UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

INTERIM REPORT ON PETROLEUM RESOURCE POTENTIAL AND GEOLOGIC HAZARDS IN THE OUTER CONTINENTAL SHELF OF THE GULF OF ALASKA TERTIARY PROVINCE

OPEN-FILE REPORT 75-592
This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards and nomenclature

Menlo Park, California
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By

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SUMMARY

The potential for discovering large accumulations of petroleum on the Outer Continental Shelf of the Gulf of Alaska Tertiary Province cannot be evaluated with much confidence at present because of the inadequacies of the available offshore geological and geophysical data. The 22 deep test wells that have been drilled since 1954 have been unsuccessful because structure is complex and because suitable reservoir rocks have not been found in favorable structural positions. Although it is possible that the factors controlling accumulation of petroleum may improve offshore, regional stratigraphic and structural considerations together with the limited geophysical data suggest that this is not necessarily the case. Extrapolation of onshore geology together with the limited amount of marine geophysical data, indicate that the eastern Gulf of Alaska Outer Continental Shelf is geologically complex and consists of several areas with markedly differing structural styles and petroleum potential.

Most of the known indications of petroleum in the province are in bedded strata of Neogene age, which have a maximum composite thickness in excess of 25,000 feet (7620 m). The exposed early Tertiary sequence is too indurated and too intensely deformed to have more than marginal potential for accumulation of petroleum in commercial quantities. Pre-Tertiary rocks are considered to be effective basement for petroleum.

The most favorable prospective area lies generally between Icy Bay on the east and Middleton Island on the west (141° W. to 146° W.). It

includes roughly one-quarter of the 14,320 miles^2 (37,135 km^2) of the Outer Continental Shelf with water depths less than 650 feet (200 m). This part of the shelf was the site of especially rapid subsidence and clastic deposition throughout much of middle and late Tertiary time and includes organic-rich strata of middle Tertiary age that are the most probable source rocks for the one small oil field, numerous seeps, and other indications of petroleum found along the adjacent coast. Large anticlinal structures occur in this segment of the Outer Continental Shelf that could provide suitable traps for petroleum. However, there is a general scarcity of suitable reservoir sandstones onshore and, barring unforeseen circumstances, reservoir qualities of the sandstones would normally tend to decrease offshore away from the northerly source areas. Additional unfavorable factors may be a) the extremely thick cover of Miocene and younger sediments over some structures in the eastern part of the area that could place the best target horizons out of practical drilling range, b) excessive structural complications that appear to exist in the anticlinal cores, especially those in the western part of the area, that may make it impossible to locate suitable structural traps at depth, and c) probable deep erosion of structural highs in the western part of the area that may have truncated the early Miocene to late Oligocene section, thereby allowing trapped oil to escape from former near-surface reservoirs.

Most of the remainder of the Outer Continental Shelf in the Gulf of Alaska Tertiary Province is judged to have less potential for large accumulations of petroleum. Sparse offshore data suggest a scarcity of anticlinal traps in areas of Neogene sediments or the presence of indurated pre-Neogene rocks at shallow depths.

Mineral resources other than petroleum are not known to be present on the Outer Continental Shelf of the Gulf of Alaska.

The seismic hazard in the Gulf of Alaska Tertiary Province is extreme. As have occurred in the past, great earthquakes in the magnitude 8 class are to be expected in the future. Although the time of occurrence of major earthquakes is not currently predictable, the general location of impending shocks is--at least to some degree. Geologic and seismic evidence indicates that the continental margin between the focal regions of the 1964 Alaska and 1958 Lituya earthquakes is a probable site for the next major earthquake (possibly in the magnitude 8 class) in southern coastal Alaska, or for a series of large earthquakes (in the magnitude 7 range). Current knowledge is not sufficient to define the fault structures that might generate such an event or series of events. Perhaps the most destructive earthquake in this region would be an event associated with oblique underthrusting of the ocean floor beneath the continental shelf between Cross Sound and Cape St. Elias. Such an event would be in the magnitude 8 range, would cause large uplift of the shelf area and possible subsidiary faulting, would generate a major sea wave, would severely shake man-made structures in the offshore and coastal areas, and would produce many types of ground failure on land and on the sea floor.

INTRODUCTION

This report provides a preliminary summary of the status of knowledge concerning petroleum potential and possible earthquake-related hazards in the Gulf of Alaska Tertiary Province (GATP). It was transmitted as an interagency report to the Bureau of Land Management (BLM) in January, 1975, to assist in writing an Environmental Impact Statement and in selection of tracts to be leased for petroleum exploration on the Outer Continental Shelf (OCS). The present report is essentially unchanged from the one submitted to BLM except that references to non-seismic geologic hazards have been deleted because these have since been discussed more fully elsewhere (Carlson and others, 1975), and minor alterations have been made to incorporate data that has become available since the report was prepared in December, 1974.

As defined herein, the GATP includes all Tertiary rocks along the mainland coast in the eastern Gulf of Alaska and their presumed offshore extensions, extending 620 miles (1,000 km) from Cross Sound on the east to about latitude 59°N on the west (fig. 1). Following previously established usage (Miller and others, 1959; Plafker, 1971) the onshore part of this province is further subdivided into six districts for convenience of discussion. From west to east these are the Prince William Sound, Katalla, Yakataga, Malaspina, Yakutat, and Lituya districts (fig. 1).

The OCS portion of the GATP covers about 20,000 miles^2 (52,000 km^2) to a water depth of 3280 feet (1000 m). Within this province the area of seafloor above specified depth ranges is approximately as follows:

Depth		Area		
0-650 ft	0-200 m	14,320 mi^2	37,135 km^2	9.1 x 10^6 acres
650-3280 ft	200-1000 m	5,900 mi^2	15,320 km^2	3.8 x 10^6 acres
	Total	20,220 mi^2	52,455 km^2	12.9 x 10^6 acres

The portion of the OCS of current primary interest for leasing by the Bureau of Land Management includes about one-quarter of the above area mainly off the Katalla and Yakataga districts (fig. 1). Accordingly, the geology and potential of the central GATP is considered in more detail than the remainder of the province in this report.

Virtually the only sources of geologic and geophysical data used in preparation of this report for both the onshore and offshore parts of the GATP are published and unpublished data by the U.S. Geological Survey. The distribution of rocks and the structures of the mainland and islands shown on figure 2 are reasonably well known from surface geologic mapping and from study of the 22 deep wells and 4 core holes that have been drilled for oil along the coast and on state land offshore from Middleton Island. In the OCS parts of the province, the only non-proprietary data available for preparation of this report are reconnaissance in scale and were generated primarily during the 1974 cruise of the R.V. Thompson. These data include five reversed refraction profiles and 3550 line miles

(5680 km) of single-channel seismic reflection profiles with one-way penetration depths that are generally less than 1-second (Bruns and Plafker, 1975).

Organization of this report includes: 1) a description of the physiography of the OCS and review of the relatively well-known stratigraphy and structure of the mainland coast and offshore islands of the contiguous continental shelf, 2) a resumé of the petroleum exploration history in the GATP, 3) inferences concerning petroleum potential with emphasis on the OCS, and 4) identification of potential geologic hazards.

The reader is urged to bear in mind that because of the rudimentary nature of the investigations carried out by the U.S. Geological Survey in the OCS to date, geological interpretations presented herein must be considered as tentative. Our understanding of the GATP OCS should be immeasurably improved by a thorough analysis of new OCS data, including CDP seismic profiles, that were acquired during 1975. These should provide critically needed data on the deep basin structure.

PHYSIOGRAPHY OF THE OCS

There is approximately 14,000 square miles (37,000 km^2) of continental shelf with water depths less than 650 feet (200 m) in the eastern Gulf of Alaska (fig. 1). Shelf widths range from as little as 8 miles (13 km) at the eastern end of the area to 65 miles (105 km) in the west. A relatively smooth and steep continental slope descends to a gentle continental rise at water depths of 6,600 to 13,200 feet (2,000 to 4,000 m) to the east of Kayak Island. West of Kayak Island the slope makes up the inner wall of the eastern Aleutian Trench, which has floor depths in excess of 14,800 feet (4,500 m) (von Huene and Shore, 1969). The portion of the slope adjacent to the trench is wider, and is considerably more irregular in topography than the segment of slope to the east of the end of the Aleutian Trench.

In general, the topography of the shelf is gently undulating except where it is broken by submarine valleys. Topographically low and high areas on the shelf tend to reflect Quaternary structural features. The most prominent named shoal areas are Fairweather Ground, Middleton Platform, and Tarr Bank. Fairweather Ground, lying near the shelf edge 35 miles (56 km) southwest of Lituya Bay has an area of about 250 $miles^2$ (647 km^2) within the 330-foot (100 m) isobath and minimum water depths of about 50 feet (15 m). Middleton Platform, which is capped by Middleton Island, has an area of about 50 $miles^2$ (128 km^2) within the 100 m isobath (330 ft). Rapid late Holocene uplift of the platform is indicated by a series of six wave-cut terraces on Middleton Island, the youngest of which was formed during the March 27, 1964 Alaska earthquake (Plafker, 1969). Tarr Bank, lying between Middleton Platform and the coast, has an area of about 2,000 $miles^2$ (5,180 km^2). Water depths over the bank are generally less than 330 feet (100 m) and as little as 60 feet (37 m) at the shallowest part (Wessels

Reef). Pamplona Ridge is a steep-sided finger-like projection of the shelf between the Yakutat Seavalley and Bering Trough that extends about 15 miles (24 km) southwestward onto the continental slope. Water depths over it are between 408 and 650 feet (134 and 200 m). It is of particular geologic interest because of speculation that it foundered to its present depth from sea level during the past few hundred years (Jordan, 1958).

