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Chapter 8

Geology of the eastern Bering Sea continental shelf

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INTRODUCTION

The Bering Sea shelf south of the Bering Strait encompasses an area of 1,300,000 km^2, more than the combined area of California, Oregon, and Washington (840,000 km^2, Fig. 1). The shelf area lies between western Alaska and eastern Siberia. The outer shelf is underlain by three large basins, Bristol, St. George, and Navarin, filled with sedimentary rocks, as well as by three bedrock ridges that extend from the Alaska Peninsula to near Siberia (Figs. 1 and 2). The innermost part of the shelf, Norton Sound, is underlain by the large, sediment-filled Norton basin (Fig. 1; Fisher and others, 1982). A similar inner basin, Anadyr basin, underlies the Gulf of Anadyr along the western side of thee Bering shelf (Fig. 1).

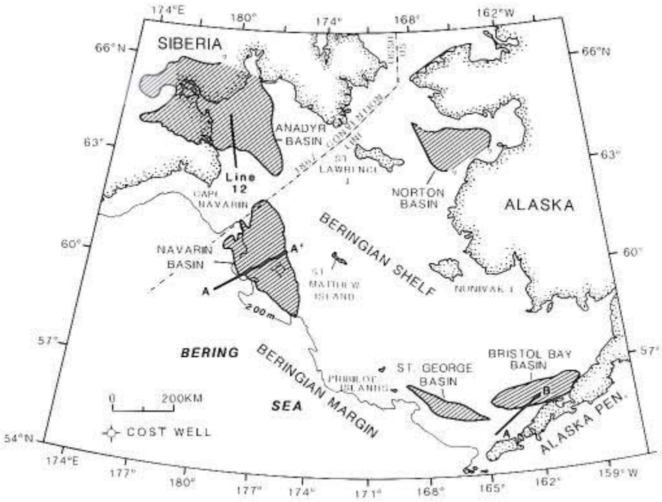

Figure 1. Outline and location of major basins beneath the Bering Sea shelf. See Table 1 for the sizes of the various basins. Location of seismic reflection profile across Navarin basin is shown by line A-A′ (see Fig. 10 for the profile). Albers equal-area projection.

Setting

The Bering shelf south of the Bering Strait is underlain by five large sedimentary basins that encompass 280,000 km^2 of the shelf. Three of them, the Norton, Anadyr, and Bristol Bay basins, are large structural sags in the Earth's crust, formed by block-faulting and down-dropping of the bedrock or basement beneath the basins. Two of the basins, Navarin and St. George, are grabens and half-grabens, which formed by extension and collapse of the outer Bering Sea margin. The latter basins are filled with 10 to 15 km of strata of mainly Cenozoic age.

Except for Anadyr, the shelf basins are mainly Cenozoic features that developed after the amalgamation of Alaska at the end of the Mesozoic. The oldest sedimentary units recovered from a well in Norton basin are Eocene in age. The oldest sedimentary bodies drilled in Anadyr basin are Cretaceous and those drilled in Navarin basin are Late Cretaceous. The bottom basin fill drilled along the flanks of St. George basin is Eocene in age.

Regional geologic studies onshore in western Alaska, along the Alaska Peninsula, and in eastern Siberia suggest that suitable source rocks for the generation of hydrocarbons exist offshore in the basins of the Bering Sea shelf. Also, the sedimentary fill in the offshore basins is sufficiently thick to favor the thermal development of hydrocarbons. Twenty onshore wells in Anadyr basin, nine onshore wells on the Alaska Peninsula, five offshore COST (Continental Offshore Stratigraphic Test) wells in the shelf basins, several offshore Deep Sea Drilling Project sites, and dredge samples from the Bering Sea continental margin all show that adequate reservoir beds of late Cenozoic age probably exist within the shelf basins. Seismic reflection data show large structural traps within the basin fills of the Bering subshelf. Such traps include anticlines, diapiric structures, growth-faults, stratigraphic pinch-outs against the bedrock flanks of the basins, discordant overlap of the basins' lower stratigraphic section by the overlying younger sequence, and drape structures formed by differential compaction of the basins' lower sequence over bedrock highs.

REGIONAL FRAMEWORK OF THE BERING SEA SHELF

Mesozoic structural trends

Large onshore geologic features in western Alaska strike toward the Bering Sea shelf, such as major strike-slip faults and tectonostratigraphic terranes. Two major strike-slip faults, the

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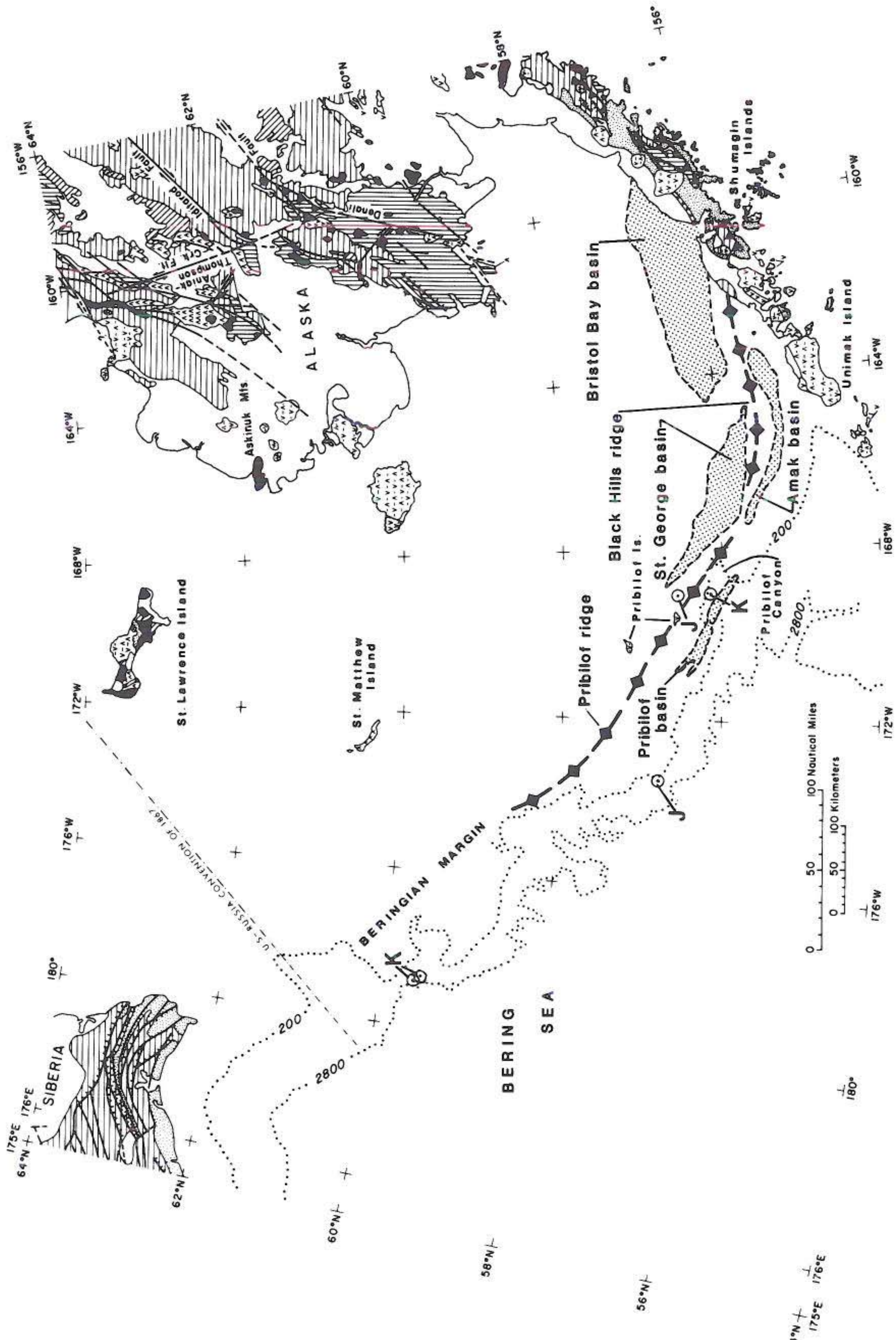

