledge: Dept. of the Army, Alaska District, Corps of Engineers, P. O. Box 7002, Anchorage, Alaska, 99510, 858 p.

Burk, C. A., 1965, Geology of the Alaska Peninsula Island arc and continental margin: Geol. Soc. America Mem. 99, 250 p.

Churkin, M., 1970, Fold belts of Alaska and Siberia and drift between North America and Asia: Proc. Geol. Seminar of the North Slope of Alaska, Pacific Sec., Am. Assoc. Petroleum Geologists, G1-G17.

Coats, R. R., 1950, Volcanic activity in the Aleutian arc: U. S. Geol. Survey Bull. 974-B, p. 35-47.

Cox, A., Hopkins, D. M., and Dalrymple, G. B., 1966, Geomagnetic polarity epochs: Pribilof islands, Alaska: Geol. Soc. America Bull., v. 77, p. 883-910.

Gates, G. O., and Gryc, G., 1963, Structure and tectonic history of Alaska, in Childs, O. E., and Beebe, B. W., eds., The Backbone of the Americas, A symposium: Am. Assoc. Petroleum Geologists Mem., v. 2, p. 264-277.

Gardner, J. V., Vallier, T. L., Dean, W. E., Kvenvolden, K. A., and Redden, G. D., 1979, Sedimentology and geochemistry of surface sediments and the distribution of faults and potentially unstable sediments, St. George Basin region of the outer continental shelf, southern Bering Sea: U.S. Geol. Survey Open-File Report 79-1562, 89 pp.

Hatten, C. W., 1971, Petroleum potential of Bristol Bay basin, Alaska: Am. Assoc. Petroleum Geologists Mem., 15, v. 1, p. 105-108.

Hoare, J. M., 1961, Geology and tectonic setting of lower Kuskokwim-Bristol Bay region, Alaska: Am. Assoc. Petroleum Geologists Bull., v. 45, no. 5, p. 594-611.

Hopkins, D. M., and others, 1969, Cretaceous, Tertiary, and early Pleistocene rocks from the continental margin in the Bering Se: Geol. Soc. America Bull., v. 80, p. 1471-1480.

Hopkins. D. M., and Silberman, M. L., 1978, Potassium-argon ages of basement rocks from Saint George Island, Alaska: U. S. Geological Survey Journal of Research, v. 6, p. 435-438.

Jones, D. L., 1978, Microplate tectonics of Alaska--significance for the Mesozoic history of the Pacific Coast of North America. Pages 71-74 in D. G. Howell and K. A. McDougall, eds. Mesozoic Paleogeography of the western United States. Pacific Coast Section, Soc. Econ. Paleontologists and Mineralogists, Pacific Coast Paleogeography Symposium, v. 2.

Jones, D. L., and Siberling, N. J., 1979, Mesozoic stratigraphy--the key to tectonic analyses of southern and central Alaska: U. S. Geological Survey Open-File Report 79-1200, 41 p.

Lisitsyn, A. P., 1966, Recent sedimentation in the Bering Sea (in Russian); Inst. Okeanol. Akad. Nauk USSR, (translated by Israel Program for Scientific Translation, available from U. S. Dept. of Commerce, Clearinghouse for Fed. Sci. and Tech Info., 1969, 614 pp.)

Lyle, W. M., Morehouse, J. A., Palmer, I. F., Jr., and Bolm, J. G., 1979, Tertiary formations and associated Mesozoic rocks in the Alaska Peninsula area, Alaska, and their petroleum-reservoir and source-rock potential: State of Alaska, Division of Geological and Geophysical Surveys, Geologic Report 62, 65 p.

Mancini, E. A., Deeter, T. M., and Wingate, F. H., 1978, Upper Cretaceous arc-trench gap sedimentation on the Alaska Peninsula: Geology, v. 6, p. 437-439.

Marlow, M. S., Alpha, T. R., Scholl, D. W., and Buffington, E. C., 1975, Physiographic diagrams of the Bering Sea Shelf, Alaska: U. S. G. S. Open File Report 75-1, 2 sheets.