Continuity of the shelf within the eastern Gulf of Alaska is interrupted by six major submarine valleys and a number of smaller ones. The more important valleys include the Alsek Canyon, Yakutat Seavalley, and four unnamed valleys which we have informally named the Cross Sound Canyon, Bering Trough, Hinchinbrook Seavalley, and the Amatuli Trough. The most easterly valley, the Cross Sound Canyon, trends southwestward from Cross Sound, which is a prominent glacially-sculpted fiord. Alsek Canyon is a prominent southwest-trending U-shaped submarine valley that heads at the mouth of the Alsek River. It has an average width of 10 miles (16 km) and depth of 240 feet (73 m) across the shelf. The Yakutat Seavalley is also a U-shaped valley over 60 miles long and 7 to 10 miles (11 to 16 km) wide that trends in an arcuate west to southwest course across the continental margin from the vicinity of Malaspina Glacier and Yakutat Bay. Bering Trough is a broad, poorly defined, southeast-trending valley that probably heads at Bering Glacier. It is roughly U-shaped in section with a floor up to 10 miles (16 km) wide. Hinchinbrook Seavalley is a major southward-trending, U-shaped trough that heads in the glacially-scoured Hinchinbrook Entrance. It averages about 240 feet (73 m) in depth and ranges in width from 8 miles (13 km) at the north end to 16 miles (26 km) at the shelf break. The most westerly valley, the Amatuli Trough, is a broad depression up to 25 miles (40 km) wide that drains easterly across the shelf from near the gap between the Kenai Peninsula and Kodiak Islands group. It may have been a major drainage for Pleistocene glaciers that extended onto the shelf from the Cook Inlet Basin.

REGIONAL STRATIGRAPHIC FRAMEWORK

Geologically, the GATP is a compound continental margin basin made up almost entirely of terrigenous clastic rocks that are intercalated with subordinate mafic volcanic and volcaniclastic rocks and with minor coal. The bedded rocks of the onshore Gulf of Alaska Tertiary Province, with a maximum thickness of tens of thousands of feet, include both marine and nonmarine units. Three major subdivisions of Tertiary rocks are recognized on the basis of fossils and gross lithologic characteristics that are believed to correspond to major changes in the depositional environment of the basin: (1) the Paleocene through lower Oligocene, (2) the middle Oligocene through lower Miocene, and (3) the middle Miocene through Pliocene (and locally Pleistocene). The changes in depositional environment are characteristically gradational and appear to be time-transgressive in different parts of the basin. General geologic features of the Tertiary basin and its margins are shown by figure 2. Figure 3 is a tentative correlation chart of stratigraphic units in the basin; the approximate thickness and inferred correlations of selected surface and well sections are shown in figure 4.

The Tertiary rocks are bordered on the north, and are underlain in the eastern part of the basin, by bedded rocks of Cretaceous and older age (figure 2). These rocks are highly deformed, locally metamorphosed and are commonly intruded by igneous plutons. Because the pre-Tertiary rocks are considered to have no potential for petroleum, they will not be discussed further herein.

Lower Tertiary Sequence

The oldest Tertiary rocks consist of complexly intertonguing, deep-water marine pillow lava, tuff, and sandstone and siltstone that comprise the Orca Group and its equivalents in the Prince William Sound and Katalla districts (Winkler, 1973; Plafker, 1967, 1974), and the "unnamed siltstone" unit of the Yakataga and Malaspina districts. These rocks are inferred to be of Paleocene and Eocene age on the basis of their stratigraphic position and the few diagnostic fossils collected from them.

The lower units appear to grade upward and laterally towards the northeast into rocks characterized by abundant intertonguing arkosic, pebbly, and coal-bearing sandstone that is commonly calcareous; the sandstone also is zeolitized in many places. These coal-bearing rocks are of shallow-marine and nonmarine origin. Their fauna and flora suggest that they were deposited during late Paleocene to late Eocene, and possibly early Oligocene, time in a subtropical to temperate environment. Rocks of this age include (1) the Kushtaka Formation and perhaps the lower Tokun Formation of the Katalla district and (2) the Kulthieth Formation in the Yakataga and Malaspina districts.

All the lower Tertiary sedimentary rocks are characteristically hard, dense, and intensely deformed. Although many of the cleaner sandstones appear porous and friable in outcrop, surface samples that have been examined microscopically have negligible porosity. These rocks are mildly metamorphosed and are cut by lower Eocene to lower Oligocene granitic plutons in the Prince William Sound, Katalla, and Yakataga districts, and by small hypabyssal mafic intrusives in the Katalla, Yakataga, and Malaspina districts.

A general scarcity of age-diagnostic fossils and lithologically distinctive beds coupled with the prevailing structural complexity in all the lower Tertiary units precludes accurate determination of relative stratigraphic positions and thicknesses. The entire sequence is estimated to be several tens of thousands of feet thick in the Prince William Sound district, and probably at least 20,000 feet (6,096 m) thick in the Katalla district. The sequence appears to thin east of the Katalla district and is not known to be exposed in the Lituya district.

In the OCS, acoustic basement at the sea bottom, or acoustic basement overlain by a relatively thin veneer of reflective sedimentary rocks, occurs in the Prince William Sound district, the western part of the Katalla district, and at Fairweather Ground in the Lituya district. In these areas acoustic basement is most probably the Orca Group and its equivalents, although available data does not preclude the possibility that some pre-Tertiary units also may crop out on the sea floor in the eastern part of the basin.

Middle Tertiary Sequence

The lower Tertiary rocks are overlain onshore by a marine sequence consisting predominantly of interbedded concretionary mudstone and siltstone with subordinate sandstone. Locally, this sequence contains abundant interbedded aquagene tuff, agglomerate, glauconitic sandstone, and pillow lavas. Coeval small porphyritic alkaline to mafic plugs and dikes are common in the Katalla district and mafic dikes of middle Tertiary age are sporadically present elsewhere in the GATP. The contact between these units generally is not well exposed, but prevailing abrupt changes in lithology and structural deformation across it indicate that it is most probably an unconformity in parts of the region.

The middle Tertiary sequence, which includes the Katalla, upper Tokun(?), Poul Creek, Cenotaph, and Topsy Formations, was deposited during Oligocene and early Miocene time in temperate water. Water depths were moderately deep to deep in the southern Katalla district and somewhat shallower toward the east. Intermittent submarine volcanic activity is recorded by mafic flow and pyroclastic rocks at intervals throughout these units. The mudstone and siltstone are richly organic in the central part of the GATP, where the sequence contains many petroliferous beds and oil and gas seeps. The sandstone-"shale" (actually mainly siltstone and mudstone) ratio of these units is 20 percent or less; most of the thicker sandstone beds are concentrated near the base.

The thickness of the middle Tertiary sequence is extremely varied, and there are abrupt changes in short distances. Measured maximum outcrop thickness is only a few hundred feet in the Malaspina district, 6,100 feet (1,859 m) in the Yakataga district, and about 5,190 feet (1,581 m) in the central Katalla district and 5,600 feet (1700 m) on Kayak Island.

The middle Tertiary sequence extends offshore at least to the continental margin where it may be on the order of 7,000 feet (2,134 m) thick in the Middleton Island well, assuming no steep dips or repetition by faulting. The sequence probably crops out on the sea floor in the portion of OCS between Kayak and Middleton Island, but is not known to be exposed elsewhere in the offshore parts of the basin.

Upper Tertiary and Pleistocene Sequence

Marine clastic rocks of Miocene to early Pleistocene age that locally are characterized by abundant glacial detritus lie on the temperate-water middle Tertiary sequence with local unconformity. They consist mainly of fossiliferous thick-bedded mudstone, muddy sandstone, conglomeratic sandy mudstone (marine "tillite"), and minor conglomerate of the Yakataga Formation.

The Yakataga Formation was deposited in shallow to moderately deep water during a time interval when shelf ice or tidal glaciers were intermittently present along the landward margin of the basin. An abundant megafauna suggests cold-water conditions throughout most of the interval, except for a transitional lower part in which progressive cooling is indicated by alternation of cold- and temperate-water fossils. On the basis of the megafauna, the base of the sequence is probably of early middle Miocene age in the Yakataga and Malaspina districts and possibly as old as late Oligocene in the Katalla district (Plafker, 1974). Studies of planktonic foraminifers, however, indicate that it could be as young as late Miocene (Bandy et al., 1969).