SIBERIA
ALASKA
BERING SEA
BERINGIAN MARGIN
Bristol Bay basin
Black Hills ridge
St. George basin
Amak basin
Pribilof ridge
Pribilof basin
Pribilof Is.
Pribilof Canyon
St. Lawrence Island
St. Matthew Island
Shumagin Islands
Unimak Island
Askinuk Mts
Iditarod Fault
Denali Fault
Aniak-Thompson Crk. Flt
U.S.-RUSSIA CONVENTION OF 1867
200
2800
100 Nautical Miles
100 Kilometers

EXPLANATION

- Surficial deposits including glacial drift.
- Tertiary and Quaternary volcanic rocks. Includes basaltic rocks on Nunivak, Nelson, and St. Lawrence Islands, and interbedded basalt and andesite along the northern Alaska Peninsula.
- Tertiary volcanic rocks. Basalt and andesite flows and some rhyolite, trachyte, and latite.
- Tertiary sedimentary rocks.
- Cretaceous and Tertiary volcanic rocks.
- Jurassic, Cretaceous, and Tertiary granite rocks.
- Undifferentiated Jurassic and Cretaceous volcanic and sedimentary rocks.
- Undifferentiated Palozoic and Mesozoic volcanic and sedimentary rocks. Includes the Gemuk Group of southwestern Alaska.
- Undifferentiated Paleozoic volcanic and sedimentary rocks. (In part metamorphosed.)
- Undifferentiated Precambrian volcanic and sedimentary rocks.
- Ridge crest.
- Normal fault, hachures on downthrown side, dashed where inferred.
- Thrust fault, barbs on upthrown side.
- Bathymetric contours in meters.

Figure 2. Generalized geology of western Alaska, Alaska Peninsula, and eastern Siberia. Onshore geology modified from Burk (1965), Yanshin (1966), and Beikman (1974; this volume). Dots enclosed by circles show sites where Jurassic (J) and Cretaceous (K) sedimentary rocks were dredged from the continental slope. Adapted from Marlow and Cooper (1980a). Albers equal-area projection.

Kaltag and the Denali faults, trend southwest from central and western Alaska toward the Bering Sea. The Goodnews and Togiak tectonostratigraphic terranes trend from western Alaska toward the Bering Sea (Jones and Silberling, 1979; Silberling and others, this volume, Plate 3); they continue offshore at least 50 to 100 km (Cooper and Marlow, 1983).

Gravity, magnetic, seismic reflection, dredge, and drill data suggest that the Upper Jurassic, shallow-marine rocks exposed in the Black Hills on the Alaska Peninsula extend west to northwest along the south flank of St. George basin and connect with Pribilof Ridge (Fig. 2; Marlow and Cooper, 1980a). In addition, Upper Cretaceous (Campanian) rocks were dredged from the southern flank of this ridge in nearby Pribilof Canyon (Fig. 2; Hopkins and others, 1969). Seismic reflection data show that the Cretaceous dredge samples may have been recovered from an isolated, intrabasement rock sequence that is folded into the flank of Pribilof Ridge (Marlow and Cooper, 1980b). Other dredge samples along the margin show that Mesozoic bedrock is unconformably overlain by shallow-water, diatomaceous mudstone of early Tertiary age (Jones and others, 1981).

The Upper Jurassic rocks that extend offshore beneath the Bering shelf are coeval with the Naknek Formation exposed along the Alaska Peninsula (Burk, 1965), and both Jurassic sections are part of the Peninsular terrane of Jones and Silberling (1979). The Peninsular terrane extends about 1,200 km from south-central Alaska to the western tip of the Alaska Peninsula (Fig. 3). Paleomagnetic studies of Mesozoic rocks from the Peninsular terrane suggest that the terrane originated at a paleolatitude south of the equator in Jurassic time (Packer and Stone, 1972; Stone and others, 1982). Geologic data suggest that the docking of the Peninsular terrane against the ancient North American continent was complete by the end of the Mesozoic (see Marlow and Cooper, 1983, for more detailed discussion of the docking time of the Peninsular terrane).

The offshore part of the Peninsular terrane can be traced by geophysical and dredge data about 1,000 km beneath the outer shelf of the Beringian margin (Figs. 2 and 3). Thus, docking of the Peninsular terrane in southern Alaska probably coincided in time with docking along the Beringian margin. Formation of the margin at the end of the Mesozoic presumably occurred about the same time that the large outer shelf basins, such as St. George and Navarin, began to form and fill with sediment.

We proposed in an earlier paper (Marlow and others, 1976) that a Jurassic, Cretaceous, and earliest Tertiary magmatic arc extended parallel to and inside (landward or toward Alaska) the outer shelf basins. This igneous belt is characterized by high-amplitude, high-frequency magnetic anomalies (Marlow and others, 1976). The magmatic arc is exposed as calc-alkalic volcanic and intrusive rocks of late Mesozoic and earliest Tertiary age on St. Matthew and St. Lawrence Islands on the Bering shelf and as similar rocks in southern and western Alaska and eastern Siberia (Reed and Lanphere, 1973; Patton and others, 1974, 1976; Scholl and others, 1975; Marlow and others, 1976). However, Cooper and Marlow (1983) suggest that the southern, inner

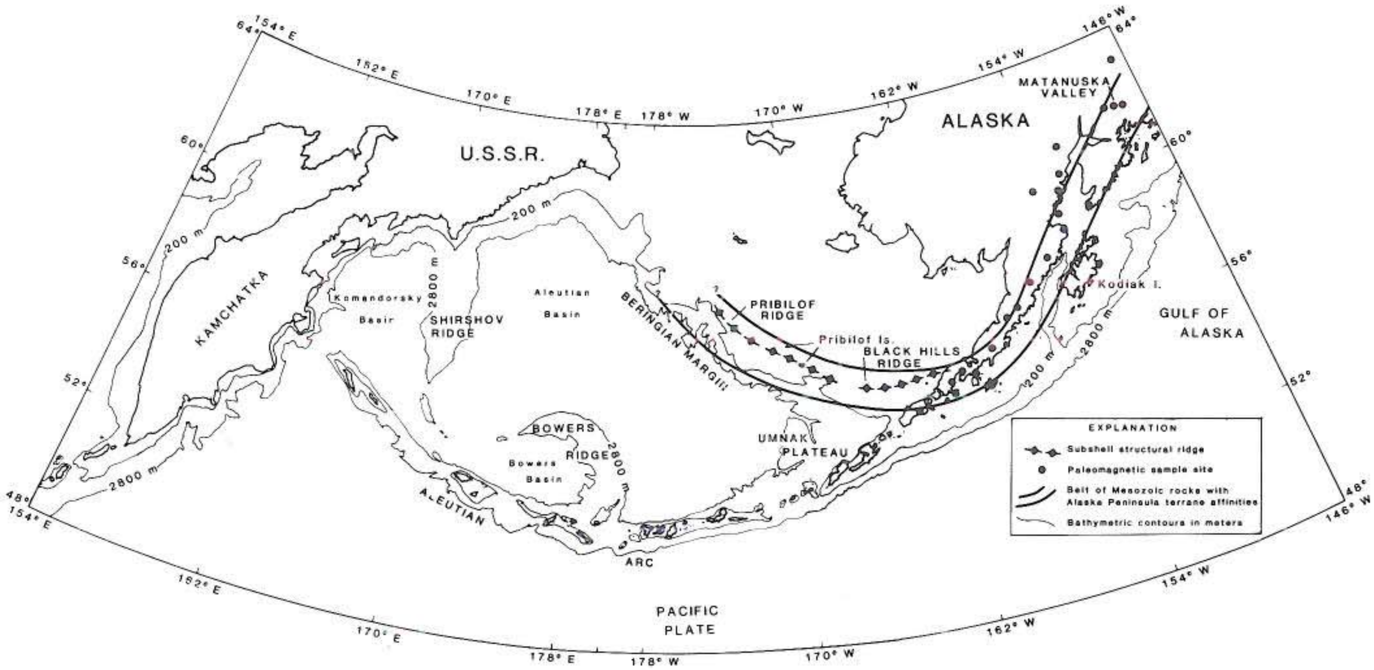

Figure 3. Locations of sample sites used in paleomagnetic studies of southern Alaska by Stone and others (1982). Offshore extension of the Peninsular terrane is shown by diamond pattern over bedrock ridges beneath the outer Bering Sea shelf (from Marlow and Cooper, 1980a). Adapted from Marlow and Cooper (1983).