Marlow, M. S., Scholl, D. W., Cooper, A. K., and Buffington, E. C., 1976a, Structure and evolution of the Bering Sea shelf south of St. Lawrence Island: Am. Assoc. Petroleum Geol. Bull., v. 60, p. 161-183.

Marlow, M. S., McLean, H., Vallier, T. L., Scholl, D. W., Gardner, J. C., and Powers, R. B., 1976b, Prenomination report on the regional geology, ol and gas potential and environmental hazards of the Bering Sea shelf south of St. Lawrence Island, Alaska: U. S. Geol. Survey Open- File Report 76-785, 60 p.

Marlow, M. S., Scholl, D. W., and Cooper, A. K., 1977, St. George basin, Bering Sea shelf: a collapsed Mesozoic margin, in Island Arcs, Deep Sea Trenches, and Back-Arc Basins, Maurice Ewing series: Amer. Geophysical Union, v. 1, p. 211-220.

Marlow, M. S., Scholl, D. W., Cooper, A. K., and Jones, D. L., 1979a, Mesozoic rocks from the Bering Sea: The Alaska-Siberia Connection: (abs.) Cordilleran Section Geol. Soc. Amer. Ann. Mtg. 1979, v. 11, no. 3, p. 90.

Marlow, M. S., Cooper, A. K., Scholl, D. W., Vallier, T. L., and McLean, H., 1979b, Description of dredge samples from the Bering Sea Continental Margin: U. S. Geological Survey Open-File Report OF79-1139, 5 p.

Marlow, M. W., and Cooper, A. K. 1980, Mesozoic and Cenozoic structural trends beneath the southern Bering Sea shelf: Am. Assoc. Petroleum Geol. Bull., in prep.

McLean, H., 1977, Organic geochemistry, lithology, and paleontology of Tertiary and Mesozoic rocks from wells on the Alaska Peninsula: U. S. Geological Survey Open-File Report 77-813, 63 p.

McLean, H., 1979, Tertiary stratigraphy and petroleum potential of Cold Bay-False Pass area, Alaska Peninsula: Am. Assoc. Petroleum Geol. Bull, v. 63, p. 1522-1526.

McRoy, C. P., and Goering, J. J., 1974, the influence of ice on the primary productivity of the Bering Sea, in Hood, D. W., and Kelley, E. J., eds., Oceanography of the Bering Sea with emphasis on renewable resources, p. 403-419.

Miller, B. M., and others, 1975, Geological estimates of undiscovered recoverable oil and gas resources in the United States: U. S. Geol. Survey Circular 725, 78 p.

Miller, T. P., and Smith, R. L., 1977, Spectacular mobility of ash flows around Aniakchak and Fisher Calderas, Alaska: Geology, v. 5, p. 173-176.

Moore, J. C., 1972, Uplifted trench sediments-Southwestern Alaska-Bering Shelf edge: Science, v. 175, p. 1103-1105.

_____, 1973a, Cretaceous continental margin sedimentation, southwestern

Alaska: Geological Soc. of Amer. Bull., v. 84, p. 596-614.

_____, 1973b, Complex deformation of Cretaceous trench deposits, southwestern Alaska: Geological Soc. of Amer. Bull. v. 84, p. 2005-2020.

_____, 1974, The ancient continental margin of Alaska, in Burk, C. A., and Drake, C. L., eds., The geology of continental margins: New York Springer-Verlag, p. 811-816.

Nelson, C. Hans, Hopkins, David M., and Scholl, David W., 1974, Cenozoic sedimentary and tectonic history of the Bering Sea: In Hood, D. W. and Kelley, E. J. (Eds.), Oceanography of the Bering Sea, Occasional Pub. No. 2, Inst. of Marine Science, University of Alaska, Fairbanks, p. 485-516.

Patton, W. W., Jr., 1973, Reconnaissance geology of the northern Yukon-Koyukuk Province, Alaska: U. S. Geol. Survey Prof. Paper 774-A, 17 p.