The composite onshore outcrop thickness of the Yakataga Formation is about 16,500 feet (5,030 m). The sandstone content of the formation ranges from as much as 55 percent in sections on the mainland near the northern margin of the basin to as little as 9 percent at Middleton

Island near the edge of the continental shelf. Middleton Island is underlain by the uppermost part of the Yakataga Formation, which has a measured thickness of 3,875 feet (1,181 m). About 2,000 feet (610 m) of the formation was penetrated at the top of the Middleton Island well.

Based on its onshore distribution and the character of its near-surface reflectors over adjacent offshore areas, the Yakataga Formation is inferred to underlie most of the continental shelf. The major exceptions are areas of acoustic basement and acoustically transparent, unconsolidated deposits. Seismic reflection data indicate that the Yakataga Formation laps onto structural highs at the Fairweather Ground and the Middleton Platform. Extrapolation of data from onshore sections and wells suggests that the depositional axis of the Yakataga Formation in the area east of the Kayak-Middleton trend is probably offshore and within 10 to 20 miles (16 to 32 km) of the coast. Maximum offshore thickness of the sequence along the depositional axis is at least 15,000 feet (4,572 m) and could be as much as 25,000 feet (7,620 m). The seismic data suggest that in the part of the OCS wwst of the Kayak-Middleton trend, the distribution of the Yakataga Formation is probably considerably more variable than to the east.

Unconsolidated Deposits

The Gulf of Alaska margin east of Prince William Sound has a discontinuous coastal plain as much as 20 miles (32 km) wide that is underlain by unconsolidated deposits, ice, or water. In this stretch much of the coastline is remarkably even, the water is shallow for a considerable distance offshore, and the shore is, in general, prograding seaward as a result of combined extremely rapid sedimentation and tectonic uplift relative to sea level. This is in striking contrast to the irregular ria coast from Prince William Sound westward, which characteristically has deep water close to shore and no coastal lowland of unconsolidated deposits.

The sediments comprising the coastal lowland consist of Holocene sand, gravel, mud, and till deposited by the sea, streams, and glaciers on a wave- and stream-planed surface of Tertiary and older rocks. The Copper and Alsek Rivers are the only drainages with headwaters in the interior to the north of the coastal mountains. The remaining streams entering the Gulf of Alaska are short and most of them originate at glaciers. The streams and rivers are muddy and swift during the summer, but during the winter they are greatly reduced in volume.

The Copper River has built an asymmetrical late Holocene delta into the Gulf of Alaska and the prevailing westward current set has caused Copper River sediments to fill fiords in the eastern part of Prince William Sound (Reimnitz, 1966). Similarly, sediment from the Alsek River probably has contributed to formation of the broad Yakutat Foreland west of the river mouth, although part of the Alsek River sediment has probably been lost to the coastal regime through movement down the Alsek Canyon. On the open coast, sand bars built by the prevailing strong westward longshore drift commonly cause the river mouths to go through cycles of westward migration followed by breakthrough at their original sites during periods of high runoff.

Icy Bay, Yakutat Bay, and Lituya Bay, the only major indentations in the coast, were formed by late Holocene retreat of the Guyot, Hubbard, and La Perouse-Crillon Glaciers, respectively. These bays have one or more arcuate ridges of glacial moraine across their mouths and along their margins that mark the approximate maximum late Holocene extent of the glaciers that deposited them (Plafker, 1967).

Much of the continental shelf is mantled with a veneer of unconsolidated Holocene, and possibly late Pleistocene, deposits. Sediment distribution off the Copper River Delta was discussed by Reimnitz (1966) and western Yakutat, Malaspina, and eastern Yakataga districts by Wright (1972). Bottom sediments on the shelf include submarine moraines of poorly sorted till and their closely associated fluvioglacial outwash fans of sand and gravel near the present major glaciers. In addition, mud and silt that were discharged into the sea by streams have been widely dispersed offshore by current and wave action. Dropstones ranging in size up to boulders and blocks have been deposited over the entire shelf and out onto the deep ocean floor from icebergs calved into the sea at the fronts of tidal glaciers (Gershanovich, 1968). On the OCS, unconsolidated deposits are generally concentrated in topographic depressions whereas topographically high areas tend to be swept bare of all but the coarsest sediment by the prevailing strong currents and storm waves. Some of the highs that were planed off by surf zone erosion may be surrounded by lag gravel aprons similar to those that are now forming on the leeward side of Middleton Island (Miller, 1953).

STRUCTURE

Onshore

The Tertiary rocks along the Gulf of Alaska rim are bordered on the north and are in part underlain by highly deformed, metamorphosed, and intruded Cretaceous and older bedded sedimentary and volcanic rocks. In most places west of the Malaspina Glacier where the contact between the Tertiary and pre-Tertiary sequences has been studied in detail, it consists of a system of major steep faults or north-dipping thrust faults along which there has been relative uplift of the older rocks. In the eastern part of the Malaspina District, in the subsurface of the Yakutat district, and in the western part of the Lituya district, Tertiary rocks ranging in age from probable Paleocene to Pliocene unconformably overlie the pre-Tertiary rocks. The resulting structural style along selected sections across the onshore parts of the basin is illustrated in figure 5a.

Deformation in varying degrees of intensity affected the basin throughout much of Cenozoic time. The fold-fault pattern and stratigraphy suggests, however, that the deformation in onshore areas occurred primarily during two orogenic episodes that culminated in early and late Cenozoic time. Lower Tertiary rocks that have been involved in both major orogenies are markedly more deformed than, and locally differ in trend from, the younger sequence. Complex structural trends in the region result from multiple deformation and from superimposed gravitational tectonics, which followed orogenic uplift of the basin margins.

The older orogenic episode, which may have begun as early as Cretaceous time and probably culminated in early Eocene time, resulted in complex folding and faulting of the lower Tertiary sequence with local emplacement of granitic stocks and zeolite-facies metamorphism of the intruded bedded sequences. Folds commonly are of short wavelength and are tightly appressed, having flank dips greater than 50°; locally folds are overturned toward both the north and south (fig. 5A, A-A'). The strike of bedding planes and fold axes tends to parallel the structural trend of the bounding faults, but there are numerous exceptions. The trends are most notably divergent in the northeastern part of the Prince William Sound district and in the western Katalla district. The structural complexity of the Prince William Sound-Katalla area is related to its position near an axis of oroclinal bending (Carey, 1958), where there must have been a significant local east-west component of compressive stress during early Tertiary orogeny.

The younger orogenic episode, beginning perhaps in middle Miocene time in the Yakataga district and continuing to the present, resulted in pronounced differential uplift and faulting throughout southern Alaska. During this orogeny, the Pacific Border Ranges were markedly uplifted, and in places they were thrust relatively seaward along a system of major faults. Local multiple angular unconformities record active deformation in the depositional basin during Yakataga time Abundant glacial-marine detritus in strata containing an early middle Miocene megafauna attests to a mountainous area along the northern margin of the basin high enough to nourish glaciers that reached tidewater. Continuing active deformation is indicated by 1) tilting, faulting, and uplift of marine rocks as young as middle Pleistocene on Middleton Island, 2) by active seismicity and earthquake-related deformation, and 3) by the extreme topographic relief along the northern margin of the basin (Plafker, 1969). The fold-fault pattern on land and on the offshore islands extending out to the edge of the continental shelf, as well as the pattern of deformation associated with the 1964 Alaska earthquake (Plafker, 1969) and 1958 Lituya earthquake (Tocher, 1960), suggest predominant regional NW-SE-oriented horizontal compressive deformation across the continental margin during the late Cenozoic. The regional fold-fault pattern may have been modified significantly in the foothills belt by gravitational sliding off the markedly uplifted coastal mountains.

Faults and folds in the upper Cenozoic sequence tend to parallel the trends of the older structures, and there is an apparent increase in the intensity of folding and magnitude of fault displacement from south to north across the basin. Transverse trends are present in the structurally complex Katalla district, where folds involving Oligocene and Miocene strata are typically of small amplitude, tightly compressed and asymmetric or overturned, having axial planes inclined toward the west or north (fig. 5A, B-B'). The origin of the notably discordant trends in the western part of the Katalla district is uncertain. They may reflect a combination of rejuvenated early Tertiary structures and local deformation of the younger rocks against more competent highs of older Tertiary rocks. On Kayak and Wingham Islands the post-Orca strata dip steeply or are overturned with tops facing towards the northwest and the sequence is imbricated into narrow slices by displacement on at least five large up-to-the-northwest reverse faults (Plafker, 1974). On these islands, the bedded Neogene rocks do not include any major angular unconformities. They appear to have been deformed essentially as a packet against a marginal high of Orca rocks to the northwest in post-middle Miocene time. Net displacement on the bounding fault between the Orca terrain and younger rocks at Wingham Island is probably on the order of several miles; displacement on several of the larger faults within the Neogene sequence may be as much as 8,000-15,000 feet each (2,440-4,570 m).