Bering shelf is underlain in part by offshore extensions of allochthonous terranes of southern Alaska (Jones and Silberling, 1979; McGeary and Ben-Avraham, 1981). Whether these terranes merge with the Mesozoic igneous belt near St. Matthew Island is not known.

Cenozoic isolation and collapse

Plate motion along the Bering Sea margin apparently ceased with the formation of the Aleutian Island Arc in earliest Tertiary time, when the plate boundary shifted from the Bering Sea margin to a site near the present Aleutian Trench, thereby trapping a large section of oceanic plate (Kula?) within the abyssal Bering Sea (Scholl and others, 1975; Cooper and others, 1976a, b; Marlow and others, 1976; Marlow and Cooper, 1985). Cessation of the plate motion isolated and deactivated the Bering Sea margin. In early Tertiary time, the margin underwent extensional deformation and differential subsidence, which has continued throughout the Cenozoic. Elongate basins of great size and depth, such as the St. George and Navarin basins, formed along the modern outer Bering Sea shelf (Fig. 1; Marlow and others, 1976), while parts of the inner shelf also subsided, forming Bristol Bay and Norton basins. Extensional deformation of the folded rocks of the Mesozoic bedrock beneath the shelf has continued to the present, as evidenced by the normal faults flanking the outer shelf basins that commonly offset the sea floor. These normal faults are growth-type structures that typically rupture the entire Cenozoic basin fill. Collapse of the outer shelf and adjacent margin may have been aided by Cenozoic sediment-loading and continued subsidence of the adjacent oceanic crust (Kula? Plate) flooring the Aleutian Basin of the abyssal Bering Sea.

ST. GEORGE BASIN

Description

St. George basin is a long (300 km) and narrow (30 to 50 km) graben whose long axis strikes northwestward parallel to the trend of the Beringian margin (Figs. 1, 2, and 4, Table 1). The basin, near the Pribilof Islands and beneath the virtually featureless shelf, is filled with more than 10 km of sedimentary deposits.

A tracing of a 24-channel seismic reflection profile, 8B, across St. George basin, is shown in Figure 5. The flat acoustic basement or bedrock surface underlying the southwest end of

TABLE 1. SEDIMENTARY BASINS IN THE BERING SHELF

Basin Name	Length (km)	Width (km)	Area (km^2)
Bristol Bay	290	75	21,750
St. George	300	50	15,000
Navarin	400	90	76,000
Anadyr	400	300	120,000
Norton	250	180	45,000

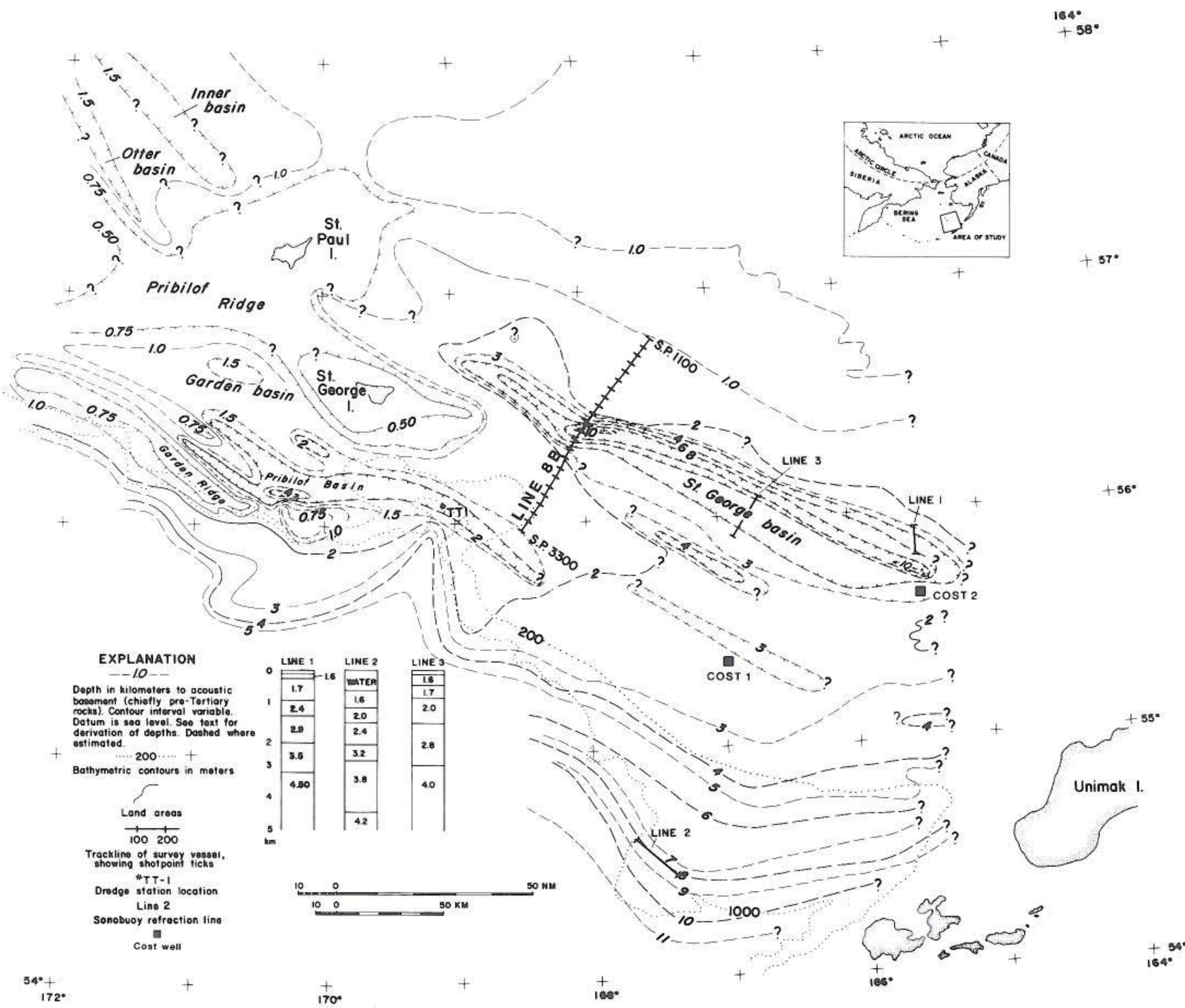

Figure 4. Structure-contour map of bedrock or acoustic basement beneath the southern Bering Sea shelf surrounding St. George basin. Line with shotpoint ticks and numbers (Line 8B) is profile 8B shown in Figure 5. Lines marked 1, 2, and 3 correspond to sonobuoy refraction stations shown in lower left of the figure (unnumbered top layer is sea water with an assumed velocity of sound of 1.5 km/s). Cretaceous dredge site in Pribilof Canyon is marked TT1 and corresponds to the site shown on Figure 2. Adapted from Marlow and others (1977).

profile 8B (Fig. 5; between shotpoints 3200 and 2700) is Pribilof ridge, which is overlain by an undisturbed, layered sequence 1.3 to 1.4 km thick (1.3 to 1.4 s). Beneath the flat-lying sequence are dipping reflectors within the bedrock of Pribilof ridge that suggest the ridge includes folded sedimentary beds (Jurassic Naknek[?] Formation). Farther north, between shotpoints 2700 and 2200, the basement or bedrock surface descends in a series of down-to-basin steps, plunging to a maximum subbottom depth of about 5.4 s (more than 10 km) beneath the axis of St. George basin. The overlying beds are broken by at least three major normal faults that dip toward the basin axis and appear to be related to offsets in the basin's bedrock. Within the basin fill, the offset along the faults increases with depth, implying that these are growth structures. Strata are synclinally deformed about the basin's structural axis. From shotpoints 2200 to about 1860, the bedrock surface rises rapidly to a minimum depth of 500 m (0.55 s; Fig. 5). Overlying strata are broken by normal faults that dip down to the basin axis.

TABLE 2. STRATIGRAPHIC SEQUENCES PENETRATED AT ST. GEORGE BASIN COST WELLS

Ate	Depth to Top (m)
COST Well No. 1	
Pliocene	487
Miocene	1,097
Oligocene	1,636
Eocene	2,563
Igneous	3,163
Basement (age unknown)	
COST Well No. 2	
Pliocene	445
Miocene	1,294
Oligocene	1,844
Eocene(?)	3,378
Early Cretaceous or Late Jurassic	3.822
Late Jurassic	4,075

Age and history

Two COST wells were drilled into the St. George basin, and data from those two wells are extensively described by Turner and others (1984a, b). We present below a short summary of each well taken from their report (Table 2). The first St. George COST well, 170 km southeast of St. George Island, Alaska, was drilled in 1976 to a total depth of 4,197 m in water 135 m deep. The second St. George COST well was drilled in 1982 to a total depth of 4,458 m in water 114 m deep, about 180 km northwest of Cold Bay, Alaska Peninsula.