Patton, W. W., Jr., Lanphere, M. A., Miller, T. P., and Scott, R. A., 1974, Age and tectonic significance of volcanic rocks on St. Matthew Island, Bering Sea, Alaska (abs.): Geol. Soc. America Abs. with Programs, v. 6, p. 9905-9906.

Patton, W. W., Jr., Lanphere, M. A., Miller, T. P., and Scott, R. A., 1976, Age and tectonic significance of volcanic rocks on St. Matthew Island, Bering Sea, Alaska: U. S. Geological Survey Jour. of Research, v. 4, p. 67-74.

Payne, T. G., compiler, 1955, Mesozoic and Cenozoic tectonic elements of Alaska: U. S. Geol. Survey Misc. Geol. Inv. Map I-84, Scale 1:5,000,000.

Pratt, R. M., Rutstein, M. S., Walton, F. W., and Buschur, J. A., 1972, Extension of Alaska structural trends beneath Bristol Bay, Bering shelf, Alaska: Jour. Geophys. Research, v. 77, no. 26, p. 4994-4999.

Scholl, D. W., Buffington, E. C., and Hopkins. D. M., 1966, Exposure of basement rock on the continental slope of the Bering Sea: Science, v.

153, p. 992-994.

Scholl, D. W., Buffington, E. C., and Hopkins, D. M., 1968, Geologic history of the continental margin of North America in Bering Sea: Marine Geology, v. 6, p. 297-330.

Scholl, D. W., and Hopkins, D. M., 1969, Newly discovered Cenozoic basins, Bering shelf, Alaska: Amer. Assoc. Petroleum Geologists Bull., v. 53, p. 2067-2078.

Scholl, D. W., and Hopkins, D. M., 1969, Newly discovered Cenozoic basin, Bering Sea shelf, Alaska: Am. Assoc. Petroleum Geologists Bull., v. 53, no. 10, p.2067-2078.

Scholl, D. W., Alpha, T. R., Marlow, M. S., and Buffington, E. C., 1975, Plate tectonics and the structural evolution of the Aleutian-Bering Sea region: Geol. Soc. america Mem., 151, p. 1-31.

Sharma, G. D., Naidw, A. S., and Hood, D. W., 1972, Bristol Bay: A model contemporary graded shelf: Amer. Assoc. Petroleum Geologists Bull., v. 56, p. 2000-2012.

Sharma, G. D., 1974, Contemporary depositional environment of the eastern Bering Sea: In Hood, D. W., and Kelley, E. J. (Eds.), Oceanography of the Bering Sea, Occasional Pub. No. 2, Inst. of Marine Science, University of Alaska, Fairbanks, p. 517-540.

Sharma, G. D., 1975, Contemporary epicontinental sedimentation and shelf grading in the southeast Bering Sea: In Forbes, R. B. (Ed.), Contributions to the geology of the Bering Sea Basin and adjacent regions, Geol. Soc. Amer. Spec. Paper 151, p. 33-48.

Sykes, Lynn R., 1971, Aftershock zones of great earthquakes, seismicity gaps, and earthquake predicion for Alaska and the Aleutian: Jour. Geophys. Res., v. 76, p. 8021-8041.

Vallier, T. L. and Gardner, J. V., 1977, Maps showing types and data of faults interpreted from seismic profiles in the St. George Basin, southern Bering Sea: U. S. Geol. Survey Open-File Report 77-591, 14 pp. plus maps.

Vallier, T. L., Underwood, M. B., Jones, D. L., and Gardner, J. V., 1980a, Petrography and geological significance of Upper Jurassic rocks dredged near Pribilof Islands, southern Bering Sea continental shelf: AAPG Bulletin, in press.

Watts, A. B., 1975, Gravity field of the northwest Pacific ocean basin and its margin - Aleutian Island arc. Trench system, Geol. Soc. America Map - Chart Series MC-10.

Yanshin, A. L., ed., 1966, Tectonic map of Eurasia: Geol. Inst. Acad. Sci. U.S.S.R., Moscow (in Russian), scale 1:5,000,000.