East of the Katalla district the structure of the upper Cenozoic strata is dominated by broad synclines and tightly appressed asymmetric anticlines cut by north-dipping overthrust faults that strike roughly parallel with the coast (fig. 5A, C-C', D-D', E-E'). The structural style of some of these longitudinally faulted anticlines, particularly in the Yakataga, Malaspina, and Lituya districts, suggests that they represent the leading edges of imbricate _décollement_ sheets that slid southward off the uplifted northern margin of the basin. However, the degree to which gravitational sliding contributed to the development of these structures cannot be ascertained without additional subsurface control. Rooted compressional folds are most likely to be found seaward from the belt of _décollement_ sheets where there is less topographic and structural relief.

The structural style, topography, basin architecture, and seismotectonic activity within the GATP, to a considerable extent, reflect the interactions that have occured during late Cenozoic time along the interface between the North American continent and the Pacific Ocean basin (fig. 7). As a consequence of these movements, the western part of the GATP adjacent to the Aleutian Trench is essentially a zone of compressive deformation along which the Pacific oceanic plate is underthrusting the continental margin, the easternmost part of the province is a zone of shear in which the oceanic plate is moving laterally past the continent along the Queen Charlotte and related strike-slip faults, and the central part of the province is a zone of combined compression and shear due to oblique underthrusting of the continental margin. Both the availability of structural traps for petroleum accumulation and the geologic hazards in the GATP are a direct result of its unique tectonic setting.

Offshore

On the GATP continental shelf numerous folds have been located by seismic profiling. The larger, more continuous folds are concentrated mainly in the area offshore from the Yakataga and Katalla districts, although more complex structure also are locally present on the shelf off the eastern part of the Prince William Sound district. One of the large folds, the Sullivan Anticline, can be traced from onshore in the western Yakataga district southwestward onto the continental shelf; the others are known only from marine geophysical data. In addition, there are discontinuous shelf-edge arches along the outer margin of the OCS that may also constitute structural traps. Generalized anticlinal axes are shown on figure 2, interpreted sections along four seismic profiles are shown on figure 5B; and areas of the shelf having common structural characteristics are shown on figure 6.

Interpretation of offshore structure is derived mainly from preliminary examination of single trace air gun seismic records with line spacings of between 5 and 8 miles (9 and 15 km) providing a relatively uniform distribution of data over the shelf. Interpretation is complicated by the relatively shallow penetration achieved and by the presence of persistent water bottom multiples, especially in areas of shallow dip. Basic data on which the following discussion is based have been published elsewhere (Bruns and Plafker, 1975). Gravity and magnetic data were taken concurrently with the seismic data, but are still being processed and were not available for use in this preliminary analysis; they should prove valuable for interpreting basin configuration of the GATP when they are available.

Discussion of offshore structure will be by area from east to west. Emphasis is placed mainly on the segment of OCS between Icy Bay and Montague Island; most of the potential targets for exporatory drilling were believed to lie within this area, and most of the data collection was therefore concentrated between these two points. Data east of Icy Bay and southwest of Middleton Island are sparse.

Cross Sound to Icy Bay. The only structural high in this area is the Fairweather Ground. Fairweather Ground comprises a large shelf edge arch that roughly parallels the coast between Cross Sound Canyon and Alsek Canyon (figs. 1 and 6). On seismic records it appears as acoustic basement, with sedimentary strata dipping gently to the northeast away from the axis of the arch. High resolution data show no unconsolidated sediments covering the exposed core, and no structure can be resolved on the seismic records. The arch has a pronounced magnetic high associated with it that is suggestive of an igneous body (Taylor and O'Neill, 1974). Sampling of the exposed basement was attempted during the cruise of the R. V. THOMPSON, but no samples were recovered, apparently due to the hardness of the rocks. The exposed core of the arch may be of Cretaceous or early Tertiary age.

The remainder of this segment of OCS is characterized by a basin with the axis near the coast. Lines shot north of Fairweather Ground indicate monoclinal dip to the northeast.

Icy Bay to Kayak Island. Structures in this area are broadly divisable into two types on the basis of trend and amplitude. The first type, which trends roughly parallel to the coast, consists of gentle downwarps and arches with maximum dips on the order of 2-3°, located mainly between the eastern edge of the Bering Trough and Kayak Island (see section H-H', fig. 5B). In this area there is a shelf edge arch with a width on the order of 6 miles (10 km) and length approaching 30 miles (48 km). Local angular unconformities are present at the crest of this arch. Closure is present over at least part of this structure. Interpretation of the seismic profiles, however, is complicated by the presence of multiples which blank out reflectors in this area of very gentle dip. Between the arch and the coast is a broad downwarp up to 30 miles (48 km) wide with some minor upwarped areas within it.

A second type of folding trends obliquely across the shelf, roughly between northeast to southwest and east-west, herein termed the Icy Bay structural trend (fig. 6). The Icy Bay trend consists of a series of asymmetric anticlines and synclines that vary in tightness along strike and are locally bounded on the south by north-dipping reverse or thrust faults (see section I-I', fig. 5B). Width of individual folds ranges from 2.5 to 5 miles (4-8 km). Dips on the flanks of the anticlines commonly range between 3-15° on the landward side and from 5-30° on the seaward side. Apparent dips of greater than 30° are generally not resolvable on the seismic profiles; however, there are very few places on the Icy Bay folds where steeper dips might be found. It appears as if these structures are more open and less complex than those on the adjacent land areas (compare figs. 5A and 5B). Closure of structural highs in the Icy Bay trend is inferred from some of the relatively few strike lines shot, and is present along strike for distances on the order of 10-25 miles (16-40 km).

Between Icy Bay and Kayak Island, possible unconformities are weakly developed on several lines and major unconformities may be expected in the area based on geology of the late Cenozoic section on the adjacent land. Well control on land and seismic refraction data indicate that this area may have a very great thickness of upper Cenozoic sediments. Deep penetration reflection data are required, however, to determine the depth to possible reservoir horizons in the anticlinal structures and the degree of deformation at depth.

Pamplona Ridge is an isolated enigmatic southwesterly-trending structure. It juts out onto the continental slope and is not on trend with any nearby onshore or offshore structural features (fig. 6). Profiles over the ridge show an area of complex folding along an axis that trends roughly north-south. The eastern side of the ridge appears to be faulted. Two possible anticlinal folds with widths of less than one mile (1.6 km), are seen on a line perpendicular to the ridge. Closure of any structures, and age of this feature are unknown. Jordan (1958) inferred from reports of early expeditions in the Gulf of Alaska that Pamplona Ridge may have been a shoal area as recently as 200 years ago, and that it subsequently has subsided to its present minimum depth of 408 feet (134 m). No evidence of submerged shorelines or terraces was found on the airgun or high resolution records to substantiate this hypothesis.

Kayak Island to Montague Island. Structures on the continental shelf between Kayak and Middleton Islands are complicated and are difficult to interpret with the type and amount of reflection profiling available. Preliminary analysis indicates a broad zone of complex structure trending between east-west and northeast-southwest between Kayak and Middleton Islands, and subparallel with Kayak Island, the Aleutian Trench, and the Icy Bay structural trend (fig. 2 and section G-G', fig. 5B). Structural highs tend to be assymetrical and to be bounded by thrust faults on their southeast limbs. Amount of throw on these faults is unknown but may be quite large (see p. 27). The intensity of folding, is generally considerably greater than in the Icy Bay structural trend. Flank dips at shallow levels commonly range between 10° to 30° on the northwest limbs and from 15° to greater than 30° on the seaward limbs. There are large areas on the tops of the structures where dip is not resolved and is apparently much greater than 30°. Some of these structures are of the order of

5 to 10 miles (8 to 16 km) long and between 2 and 4 miles (3 to 6.5 km) wide. Crests of many of the highs appear to have undergone extensive erosion and truncation, and relatively old rocks may be exposed on the seafloor or covered by very young sediments. Closure appears to be present on some of these structures.

Two large structural highs trending northwest-southeast and separated by a deep basin are found northwest of Middleton Island on the Middleton Platform (figs. 2, 6, and section G-G', fig. 5B). These divergent structures show severe deformation with high dips of 15° to greater than 30° on the flanks. Central cores of the structures, ranging from 3 to 5 miles (5 to 8 km) in width on the larger one and up to 3 miles (5 km) on the smaller are relatively devoid of recent sediment, and no structure is resolved on the airgun data. Dips within this corerare beyond the resolving power of the seismic reflection technique (greater than 30°). Total width of the larger structure is up to 6 miles (10 km) and a length of at least 20 miles (32 km) is inferred from the data. Width of the smaller structure is 3 to 5 miles (5 to 8 km) and length of approximately 8 to 10 miles (13 to 16 km) is inferred. Smaller structural highs with the same trend are inferred from meager data to the southwest of these two large highs. Analysis is not sufficient to completely define structural relations in this complex area. However, Middleton Island appears to be on the northwest flank of a large northeast-trending structural high and appears to be separated from these two structures by a relatively deep basin.

Landward of the Kayak-Middleton trend is an area, which includes Tarr Bank, where basement appears high, and post Orca sediment cover may be thin (fig. 6, section G-G', fig. 5B). Seismic data are in general poor, and structure within much of the Hinchinbrook Seavalley, Tarr Bank, and the Copper River Delta area is not well defined. Further study of the seismic records is needed; the gravity data may help indicate areas of high basement.