The Cenozoic sedimentary section penetrated in the wells includes interbedded sandstone, siltstone, mudstone, diatomaceous mudstone, and conglomerate. The section was derived predominantly from volcanic source terranes, and the detrital material is mechanically and chemically unstable. Porosity and permeability in the section are reduced by ductile deformation of individual sediment grains, and by cementation and diagenesis of the section.

The Mesozoic sedimentary section at the bottom of the COST No. 2 well consists of shallow marine sandstone, siltstone, shale, conglomerate, and minor amounts of coal. Porosities and permeabilities in this section are also low.

BRISTOL BAY BASIN

Description

Underlying a large portion of the Bering Sea shelf, north of the Alaska Peninsula, is a sediment-filled structural depression known as Bristol Bay basin (Fig. 1, Table 1). The sedimentary deposits along the southern flank of the basin are exposed on the northern fringe of the Alaska Peninsula. The basin trends northeastward along the peninsula, about four-fifths of it lies offshore beneath the flat Bering Sea shelf. The basin is asymmetrical in cross section; the basement rocks of the northwest flank dip gently toward the basin axis, but the southeast flank of folded Jurassic rocks is steeply inclined, probably faulted, and crops out in the northern foothills of the Alaska Peninsula. The basin's sedimentary section, more than 6,000 m thick, is composed chiefly of Cenozoic deposits; they are thickest in the southeast part of the basin.

The northeast end of Bristol Bay basin is bounded by exposures of highly deformed, locally intruded, metamorphosed Paleozoic and Mesozoic rocks (Hatten, 1971). To the southwest, the basin is bordered by the offshore extension of the Black Hills, an anticlinal structure composed of Jurassic sedimentary rocks (Fig. 2; Marlow and Cooper, 1980a). South of the basin, the basement consists mainly of Mesozoic and Cenozoic volcanic and plutonic units that form the core of the Alaska Peninsula (McLean, 1977). To the north, beneath the Bering Sea shelf, the acoustic basement (as shown on geophysical records) flooring the basin probably consists of Mesozoic sedimentary, igneous, and metamorphic rocks.

The interpreted section of a 24-channel seismic reflection profile shown in Figure 6 illustrates the spatial relation of such large subshelf structures as the Amak basin, the Black Hills ridge, and the Bristol Bay basin (see Fig. 1 for location). Near the center of the profile, at a subbottom depth of about 1.0 s, moderately dipping strata are resolved within the core of a bedrock ridge, informally called the Black Hills ridge after similarly deformed rocks exposed nearby in the Black Hills of the Alaska Peninsula. Strata in the Black Hills ridge are cut by a major unconformity (Fig. 6). The age of this unconformity may be Cretaceous in age because middle Cretaceous rocks are missing on the nearby Alaska Peninsula owing to uplift and erosion (Burk, 1965). The unconformity can be traced to the east into Bristol Bay basin, where the surface of the unconformity appears to grade into a depositional contact having parallel reflectors above and below it (Fig. 6). If this horizon is indeed Cretaceous in age, then the layered strata beneath it could be 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 the Amak basin along the western end of the same profile (Fig. 6). However, a major unconformity along the Bering Sea continental margin west of Bristol Bay basin is early Tertiary in age (Marlow and Cooper, 1985). If the unconformity along the margin is contemporaneous with the cutting of the Black Hills ridge, then the Bristol Bay and Amak basins may be no older than early Tertiary.

As shown by the northeastern half of profile A-B, Bristol Bay basin is a long structural sag containing more than 6.6 km (4.5 s) of moderately dipping to flat-lying reflectors (Fig. 6). The upper half of the fill (above the heavy line) is virtually flat lying and undeformed, and we interpret it to be late Cenozoic in age. The lower half of the basin fill contains discontinuous and dip-

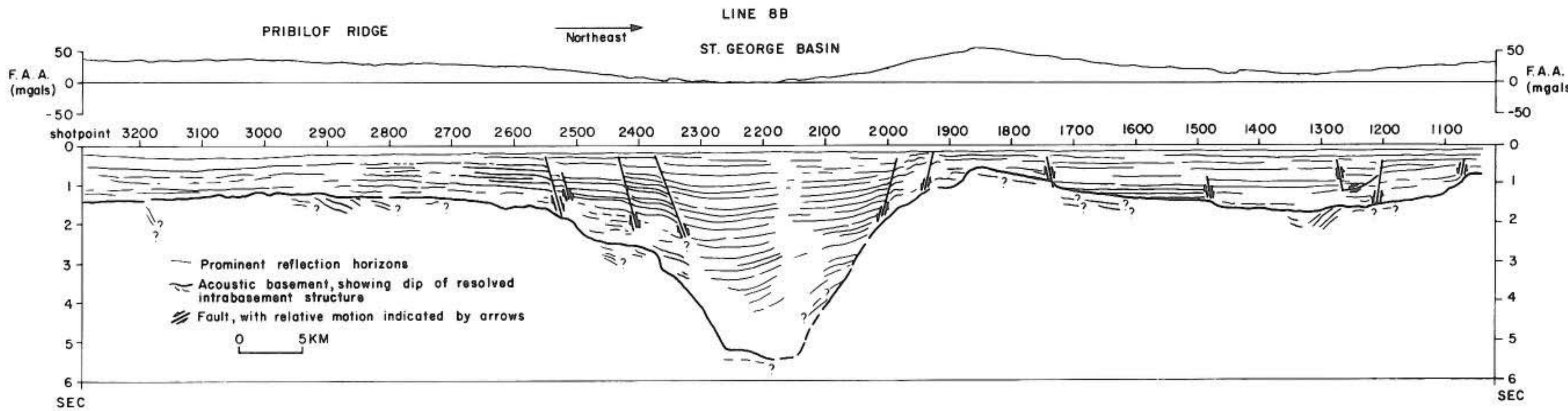

Figure 5. Interpretive drawing of seismic reflection profile 8B across St. George basin. The vertical exaggeration applies only to the water layer (assumed velocity of sound in sea water of 1.5 km/s) and will decrease with depth in the section. For location of profile, see Figure 4. Adapted from Marlow and others (1977).

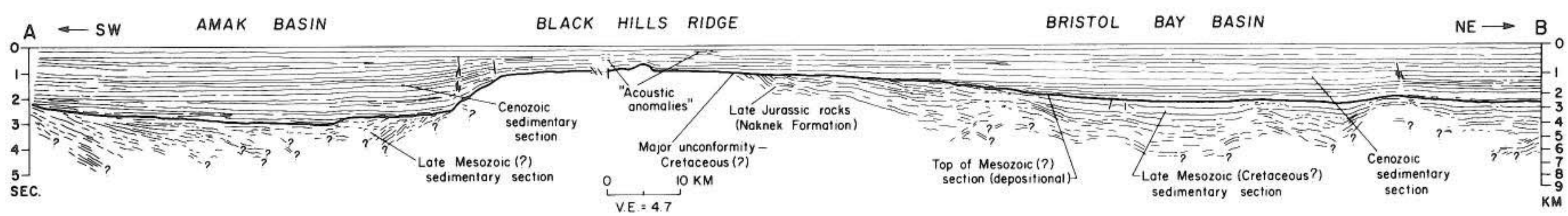

Figure 6. Interpretive drawing of 24-channel seismic reflection profile A-B across the southern Bering Sea shelf and the western end of Bristol Bay basin. For location of profile see Figure 1. Travel time, in seconds, is two-way time. From Marlow and Cooper (1980a).

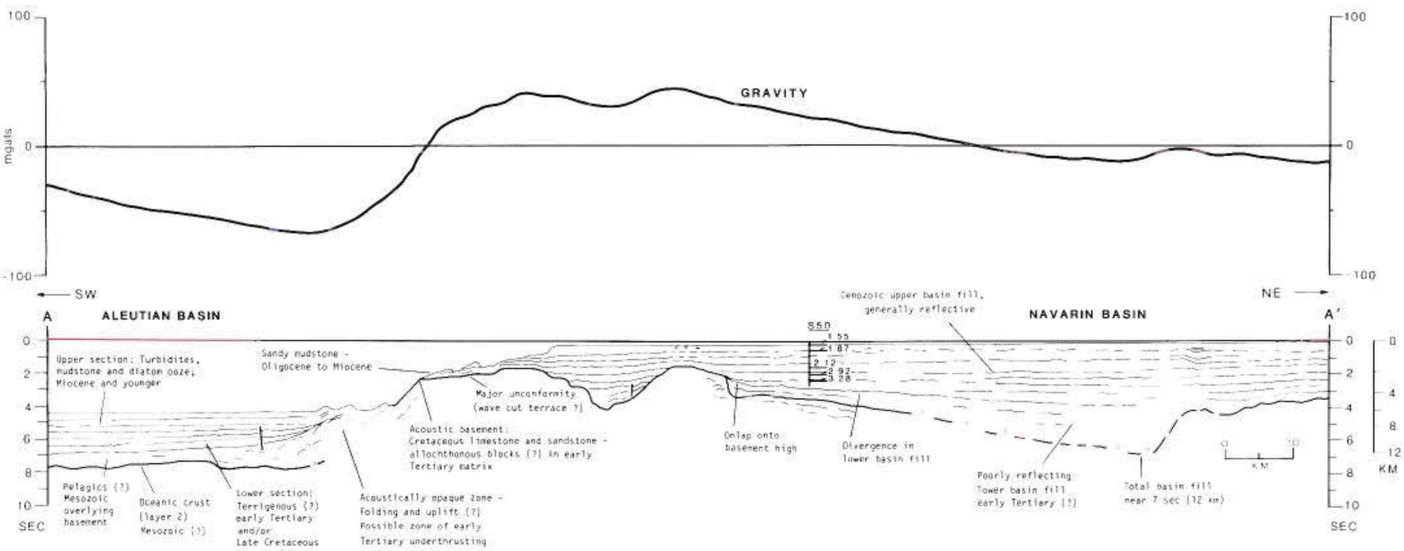

Figure 7. Interpretive drawing of seismic reflection and gravity profiles across the northern Beringian margin and Navarin basin. For location see A-A′ on Figure 1. The strong reflector beneath the Aleutian Basin can be traced beneath the base of the margin into an acoustically opaque zone. The thick sedimentary fill in Navarin basin extends to a subshelf depth of about 12 km. Adapted from Marlow and Cooper (1985).

ping reflectors, which suggest gentle folding and draping over older basement (bedrock) highs. Our profile was recorded to a subbottom depth of 5 s, which indicates that Bristol Bay basin is filled with more than 6 to 7 km of strata. The nearby Gulf Sandy River No. 1 well on the Alaska Peninsula bottomed in Oligocene sedimentary rocks of the Stepovak Formation at a total depth of about 4 km without reaching a basement or bedrock complex (Hatten, 1971; Brockway and others, 1975), indicating that the adjacent Bristol Bay basin may contain a much thicker Cenozoic sedimentary section.

Age and history

Only one COST well has been drilled in Bristol Bay basin, and data from that well are proprietary. Thus, little is publicly known about the stratigraphy and age of the fill in the offshore portions of the basin.

Bristol Bay basin, as a distinct structural trough, probably began to form in late Mesozoic or early Tertiary time, and the basin has continued to subside during most of Cenozoic time. The basin probably began to form after the docking of the Peninsular terrane in late Mesozoic time and during the formation of the ancestral Aleutian Island arc in earliest Tertiary time (Scholl and others, 1975, 1987; Marlow and others, 1976; Marlow and Cooper, 1983, 1985).

NAVARIN BASIN

Description

The Navarin basin province underlies the northwest corner of the Bering Sea shelf just south of Cape Navarin of eastern Siberia (Fig. 1). Isopach contours of sediment thickness derived from seismic reflection data define three basins within the province that contain 10 to 15 km of strata and underlie about 76,000 km^2 of the Bering Sea shelf (Table 1; Marlow, 1979).

A 160-km-long seismic reflection profile, A-A′ (see location on Fig. 1), transects the northwestern Beringian margin west of St. Matthew Island, and an interpretive drawing of the profile (Fig. 7) crosses on to the Aleutian Basin (southwestern end of profile) in water more than 3,000 m (4.0 s) deep. Underlying the basin floor are 4 to 5 km of undeformed strata that overlie a distinct acoustic basement. Magnetic and refraction-velocity data suggest that the basement is oceanic crust of Mesozoic age (Kula? plate; Cooper and others, 1976a, b).

Below the lower part of the continental slope, the rock sequence is characterized by scattered and discontinuous reflectors (Fig. 7). Oceanic basement was not resolved. In contrast, a strong basal reflector, a subshelf basement, can be traced beneath the continental slope to a basement outcrop. Dredged rocks from this exposure, and the flatness of the subslope basement surface, suggest that it is a wave-base unconformity cut across broadly folded rock sequences. These dredge and seismic reflection data attest that the subslope basement platform has subsided from a former shelf depth to at least 1,500 to 1,700 m since about Oligocene time (Marlow and Cooper, 1985).

Basement beneath the shelf can be followed to the northeast below the thick sedimentary section filling Navarin basin (Fig. 7). Near the northeastern end of the profile, strata in the basin are 12 km (7 s) thick. Reflections from the upper basin fill are strong, continuous, and flat. Apparent breaks in the continuity of these reflectors are associated with columnar "wipe-out" zones beneath short discontinuous reflectors in the upper few hundred meters of the section. The acoustic "wipe-out" zones may be produced by shallow accumulations of gas that mask the lateral continuity of deeper reflectors (Marlow and others, 1982). Dredge data originally indicated that the upper 3 to 4 km of the Navarin basin section included beds younger than Oligocene. Deeper strata are poorly reflective, diverge in dip from the overlying strata, and near the base of the section may be early Tertiary in age (Marlow and Cooper, 1985). In 1983, the basin's stratigraphic sequence was explored at a COST well.

Age and history

The Navarin basin province has been covered by many geophysical surveys, thus allowing the mapping of major basins and major structures capable of trapping hydrocarbons. The geologic history of the Navarin basin is poorly known because only one COST well has been drilled in the basin. The well, located on Figure 1, was drilled in 1983 to a total depth of 4,998 m in water 132 m deep (Table 3). Data from this well are described extensively in Turner and others (1984c).

The Cenozoic sedimentary section sampled includes silty and sandy mudstone, diatomaceous mudstone, muddy and fine-grained sandstone interbedded with sandy mudstone, and claystone. The Upper Cretaceous section consists of siltstone, fine-grained sandstone, mudstone, claystone, tuff, and coal. The sedimentary section below 335 m and above 3,895 m was deposited in a marine environment, whereas the section between 3,895 and 4,663 m was deposited in fluvial, flood-plain, and deltaic environments. The section from 3,901 to 4,587 m of Upper Cretaceous strata is intruded by numerous basaltic and diabasic sills. Minimum K-Ar dates on the igneous samples suggest that the emplacement of the sills was in late Oligocene or early Miocene time.

Dredge samples were recovered from the continental slope near the base of the section overlying the structural highs that flank Navarin basin. These samples are Paleocene to Oligocene in age (Jones and others, 1981). While it is difficult to trace this early Tertiary section into the subshelf basins in the Navarin basin, we suspect that a thick Cenozoic section fills the basins. The dipping strata observed in the lower fill of the basin are probably in large part early Tertiary in age. The flat-lying overlying section is probably Miocene and younger. In places, the upper section is broadly folded and truncated, especially in the northeastern end of Navarin basin. This period of deformation may be related to late Miocene and Pliocene uplift and folding in the nearby Koryak Mountains of eastern Siberia (Marlow, 1979; Marlow and others, 1983). Subsidence in the Navarin basin has apparently been continuous during the Cenozoic, possibly extending even into the present day.