No new data were acquired south of Middleton Island towards the Kodiak Shelf. Published widely-spaced sparker profiles across the western part of the OCS (von Huene and others, 1971) do not show any near-surface anticlinal structures although the area is moderately faulted.

PETROLEUM EXPLORATION HISTORY

Abundant oil and gas seeps in the Katalla, Yakataga, and Malaspina districts, discovered in about 1896, first directed attention to the petroleum possibilities of the Gulf of Alaska Tertiary province and have been a major factor in encouraging exploration. In 1902, the second of two wells drilled near the Katalla discovery seeps found oil at a depth of 366 feet (116 m). Between 1902 and 1931, 28 wells were drilled in the Katalla field and 16 wells were drilled at nearby locations in the district. A well also was drilled near oil seeps on the Sullivan Anticline in the Yakataga district. The deepest of these wells was 2,350 feet (716 m). In the period 1902-1933, the Katalla field produced about 154,000 bbl of paraffin-base oil with a gravity of 41-45° Baume at depths ranging from 360 to 1,750 feet (110 to 533 m). The oil accumulation was probably largely in fracture porosity in a fault zone cutting steeply dipping, well-indurated sandstone and siltstone of the Katalla Formation. Production ended in 1933 when a fire destroyed the small refinery at the field.

Between 1954 and 1963, 25 wells and core-holes were drilled and abandoned on the mainland in the Gulf of Alaska Tertiary province. Data relevant to these wells and to one well drilled in the Yakataga district in the period 1926-1927 are listed in Table 1; information on the 44 shallow holes in the Katalla district was summarized by Miller, et al. (1959, Table 3). The total drilled footage for the wells listed in Table 1 is 237,090 feet (72,265 m), and the greatest depth reached is 14,699 feet (4,480 m). Geological and geophysical work has been renewed over the onshore and offshore parts of the entire basin

Table 1.--Wells drilled for petroleum in the Gulf of Alaska Tertiary Province, Alaska, through year 1969

[Does not include 44 shallow wells (depths less than 2,350 feet) drilled in and near the Katalla oilfield between 1901 and 1932]

Location No. on map	Company and name of well	Location	Year	Total depth (feet)	1/ Unit penetrated	Results
45	Richfield Oil Corp. Bering River 1	Bering Lake, Katalla district	1961	6,175	Tokun and Kulthieth(?) Formations	Abandoned
46	Richfield Oil Corp. Bering River 2	Bering River, Katalla district	1961-62	6,019	Katalla and Tokun(?) Formations	Abandoned
47	Richfield Oil Corp. Kaliakh River Unit 1	Near Tsivat River, Yakataga district	1959-60	14,699	Yakataga and Poul Creek(?) Formations	Abandoned. Shows of gas
48	Richfield Oil Corp. Kaliakh River Unit 2	do.	1960	9,575	Yakataga and Poul Creek(?) Formations	Abandoned
49	Richfield Oil Corp. Kaliakh River Unit 2, redrill	do.	1960-61	12,135	do.	Abandoned
50	Richfield Oil Corp. Duktoth River 1	Near Kaliakh River, Yakataga district	1961	10,390	Yakataga, Poul Creek, and Kulthieth(?) Formations	Abandoned. Shows of gas
51	Richfield Oil Corp. White River 1	Near Cape Yakataga, Yakataga district	1961	7,982	Yakataga and Poul Creek Formations	Abandoned. Shows of gas and strong flow of saline water
52	BP Exploration Co. (Alaska), Inc. White River 2	White River, Yakataga district	1962	12,417	Yakataga, Poul Creek, and Kulthieth Formations	Abandoned
53	BP Exploration Co. (Alaska), Inc. White River 3	do.	1963	6,984	do.	Abandoned. Shows of gas
54	General Petroleum Corp. Sullivan 1	Johnston Creek, Yakataga district	1926-27	2,005	Poul Creek Formation	Abandoned. Shows of oil and gas
55	Phillips Petroleum Corp. Sullivan Unit 1	Little River, Yakataga district	1954-55	10,013	Yakataga, Poul Creek, and Kulthieth(?) Formations	Abandoned. Shows of oil and gas

Table 1 (Cont'd)

56	Phillips Petroleum Corp. Sullivan Unit 2	do.	1956-57	12,052	do.	Abandoned. Shows of oil and gas
57	Phillips Petroleum Corp. Sullivan Strat. 1	Big River, Yakataga district	1954	4,837	Yakataga and Poul Creek(?) Formations	Abandoned. Strong flow of slightly saline water
58	Standard Oil Co. of California Riou Bay 1	Riou Bay, Malaspina district	1962	14,107	Yakataga Formation	Abandoned
59	Standard Oil Co. of California Chaix Hills 1	Chaix Hills, Malaspina district	1961	10,015	Yakataga Formation	Abandoned
60	Standard Oil Co. of California Chaix Hills 1A, redrill	do.	1961-62	10,121	Yakataga and Poul Creek Formations	Abandoned
61	Colorado Oil and Gas Co. Malaspina 1	West shore of Yakutat Bay, Malaspina district	1962	1,802	Yakataga Formation	Abandoned
62	Colorado Oil and Gas Co. Malaspina 1A (redrill)	do.	1962	13,823	Yakataga and Kulthieth Formations, and pre-Tertiary(?) rocks	Abandoned
63	Colorado Oil and Gas Co. Yakutat 1	Near Yakutat, Yakutat district	1957	9,314	Yakataga, Poul Creek, and Kulthieth Formations	Abandoned

Table 1 (Cont'd)

64	Colorado Oil and Gas Co. Yakutat 3	do.	1958-59	10,494	Yakataga, Poul Creek(?), and Kulthieth Formations, and pre-Tertiary rocks	Abandoned
65	Colorado Oil and Gas Co. Yakutat A-1(2)	do.	1957-58	11,765	Yakataga and Kulthieth Fms., and pre-Tertiary	Abandoned. Shows of oil and gas
66	Colorado Oil and Gas Co. Core hole 1	do.	1961	3,230	Yakataga, Poul Creek(?), and Kulthieth Formations	Abandoned
67	Colorado Oil and Gas Co. Core hole 2	Near Dangerous River, Yakutat District	1961	5,690	Yakataga, Poul Creek, and Kulthieth(?) Formations	Abandoned
68	Colorado Oil and Gas Co. Dangerous River 1	do.	1960	8,634	Yakataga, Poul Creek(?), and Kulthieth(?) Formations, and pre-Tertiary rocks	Abandoned
69	Colorado Oil and Gas Co. Core hole 3	Akwe River, Yakutat district	1961	5,484	Yakataga and Poul Creek(?) Formations	Abandoned
70	Colorado Oil and Gas Co. Core hole 4	Dry Bay, Yakutat district	1961	5,326	do.	Abandoned
71	Tenneco Middleton Island State 1	Middleton Island	1969	12,002	Yakataga, Katalla, Tokun, and Kushtaka(?) Formations	Abandoned

1/ Inferred from lithology and microfauna since 1963 in anticipation of state and federal lease sales on the continental shelf.

In the sale held July 19, 1966, bonuses paid to the State of Alaska for leases in the Gulf of Alaska averaged $164 per acre; the highest bid was $761 per acre. During the summer of 1969, Tenneco drilled the first well to test the offshore potential of the basin near Middleton Island (Fig. 2, Table 1, No. 71). The well, which was drilled to a depth of 12,002 feet (3,658 m), bottomed in late Eocene or older strata. No oil shows, attractive source rocks, or suitable reservoir sands were encountered in the section drilled. The hole was abandoned and Tenneco subsequently dropped its Middleton Island leases.

PETROLEUM POTENTIAL

General Considerations

The occurrence of petroleum in commercially exploitable deposits requires a combination of: 1) suitable source rocks and burial history for generation of petroleum, 2) strata with permeability and porosity adequate to permit migration of the petroleum towards traps and to reservoir the petroleum, and 3) the presence of traps where the petroleum can accumulate in pools and be preserved against loss and destruction. If any one of these essential elements is missing in a sedimentary basin, commercial petroleum deposits cannot occur.

The critical factor for accumulation of commercial petroleum deposits in the GATP OCS probably is the availability of adequate reservoir sandstone in close association with middle Tertiary petroliferous mudstone and siltstone. The necessary conditions are most likely to be fulfilled along the flanks and over the crests of structural highs that were growing synchronously with middle Tertiary sedimentation. Stratigraphic relations onshore suggest that some anticlines in the Yakataga and Malaspina districts were growing intermittently throughout much of Miocene and probably all of Pliocene time. If comparable or older synchronous highs are present on the continental shelf, and were at or near sea level for sufficient periods of time, they could have been the loci for accumulation of winnowed sandstone wedges with better sorting than that of coeval sands laid down in the deeper water of the intervening areas. Furthermore, early accumulation of hydrocarbons in such winnowed sandstone bodies could have inhibited the type of secondary cementation that in the outcrop has made the sandstone generally unsuitable for commercial reservoirs.