TABLE 3. STRATIGRAPHIC SEQUENCES PENETRATED AT NAVARIN COST WELL

Age	Depth to Top (m)
Pliocene	468
Miocene	969
Oligocene	1,739
Eocene	3,743
Late Cretaceous (unconformity)	3,895

ANADYR BASIN

Description

Anadyr basin is a large structural depression that encompasses about 120,000 km^2 and is filled with Upper Cretaceous and Cenozoic sedimentary rocks (Table 1). Onshore, the basin underlies the Anadyr lowlands and is flanked on the south and west by folded Mesozoic rocks of the Koryak foldbelt (McLean, 1979). To the north and east the basin is flanked by the Okhotsk-Chukotsk volcanic belt, a broad bedrock high composed of plutonic and volcanic rocks that extends southeastward from eastern Siberia across the Beringian shelf at least to St. Matthew Island (Patton and others, 1974, 1976; Marlow and others, 1983). To the east and southeast, the basin extends offshore as far as 200 km (Fig. 1). The thickest part of the basin fill is more than 9 km (Marlow and others, 1983).

Seismic reflection and refraction data show that the Anadyr basin is separated from Navarin basin by Anadyr ridge, a northwest-trending bedrock high that is characterized by high-amplitude, short-wavelength magnetic anomalies (Figs. 1 and 8; Marlow and others, 1983). Anadyr ridge may be an offshore extension of a melange belt underlying the Koryak Range. Sonobuoy refraction data suggest that the velocity profile of strata in the offshore part of Anadyr basin is similar to that in Navarin basin. However, the basins are different structurally. Navarin basin is complex and contains both compressional and extensional elements, whereas Anadyr basin is a simple, broad crustal sag, semicircular in outline.

A smaller basement ridge underlies the south end of line 12 (Fig. 9) and is associated with a magnetic high (Fig. 10). Reflectors above horizon Beta (the presumed Paleogene-Mesozoic boundary; Marlow and others, 1983) are deformed in a diapir-like fashion toward the sea floor, suggesting Holocene(?) tectonism. Anadyr basin, in contrast, contains mainly undeformed fill, and appears in cross section as a saucer-shaped structural sag, undisturbed by faulting (Fig. 10).

Age and history

By 1973, 20 wells had been drilled into the onshore part of the basin; these wells are discussed by McLean (1979). Reconstructions of plate motions for the North Pacific suggest that during the Mesozoic, before the formation of the Aleutian arc, the Bering Sea continental margin was a zone of either oblique underthrusting or transform motion between the North American and Kula(?) Plates. Subduction of the Kula(?) Plate beneath Siberia presumably resulted in the formation of the Okhostsk-Chukotsk volcanic arc (Scholl and others, 1975; Marlow and others, 1976; Patton and others, 1976). South of the Okhotsk-

Chukotsk volcanic belt, the melange and olistostrome units, now exposed as discrete tectonic terranes in the Koryak Range (Aleksandrov and others, 1976), were formed by obduction of fragments scraped off the Kula(?) Plate (Scholl and others, 1975).

Uplift of the Okhotsk-Chukotsk volcanic belt as it formed, and uplift of the Koryak melange belt during the middle Cretaceous, presumably resulted in relative crustal downwarping of the intervening area and the initial formation of the forearc Anadyr basin. The bedrock sequence in Anadyr basin, as deduced from seismic reflection data and extrapolation from onshore geology, consists of strongly folded and broken tectonic blocks of Upper Jurassic and Lower Cretaceous rocks (Agapitov and others, 1973; Burlin and others, 1974; McLean, 1979; Marlow and others, 1983). This basement complex probably forms the lower reflecting sequence below the Beta horizon in our seismic reflection profile (Fig. 9) and is characterized by refraction velocities of 5 km/s or greater (Marlow and others, 1983). Offshore data further suggest that the pre-Cretaceous sequence below Anadyr basin is deformed into a broadly semicircular sag that trends southeast beneath the Gulf of Anadyr.

McLean (1979) compared the Anadyr basin and the flanking Okhotst-Chukotsk volcanic arc, respectively, to the Great Valley sequence in central California and its flanking Sierra Nevadan plutonic belt. The Great Valley sequence, which fills a forearc basin, is flanked on its seaward side by the Franciscan Complex or assemblage of coastal California. This sequence of tectonic elements is similar to that associated with Anadyr basin because Anadyr basin is bounded seaward by the Koryak assemblage of eastern Siberia.

NORTON BASIN

Description

The Norton basin underlies the northernmost part of the Bering Sea and Norton Sound and is made up of the St. Law-

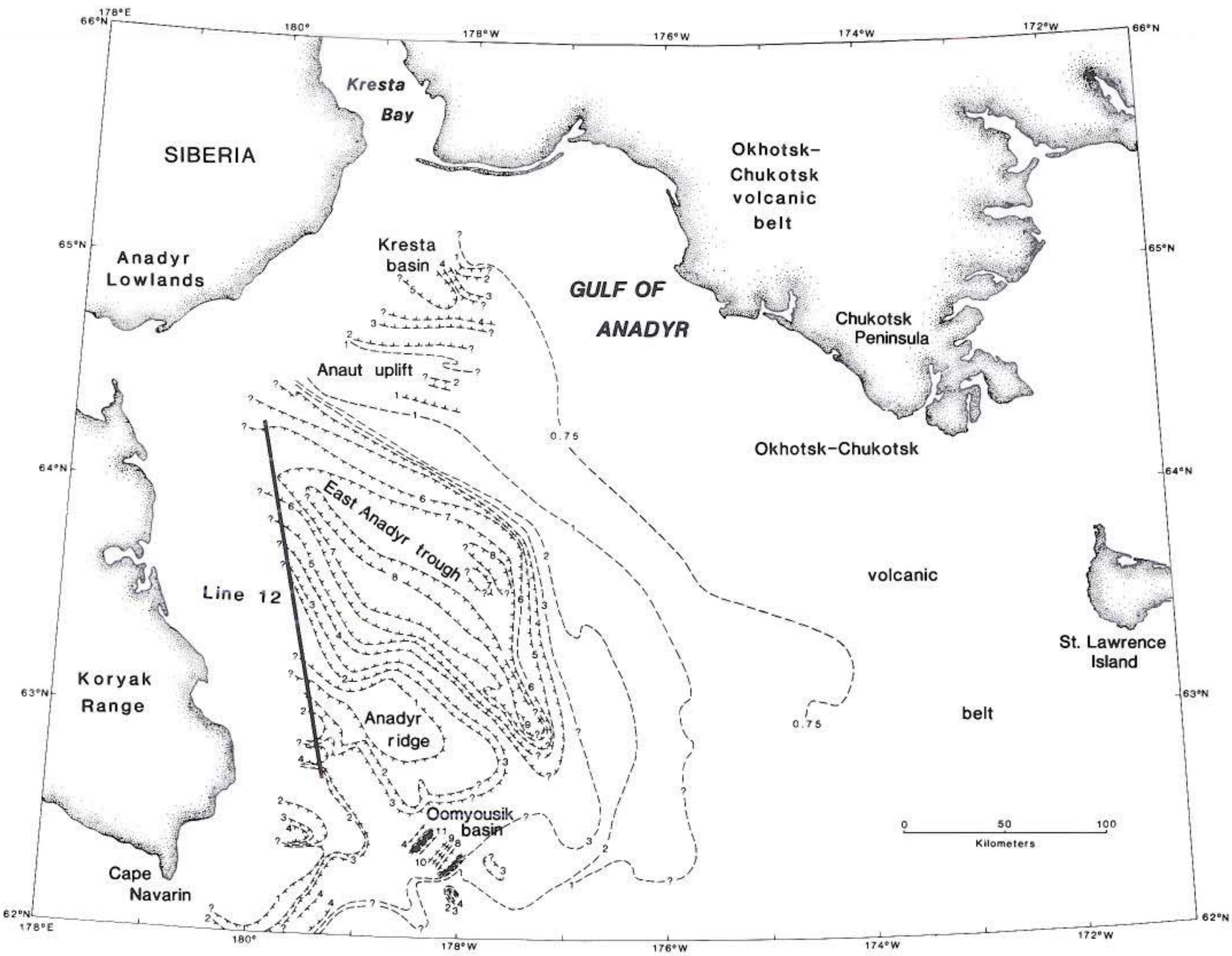

Figure 8. Structure-contour map of total sediment accumulation in the offshore portions of Anadyr basin. Albers equal-area projection. From Marlow and others (1983).

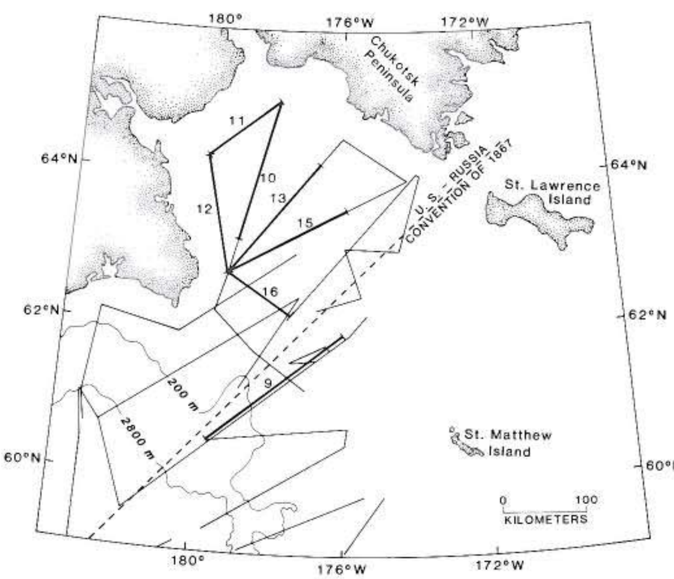

Figure 9. Trackline chart of multichannel seismic reflection surveys across the northern Bering Sea shelf and Anadyr basin. Heavy trackline number 12 is profile shown in Figure 10. Tracklines include surveys made in 1976, 1977, and 1980. Albers equal-area projection. From Marlow and others (1983).

rence and Stuart subbasins (Fisher and others, 1982). The St. Lawrence subbasin lies northeast of St. Lawrence Island and west of the Yukon horst, a structure that extends from the Yukon Delta toward Nome (Fig. 11). The St. Lawrence subbasin is surrounded by shallow basement that dips toward the basin from the Seward Peninsula and St. Lawrence Island, where Precambrian and Paleozoic rocks crop out. Although major normal faults have been active adjacent to the Yukon Delta, gravity data suggest that the Norton basin does not extend beneath the land areas covered by the delta (Fisher and others, 1982).

The Stuart subbasin lies west of the Yukon horst and north of Stuart Island. The main part of the Stuart subbasin is a subcircular depression and includes the deepest part of the Norton basin, where the basin fill is 6.5 km deep. Fault-bounded troughs, filled with basin rocks up to 3 to 4 km thick, extend northeastward and northwestward from the main basin deep. The Nome horst trends east, separating a narrow east-striking graben from the main part of the basin. Thus, the subbasins of the Norton basin differ both in structure and depth of basin fill. Large normal faults in the St. Lawrence subbasin strike northwest, and the maximum thickness of fill in this area is 5 km. In contrast, major normal faults in the Stuart subbasin strike east and northeast.

Stratigraphy

Two COST wells were drilled in the Norton basin by a consortium of oil companies (Table 4). Data from these wells are summarized by Turner and others (1983a, b).

The COST No. 1 well was drilled in the St. Lawrence subbasin, and the COST No. 2 well was drilled in the Stuart subbasin. The oldest rocks penetrated by the two COST wells are quartzite, phyllite, and marble of Precambrian or Paleozoic age. The only evidence for this age is that the rocks in the wells are similar to those of Precambrian and Paleozoic age exposed in the York Mountains on the western Seward Peninsula. These rocks form the acoustic basement and the economic basement for oil and gas. The deepest units of the basin fill penetrated by both wells are poor in fossils, but may be Eocene or older. Nonmarine sandstone, and some conglomerate and coal are 94 m and 537 m thick in wells 1 and 2, respectively. In the COST 2 well, these poorly dated rocks are separated by an unconformity from a 774-m-thick section of middle and upper Eocene siltstone, mudstone, conglomerate, and coal that was deposited in nonmarine and transitional environments. Rocks in the COST No. 1 well that may correlate with this Eocene section form a 776-m-thick unit of sandstone, mudstone, and siltstone dated as Oligocene or older that may have been deposited in a marine environment. Basalt that is anomalously low in alkalis was also encountered in this rock unit; the basalt yields a Miocene K/Ar age of 19.9 Ma. Because the sedimentary rocks that surround the basalt are probably older than Miocene, the basalt is intrusive. In the COST No. 1 well, Oligocene mudstone and shale are 1,584 m thick and

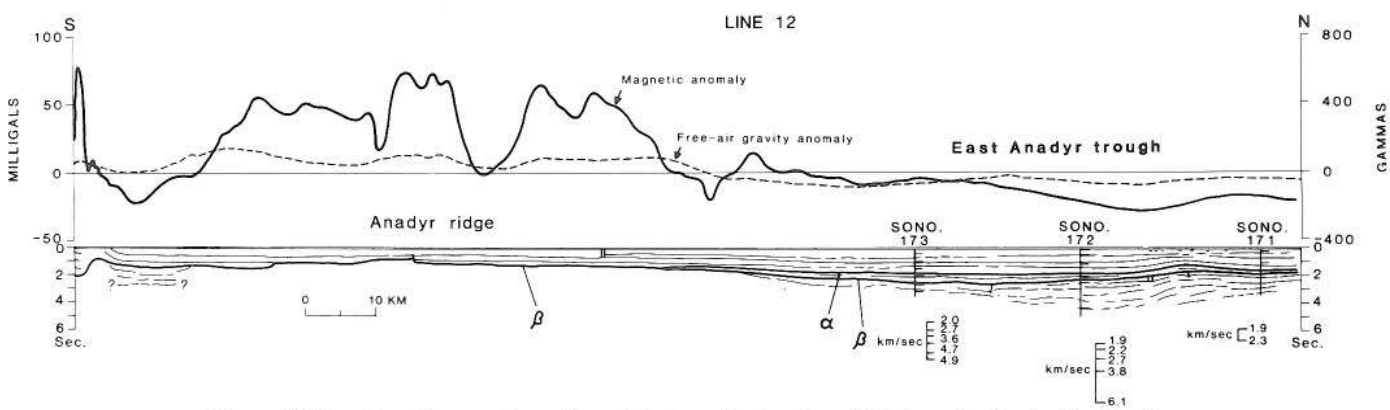

Figure 10. Gravity and magnetic profiles and interpretive drawing of 24-channel seismic reflection line 12 across Anadyr basin and ridge. For location of profile see Figure 9. Sono. 173 refers to sonobuoy refraction station 173 (Marlow and others, 1983).