Source Rocks and Surface Indications

On the basis of the stratigraphic units in which most of the oil seeps and other indications of petroleum are found, a probable source in the middle part of the Tertiary sequence is indicated. Bedded rocks of early Tertiary age are believed to have little petroleum potential because of their characteristically high degree of induration. The Orca Group and pre-Tertiary rocks in this region are effective basement for petroleum.

In the Katalla and Yakataga districts, most of the known oil seeps, as well as indications of oil in wells and small production from the Katalla field, are in areas with fractured outcrops of the middle part of the Katalla Formation, the Poul Creek Formation, and the lower part of the Yakataga Formation. The Katalla and Poul Creek Formations contain thick units of predominantly brown, dark brown, brownish black and black argillaceous strata containing sufficient organic remains to suggest that they were probably good source rocks for petroleum. Organic-rich shale and claystone units as much as 800 feet (244 m) thick occur within the upper Katalla Formation on Kayak Island, and similar thinner units of comparable lithology occur within the lower part of the formation. Such rocks commonly have petroliferous odors on freshly broken surfaces and in some places they produce oily films when ground and placed in water. Analysis of a typical sample of organic shale from the central Katalla district yielded 5.1 percent total organic matter and about 0.8 gallon of oil per ton (analysis of W. W. Brannock, U. S. Geological Survey).

In the outcrop, potential source rocks are known only in the Katalla and Yakataga districts. Although source rocks are not exposed in the Malaspina district, the presence of numerous oil and gas seeps in the Samovar Hills suggests the possibility that organic-rich strata of the middle Tertiary sequence occur beneath the Malaspina Glacier and its fringe of unconsolidated deposits. Shows of oil and gas in the Yakutat A-1 (2) well (Table 1, No. 65) suggest that petroliferous rocks also are present beneath part of the Yakutat Foreland.

The offshore distribution of the organic-rich facies is unknown. It does not occur in the Middleton Island well. Offshore seepages of oil or gas have not been reported despite heavy commercial fishing over much of the continental shelf and despite the known occurrence of numerous geologically young faults in the sub-bottom sequence along which petroleum could leak to the sea floor if it were present.

Oil resembling that found elsewhere in the province seeps from hard siltstone and sandstone of probable early Tertiary age in structurally complex settings on the west side of Ragged Mountain in the western Katalla district and along the southern margin of the Samovar Hills in the Malaspina district. It has been postulated that lower Tertiary rocks are the source of the oil at Ragged Mountain and the

Samovar Hills (Plafker and Miller, 1957; Miller and others, 1959, p. 43). However, the composition of the oil and the structural setting of the seeps suggest the alternative possibility that the oil is derived from middle Tertiary rocks that lie beneath thrust sheets of the older rock units. For the lower Tertiary sequence to be a source of petroleum, its lithologic character would have to differ markedly from that seen in outcrops. Although such changes conceivably could occur within the vast parts of the basin that are covered by alluvial deposits, ice, or water, there is no geologic basis for believing that source-rock characteristics should be substantially improved in such areas.

Reservoirs

Sandstones in the GATP Tertiary sequence are the only likely potential reservoirs rocks with primary porosity and permeability.

Outcrop samples of most sandstones in the lower Tertiary sequence are compositionally and texturally immature. Even the best-sorted sandstones appear to have poor reservoir characteristics because they are greatly compacted and tightly cemented with authigenic silica, zeolites, and carbonates. Analyses show that four of the cleanest upper Eocene sandstones sampled have between 4 and 7 percent porosity and less than 0.01 md permeability. Some well-sorted, shallow-water sandstone units that appear to be porous and friable in the outcrop were found to have less than 5 percent interstitial porosity when examined microscopically.

Better sorted and less indurated sandstone is present locally in the middle and upper Tertiary sequences, but most of the outcrop samples also have fairly low porosity and permeability, mainly because of a fine-grained matrix of rock flour and primary and authigenic phyllosilicates. For example, 20 sandstone samples analyzed from the Poul Creek and Katalla Formations have porosity ranging from 1.6 to 18.34 percent, averaging around 9 percent; permeability ranges from less than 0.01 to 23 md in unfractured sandstones and averages about 4 md. The highest porosity and permeability measured are from thin sandstone beds near the middle part of the formation. Porosity and permeability of 35 sandstones from the lower, middle, and upper parts of the Yakataga Formation range from 2 to 21 percent and from less than 0.01 to 15 md, respectively. Most of the outcropping Yakataga sandstone that has been examined microscopically shows interstices effectively plugged by deformed detrital lithic fragments that comprise an average of 23 percent of the sandgrains. Locally, however, selected strandline sandstones have been found in outcrops of the lower Yakataga Formation of the western Yakataga District that have porosities over 20 percent and permeabilities of a few hundred millidarcies (W. M. Lyle, pers. comm., 11/17/75).

The source of the Neogene clastic sediments in the basin was primarily on the north and northeast. Consequently, average grain size and sorting of the sandstones normally would tend to decrease offshore with a concomitant reduction in porosity and permeability. It is conceivable, however, that sorted sands in large quantity could have been transported well out into the basin by turbidity currents, or that unsorted sands may have been reworked sometime after deposition within the basin.

Traps

In frontier basins such as the GATP, it is to be expected that initial exploratory efforts will be directed towards finding and drilling large anticlinal structures rather than the more subtle stratigraphic, fault, and combination traps. The 22 deep test wells drilled since 1954 onshore and on State land offshore were located mainly on known or inferred anticlinal highs. The wells were unsuccessful, in large part, because structures are so complex that it has proven difficult to intersect suitable traps at depth. The prevailing intense deformation characteristic of some of the anticlinal cores may also have been a contributing factor in reducing the porosity and permeability of potential reservoir sandstones. All of the favorable accessible structures exposed along the coast have been tested adequately by the exploration carried out to date. Structures that are exposed onshore elsewhere along the Gulf of Alaska coast have proven to be either inaccessible or too small and complex to justify exploratory drilling.

All of the large closed anticlinal structures that occur in the central part of the GATP on the OCS are potential targets for exploratory drilling. Most of the offshore folds detected on the continuous reflection seismic profiles appear to be more open and less complex than onshore structures (figs 5A and 5B). However, it is probable that structural levels visible on our single-channel records are significantly shallower than those that are exposed in most coastal anticlines. For example, we may be comparing folds in the upper Yakataga Formation offshore with onshore structures exposing lower Yakataga and underlying strata, stratigraphic levels that could differ by 10-15,000 feet (3050 to 4570 m). Indeed, the available geologic evidence from the mainland and offshore islands suggests that in the western part of the Province, at least, severe late Cenozoic compressional deformation has affected the entire continental shelf.

Relative petroleum potential by area

On figure 6 we have subdivided areas of the GATP OCS that appear to have common geologic characteristics and in table 2 these areas are rated qualitatively on a scale of 1 to 5 according to our best present judgment regarding their relative petroleum potential. This evaluation will undoubtedly require revision when more and better offshore geophysical and geological data are obtained. Rankings are based primarily on 1) the relative abundance of possible anticlinal traps as determined from the seismic reflection data, and 2) the inferred offshore distribution of source rocks as extrapolated from known onshore occurrences. To the extent possible, we have also tried to weigh more speculative factors affecting petroleum potential such as the position of anticlines with respect to projected depocenters, the inferred thickness of overburden on the structures, and the possible distribution of suitable reservoir sands on the OCS.

The highest ranked area, the Icy Bay trend, contains numerous large structures and is underlain by a thick late Cenozoic sequence that includes good source rocks. Possible unfavorable factors may be 1) scarcity of suitable reservoir sands near the Poul Creek-Yakataga

TABLE 2. Tentative rating of segments of the eastern Gulf of Alaska OCS according to inferred petroleum potential (1 highest, 5 lowest)

RATING	AREA
1	Icy Bay Trend
2	Shelf-edge arch
3	Bering basin
3	Kayak-Middleton Trend
3	Middleton Platform
3	Pamplona Ridge
4	Yakutat basin area
5	Tarr Bank and vicinity
5	Fairweather Ground

unconformity, 2) excessive drilling depths to potential target horizon near the basal Yakataga Formation, and 3) structural complications at depth.

The shelf-edge arch is ranked second because it is a large, relatively simple structurally high area with well-developed flank unconformities. Deep structure is unknown and this area is probably less favorably situated for good reservoir sand development than areas closer to the northerly sediment source terrain.

The third-ranked areas, the Kayak-Middleton trend, Middleton Platform, and Pamplona Ridge, all appear to have thick late Cenozoic bedded sequences and large structural highs. However, the seismic data suggests intense deformation in the cores of the highs. The geology of Kayak and Wingham Islands and the result of the Middleton Island well do not provide grounds for optimism regarding the availability of suitable reservoirs or the presence of liquid hydrocarbons.

The Bering basin and Yakutat basin rankings of 3 and 4, respectively, are based on the occurrence of a thick sedimentary section but without known anticlinal traps. The Bering basin is ranked slightly higher because it includes probable source rocks and indications of possible local structural highs.

In the lowest-ranked categories, Tarr Bank and vicinity and the Fairweather Ground area, lower Tertiary or older "basement" rocks are either exposed at the surface in structural highs or are veneered with a thin cover of young sediments.

[1]/Estimates of petroleum resources

Oil and gas resource estimates, based upon volumetric and analog methods, are shown in Table 3. The indicated undiscovered commercially recoverable petroleum in the area considered ranges from zero up to 4.2 billion barrels of oil and 4.8 trillion feet of gas, depending upon the assumptions made. The area for which estimates of petroleum potential are given lies within the segment of the Gulf of Alaska OCS roughly bounded on the east and west by long. 141° and 146° W respectively, and extends from the onshore rock outcrops to the edge of the continental shelf, about 30 miles (50 km) offshore. The area is treated as two subsidiary basins separated by a line connecting Kayak and Middleton Islands because of marked differences in the geology on either side of Kayak Island, as outlined in the previous section. The south and north limits of the area do not include the two basins in their entirety but reflect the limits of available offshore data that outline the geology with some degree of confidence. The western basin broadly includes the Kayak-Middleton trend, Middleton Platform, and Tarr Bank and vicinity blocks outlined in figure 6, and the eastern basin includes the Icy Bay Trend, Pamplona Ridge, and western part of the Yakutat basin.

Highly optimistic estimates of OCS resources in the range of tens of billions of barrels of recoverable oil have been made by application of volumetric methods but do not seem to be realistic for the areas considered here in light of existing geologic data. For example, an estimate of up to 20 billion barrels of recoverable reserves in the total eastern Gulf of Alaska was made by the chairman of the Gulf of Alaska

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1/This section prepared in collaboration with Thane McCulloch, E. G. Sable, Gordon L. Dolton, and Richard B. Powers

Table 3. Oil and gas resource estimates in the central portion of the eastern Gulf of Alaska OCS based on analog and volumetric methods

Area	[1]Analog	Undiscovered Recoverable Oil (Billions of Barrels)	Undiscovered Recoverable Natural Gas (Trillions of Cubic Feet)
West of Kayak Island	British Columbia, Wash., Oregon OCS	0	0
	Cook Inlet (Total Resources)	0.1	0.6
	San Joaquin Basin, Ca.	1.0	1.1
East of Kayak Island	British Columbia, Wash., Oregon OCS	0	0
	Cook Inlet (Total Resources)	0.3	2.0
	San Joaquin Basin, Ca.	3.2	3.7
	TOTALS	0 - 4.2	0 - 4.8

[1]Analogs based upon exploration and production as of 1975.

Operators Committee (Anchorage Daily Times, 9/26/73). This estimate was based upon a larger geographic area and a greater volume of sediments than used in Table 3. It was assumed in their calculations and in one of our analogs that petroleum yield per cubic mile of sediment in the GATP OCS would be comparable to that of the San Joaquin Valley, an interior basin in California with a totally different geologic setting and history. On geologic grounds, more reasonable comparisons might have been made with other Tertiary continental margin clastic basins such as offshore British Columbia, Washington, and Oregon. These shelves have yet to yield commercial petroleum despite persistent exploratory efforts.

The critical values of sediment thickness and basin areas used herein for volume calculations are conservative. The western basin is about 2700 miles^2 (6,900 km^2) in area with a possible average thickness of 10,000 feet (3050m) for post-Eocene rocks, although they may be as much as 18,000 feet (5,500m) in the deepest part of the basin 20 to 25 miles (23 to 40 km) offshore. The eastern basin consists of about 3400 mi^2 (8,700 km^2) with an average thickness of probable post-Eocene rocks of 16,500 feet (5,000m) or more. Calculated volume of sediment believed to be younger than Eocene in age is conservatively estimated to exceed 3,200 miles^3 (13,100 km^3) in the western basin and 10,500 miles^3 (43,000 km^3) in the eastern basin.

The figures in Table 3 indicate very large ranges for the estimated oil and gas potential of this part of the Gulf of Alaska Basin. We feel that the resource potential of this area should fall within these indicated ranges. However, because of sparse data in this area, uncertainties of proper analog selection, and because some of the selected analogs are also frontier basins, any one of these estimates would be highly conjectural, a fact that cannot be overstressed. In evaluating these estimates, it should be borne in mind that the recent onshore exploration results have been unsuccessful. Furthermore, although it is possible that the factors controlling accumulation of liquid hydrocarbons in commercial deposits may improve offshore, we have no reasons for assuming that this is actually the case.

Undiscovered recoverable petroleum resources are those quantities of oil and gas that may be reasonably expected to exist in favorable settings, but which have not yet been identified by drilling. Such estimates, therefore, carry a high degree of uncertainty. In order to estimate the quantities of undiscovered recoverable oil and gas resources, it is necessary to make certain assumptions. In Table 3, it was assumed that 60% of the oil in place would be discovered (discovery factor), and of the oil discovered, 50% would be recovered (recovery factor). Therefore, it is estimated that 24% (the discovery factor multiplied by the recovery factor) of the oil in place in that portion of the Gulf of Alaska Tertiary Province proposed for leasing by the Bureau of Land Management will be found and produced. A discovery factor of 60% and a recovery factor of 80% was assumed for natural gas. Therefore, it is estimated that 48% of gas in place would be found and produced.

Other Mineral Resources

Mineral resources other than petroleum are not known to occur on the continental shelf in the GATP. The potential of the region, however, cannot be adequately assessed at present because of the paucity of information on the bottom sediments. The one systematic study that was made of a segment of shelf lying generally between Yakataga and Icy Bay failed to locate any anomalous concentrations of metallic minerals (Wright, 1972). Nevertheless, the sporadic occurrence of gold, platinum, magnetite, ilmenite, and other heavy minerals as beach placers along the coast (Thomas and Berryhill, 1962), suggests the possibility that these minerals might occur in commercially exploitable concentrations on the adjacent shelf.

GEOLOGIC HAZARDS

General Statement

The geology and topography of the Gulf of Alaska Tertiary province record an extremely high level of tectonic activity during the late Cenozoic, and the earthquake history of the region (see Table 4) clearly demonstrates that tectonism continues undiminished to the present. Judging from past experience, major earthquakes that could pose serious potential hazards to installations on the continental shelf or along the Gulf of Alaska coast may occur in the future. The hazard may be either direct by ground shaking, fault displacement, and tectonic warping, or indirect through ground failure or generation of tsunami waves. The earthquake-related hazards are considered more fully in the sections that follow.

Table 4.--Earthquakes in and near the Gulf of Alaska Tertiary Province, Alaska, 1899 through 1973.

[Includes earthquakes of magnitudes 6.0 or greater whose epicenters lie between 55° and 62° North latitude and between 136° and 154° West longitude.]

Date			Origin Time	Latitude	Longitude	Depth	Magnitude
Day	Month	Year	Hr/Min GMT	(Degrees N)	(Degrees W)	(Kilometers)	
4	09	99	22	60.00	142.00	0	8.30
10	09	99	1704	60.00	140.00	0	7.80
10	09	99	2140	60.00	140.00	0	8.60
9	10	00	1228	60.00	142.00	25	8.30
15	05	08	831	59.00	141.00	0	7.00
19	09	09	2100	60.00	150.00	0	7.40
22	09	11	501	60.50	149.00	60	6.90
31	01	12	2011	61.00	147.50	80	7.25
7	06	12	955	59.00	153.00	0	6.40
10	06	12	1606	59.00	153.00	0	7.00
5	12	12	1227	57.50	154.00	90	7.00
7	07	20	1841	61.00	140.00	0	6.00
24	10	27	1559	57.50	137.00	0	7.10
21	06	28	1627	60.00	146.50	0	7.00
24	12	31	340	60.00	152.00	100	6.25
14	09	32	843	61.00	148.00	50	6.25
4	01	33	359	61.00	148.00	0	6.25
27	04	33	236	61.25	150.75	0	7.00
13	06	33	2219	61.00	151.00	0	6.25
19	06	33	1847	61.25	150.50	0	6.00
4	05	34	436	61.25	147.50	80	7.20
14	05	34	2212	57.75	152.25	60	6.50
2	06	34	1645	61.25	147.00	0	6.25
18	06	34	913	60.50	151.00	80	6.75
2	08	34	713	61.50	147.50	0	6.00
11	10	40	753	59.50	152.00	0	6.00
1	04	41	1040	56.00	153.50	0	6.50
30	07	41	151	61.00	151.00	0	6.25
5	12	42	1428	59.50	152.00	100	6.50
3	11	43	1432	61.75	151.00	0	7.30
3	02	44	1214	60.50	137.50	0	6.50
3	11	45	2209	58.50	151.00	50	6.75
12	01	46	2025	59.25	147.25	50	7.20
27	09	49	1530	59.75	149.00	50	7.10
31	10	49	139	56.00	136.00	0	6.25
25	06	51	1612	61.10	150.10	128	6.25
9	03	52	2000	59.50	136.00	0	6.00
29	11	52	2346	56.30	153.80	0	6.90
15	06	53	1747	56.30	153.80	0	6.50
3	10	54	1118	60.50	151.00	100	6.70
19	07	55	2352	56.50	153.00	0	6.00
26	07	55	404	56.50	153.00	0	6.00
27	07	55	1819	56.50	153.00	0	6.25
10	04	57	1130	55.96	153.86	0	7.10