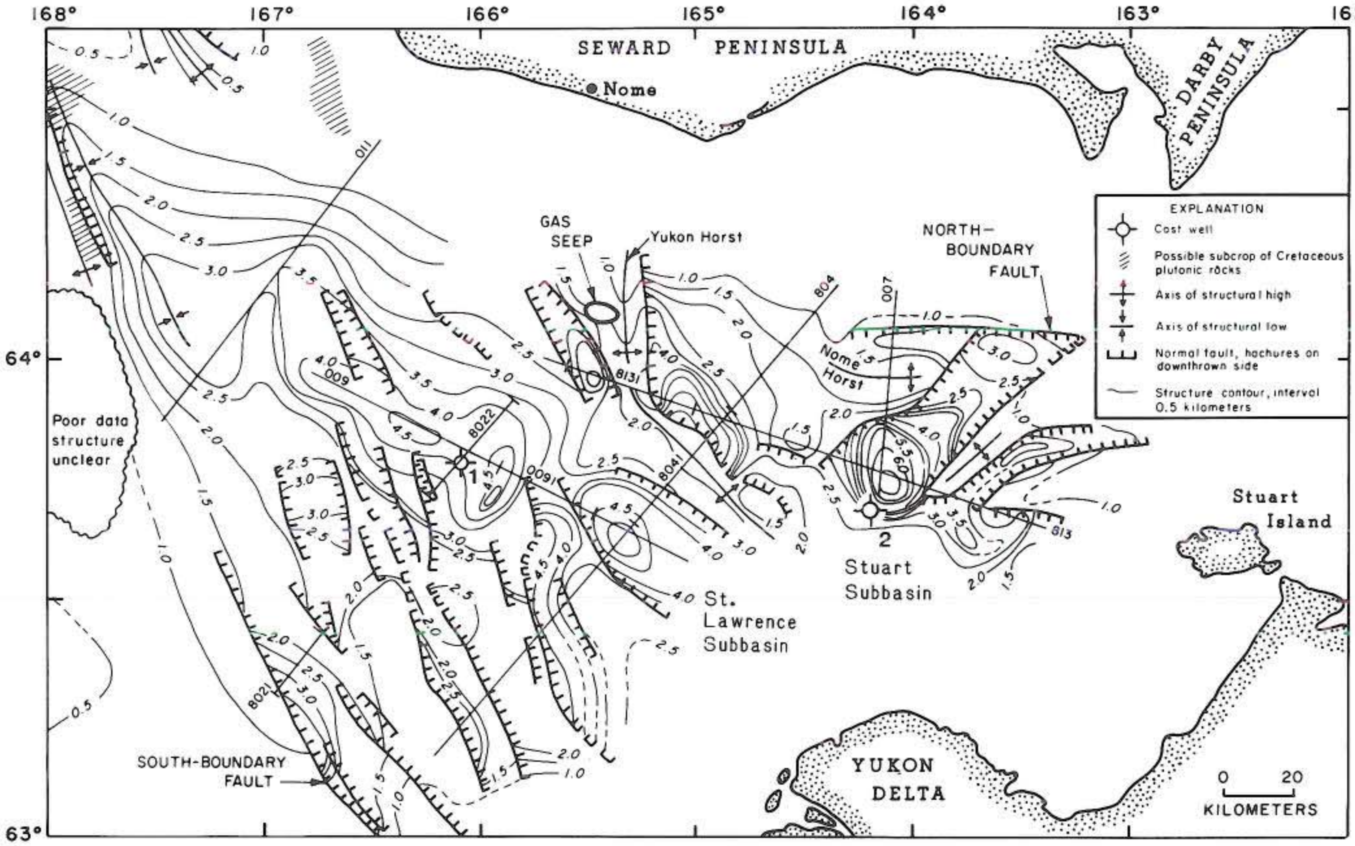

Figure 11. Structure contours on horizon A in Norton basin. Horizon A is an unconformity between probable Precambrian and Paleozoic rocks below and uppermost Cretaceous or lower Paleogene rocks above. From Fisher and others (1982).

were deposited in a middle neritic to upper bathyal environment. In the COST No. 2 well, the Oligocene section is 2,023 m thick. The lower half of the Oligocene section is composed of siltstone, mudstone, and some coal that were deposited in nonmarine or transitional environments, whereas the upper half of this section is composed of mudstone, siltstone, and sandstone that were deposited in transitional and neritic environments. Miocene neritic rocks are 566 m thick in the COST No. 1 well and they consist of mudstone, diatomite, and siltstone. In the COST No. 2 well, 288 m of Miocene siltstone, mudstone, diatomite, and some coal were deposited mainly in a neritic environment. Pliocene neritic diatomite, mudstone, and muddy sandstone in the COST No. 1 well are 402 m thick; neritic rocks of the same age and lithology in the COST No. 2 well are 384 m thick. Shallow-marine Pleistocene and Holocene sandstone, siltstone, and diatomaceous mudstone are 345 m thick in the COST No. 1 well and 355 m thick in the COST No. 2 well.

Age and history

Rocks exposed on the Seward Peninsula underwent a complex hsitory of deformation and intrusion. If basement rocks beneath the Norton basin record a similar history, then these rocks were deformed during the Late Jurassic and Early Cretaceous, during the orogeny that formed the Brooks Range of northern Alaska (Patton and Taileur, 1977; Patton and others, 1977; Roeder and Mull, 1978; Mull, 1979). During the Early and middle Cretaceous, after this orogeny, the area of Norton basin was exposed and eroded. Evidence for this erosion comes from the calcarenites preserved in the Yukon-Koyukuk province east of the Norton basin (Patton, 1973). These rocks were derived from the west and suggest that Paleozoic or older carbonate rocks were exposed where the basin now lies. During the Late Cretaceous, rocks on the Seward Peninsula and perhaps those in the basement under the Norton basin were metamorphosed by the intrusion of granitic rocks.

Fisher and others (1982) proposed, from seismic stratigraphy and onshore geology, that the Norton basin formed during the latest Cretaceous to the end of the Paleocene (70 to 55 Ma), contemporaneously with the formation of grabens in western Alaska that were filled with volcanic rocks. The COST wells penetrated basin fill of middle Eocene age or older. However, the age of the deepest basin fill penetrated is unknown, and nearly 2 km of unsampled strata underlie the basin adjacent to the deepest well penetration. Thus, the age of the initial basin formation is unknown, but is certainly before the middle Eocene. Extensional basins typically undergo rapid subsidence along major faults dur-

TABLE 4. STRATIGRAPHIC SEQUENCE PENETRATED AT NORTON COST WELLS

Age	Depth to Top (m)
COST Well No. 1	
Pleistocene	?
Pliocene	402
Miocene	804
Oligocene	1,369
Oligocene or older	2,953
Eocene(?) or older	3,729
Metamorphic basement:	
Paleozoic or older	3,824
COST Well No. 2	
Pleistocene	?
Pliocene	402
Miocene	786
Oligocene	1,074
Eocene	3,097
Eocene(?) or older	3,871
Metamorphic basement:	
Paleozoic or older	4,407

ing their early histories; consequently, the thick Oligocene section penetrated by both wells suggests that the basin was probably young and active during the Oligocene. Hence, Norton basin probably formed sometime during the early Cenozoic, from the Paleocene(?) to the middle Eocene. In the two COST wells the thickness of Oligocene rocks, uncorrected for compaction, makes up 35 to 45 percent of the basin fill. This thick Oligocene section suggests that during this epoch, and probably earlier, the basin underwent rapid subsidence. Seismic reflection data show that this subsidence occurred mainly along large normal faults. In the St. Lawrence subbasin these faults show the greatest throw near the Yukon Delta, suggesting that the Kaltag fault, a major strike-slip fault mapped east of Norton basin, may have contributed to basin formation.

Seismic reflection data show that alluvial fans were deposited along the flanks of some of the major basement highs as the basin underwent rapid subsidence during Paleocene(?) through Oligocene time. Subsidence was rapid enough in the St. Lawrence subbasin, so that during the Eocene or Oligocene, a marine incursion caused the environment to shift from nonmarine to outer neritic and upper bathyal. In contrast, in the Stuart subbasin, separated from the other subbasin by the high-standing Yukon horst, a nonmarine environment of deposition continued until well into the Oligocene. During Miocene, Pliocene, and Quaternary time, deposition of marine strata occurred in both subbasins. The Neogene and Quaternary rocks are considerably thinner (even without correction for compaction) than the Oligocene rocks, indicating that a general slowing of the rate of basin subsidence occurred during the past 22 m.y. This decreasing thickness of fill mirrors the decreasing throw of faults upward through the basin fill.

CONCLUSIONS

The major basins of the Beringian shelf are listed in Table 1. Detailed descriptions of the basins can be found in Marlow and Cooper (1980a), Fisher and others (1982), Marlow and others (1983), and Turner and others (1983a, b; 1984a, b, and c). Bristol Bay, Anadyr, Norton, and Navarin basins appear to have formed as large downwarps in the Earth's crust, and block-like structures formed during down warping. These structures are buried in places by sedimentary layers that may form traps for migrating hydrocarbons.

St. George basin and the southern half of Navarin basin are tensional features, formed by a pulling apart of the earth's crust. Continued subsidence of these basins through geologic time has formed fold structures associated with growth faults along the flanks of the basins. These fold structures may also trap oil and gas in volumes that are economically significant.

The northern half of Navarin basin is dominated by compressional structures such as anticlines and domes that formed when the basin fill may have been subjected to horizontal compression. Anticlines and domes are the classic geologic structures from which most of the world's oil has been produced.

Norton basin contains two subbasins that probably began to form in early Cenozoic (Paleocene[?] through middle Eocene) time. These subbasins are underlain by basement rocks of Precambrian or Paleozoic age. If significant amounts of hydrocarbons occur in Norton basin, then data from the COST wells suggest the hydrocarbons will be present mainly as condensate and gas.

The shelf basins are currently being explored for hydrocarbons by drilling, but their hydrocarbon potential remains unknown. Navarin basin is the second largest shelf basin, however, and contains many large geologic structures that produce geophysical signatures that may indicate hydrocarbons within the structures. The onshore portion of nearby Anadyr basin (Fig. 1) has been drilled by the Soviet Union (McLean, 1979). Those wells revealed shows of oil and gas that suggest that the offshore portion of the basin may also contain hydrocarbons.

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