Table 4.--(continued)

Date			Origin Time	Latitude	Longitude	Depth	Magnitude
Day	Month	Year	Hr/Min GMT	(Degrees N)	(Degrees W)	(Kilometers)	
24	01	58	2317	60.00	152.00	60	6.38
10	07	58	615	58.36	136.34	0	7.90
24	09	58	344	59.50	143.50	0	6.25
19	04	59	1503	58.00	152.50	0	6.25
26	12	59	1819	59.74	151.38	0	6.25
1	09	60	1537	56.30	153.70	24	6.13
20	01	61	1709	56.60	152.30	46	6.38
31	01	61	48	56.00	153.90	26	6.38
10	05	62	3	62.00	150.10	72	6.00
12	05	63	2008	57.30	154.00	60	6.10
24	06	63	426	59.50	151.70	52	6.80
28	03	64	336	61.00	147.80	33	6.50
28	03	64	454	59.80	149.40	25	6.10
28	03	64	643	58.30	151.30	25	6.10
28	03	64	710	58.80	149.50	20	6.10
28	03	64	901	56.50	152.00	20	6.00
28	03	64	1035	57.20	152.40	33	6.10
28	03	64	1220	56.50	154.00	25	6.10
28	03	64	1447	60.40	146.50	10	6.10
28	03	64	1449	60.40	147.10	10	6.10
28	03	64	2029	59.80	148.70	40	6.60
30	03	64	709	59.90	145.70	15	6.00
3	04	64	2233	61.60	147.60	40	6.20
20	04	64	1156	61.40	147.30	30	6.60
21	04	64	501	61.50	147.40	40	6.00
4	09	65	1432	58.20	152.70	10	6.20
22	12	65	1941	58.40	153.10	51	6.50
23	04	68	2029	58.70	150.00	23	6.30
15	11	68	7	58.33	150.37	26	6.38
17	12	68	1202	60.17	152.84	86	6.50
24	11	69	2251	56.20	153.56	33	6.00
16	01	70	805	60.31	152.72	91	6.00
11	03	70	2238	57.46	153.92	29	6.50
11	04	70	405	59.71	142.74	7	6.20
16	04	70	533	59.77	142.60	7	6.80
19	04	70	115	59.64	142.83	20	6.00
18	08	70	1752	60.70	145.38	16.	6.00
1	07	73	1333	57.84	137.33	33.	6.70
3	07	73	1659	57.98	138.02	33.	6.40

Primary Sources of data:

1. Table 2 in Seismicity of Alaska, in Wood, F. J., ed., 1966, Operational phases of the Coast and Geodetic Survey program in Alaska for the period March 27 to December 31, 1964, v. 1 of the Prince William Sound, Alaska, earthquake of 1964 and aftershocks: U.S. Coast and Geodetic Survey, 236 p.

2. [U.S.] National Oceanic and Atmospheric Administration, Earthquake data file, 1900-1973, National Oceanic and Atmospheric Administration Environmental Data Service.

Other potential non-seismic geologic hazards that cannot be discounted, but about which we have little data, are the possibilities of encountering overpressurized gas pockets at shallow depth during exploratory drilling and also possible instability of unconsolidated deposits on which structures may be sited.

Seismic History

The GATP is the most seismically active region in the United States apart from the Aleutian Islands. Five major earthquakes, equal to or larger than magnitude 7.8, have occurred in the province during the last 75 years (Table 4). The most recent of these shocks - the 1964 Alaska earthquake (magnitude 8.5) is one of the largest earthquakes ever recorded. The main shock and most of its aftershocks, as well as the maximum crustal deformation, occurred in remote uninhabited regions. Nevertheless, the earthquake and the resulting seismic sea waves killed 114 people and caused over $300 million of damage in Alaska and along the coasts of British Columbia and the western United States. Uplift and subsidence as large as 38 feet (11 m) and 7-1/2 feet (2.3m) respectively, were measured in the GATP, and measurable uplift and subsidence were observed over an area of 77,000 $miles^2$ (200,000 km^2) extending along the coast from west of Cape Yakataga to Kodiak Island (Plafker, 1969). The approximate focal region of the earthquake and area of uplift along the continental margin are outlined in figure 7.

At the turn of the century, in 1899 and 1900, a remarkable series of four major earthquakes occurred in the vicinity of Yakutat Bay and Icy Bay. From the few instrumental recordings available for these shocks, Richter (1958) assigns magnitudes ranging from 7.8 to 8.6 for the individual events. No deaths nor significant damage resulted because of the remote setting for the shock and the lack of seismic sea waves. The earthquakes resulted in large changes in elevation with a maximum of 47-1/3 feet (14.4 m) of uplift observed on the shoreline of Disenchantment Bay. This is the maximum change in elevation ever measured on land for an earthquake sequence. The epicenters derived from the few instrumental data are uncertain by at least 60 miles (100 km); the post-earthquake field studies are a better constraint on the locus of energy release. The absence of damaging seismic sea waves indicates that the strain energy released during the earthquake was primarily on land, rather than on the continental shelf.

In 1958, a magnitude 7.9 earthquake ruptured the Fairweather fault for at least 190 miles (300 km) from the vicinity of Yakutat Bay to Cross Sound. Evidence of surface rupture was mapped discontinuously from Icy Point to Nunatak Fiord, a distance of 120 miles (200 km). The sense of fault movement was predominantly right-lateral strike-slip, and the maximum reported lateral offset was 21 feet (7 m) (Tocher, 1960). Again because of the lack of permanent settlements in the region, damage was slight and the death toll was limited to three. The most spectacular effect of the earthquake was a giant water wave in Lituya Bay generated by a subaerial landslide that plunged into the inlet and caused water to surge to a maximum elevation of 1740 feet (520 m) on the opposite wall of the inlet (Miller, 1960).

Numerous smaller but potentially damaging earthquakes in the GATP have been recorded in this century. Shallow focus earthquakes of magnitude 6 or larger are potentially damaging to man-made structures, and earthquakes in the magnitude 5 class may also cause damage within several kilometres of the rupture surface. Table 4 lists historic earthquakes with magnitudes equal to or greater than 6.0 that have occurred between latitudes 55° N and 62° N and longitudes 136° W and 154° W during the interval 1899 through 1973. Included are events for which one of the three measurers of magnitude (surface-wave magnitude (M_S) body-wave magnitude (m_b) or Richter local magnitude (M_L)) equal or exceed 6.0. There are a total of 83 shocks of which 64 are in the magnitude range 6.0 - 6.0 and 15 in the ranges 7.0 - 7.9.

Table 4 does not include all shocks as small as magnitude 6.0 since 1899; many shocks in the magnitude 6 range could not be located because of the lack of sensitive seismograph stations early in the century. Most likely the table is nearly complete for shocks larger than magnitude 7 3/4, but is complete for shocks as small as magnitude 7.0 only since 1918 and as small as magnitude 6.0 only since the early 1930's (Gutenberg and Richter, 1954).

Epicenters of historic earthquakes occurring in and near the GATP (taken from Table 4) are plotted in figure 7. The different symbols represent different ranges of focal depth, whereas the increasing symbol sizes correspond to increasing magnitudes. The uncertainties associated with the tabulated epicentral coordinates generally decrease with time. Prior to the early 1930's uncertainties in excess of 60 miles (100 km) are common as reflected in the reporting of epicentral coordinates only to the nearest degree. From the early 1930's to the late 1950's or the early 1960's epicentral uncertainties typically were on the order of 30 miles (50 km). Since the installation of seismograph stations in southern Alaska after the 1964 earthquake, the uncertainties have been reduced to 15 miles (25 km) or less. For most earthquakes the uncertainty in focal depth is less than 30 miles (50 km). Recent detailed studies of seismicity in southern Alaska indicate that earthquakes with focal depths greater than 30 miles (50 km) do not occur in the GATP (Lahr and others, 1974; Page and other 1974; Lahr, 1975). Within the framework of existing knowledge, it is reasonable to assume that earthquakes in the GATP occur in the crust at depths of less than 20 miles (30 km).

Faulting and Warping

The known coastal late Cenozoic faults or systems of faults, around the margin of the Gulf of Alaska tend to follow the arcuate grain of the mountain ranges and the coast (fig. 7). Two short north-south trending faults with Holocene movement cross the regional grain at large angles in the Controller Bay area (Ragged Mountain fault) and in the central Kenai Mountains (Kenai lineament).

Fault displacements and large-scale vertical movements of the land relative to sea level are known to have occurred during three great earthquakes in the Gulf of Alaska Tertiary province which are described under the seismic history. The 1899 Yakutat Bay earthquake was accompanied by a complex pattern of tectonic warping and tilting over an area of about 580 miles^2 (1500 km^2) centered on Yakutat Bay (Tarr and Martin, 1912). The 1958 Lituya earthquake was accompanied by right-lateral slip of up to 21 feet (7 m) on the Fairweather fault (Tocher, 1960); and the most recent and largest earthquake to affect the region, the 1964 Alaska event, is believed to have been generated by dip-slip displacement of 66 feet (20 m) or more on a segment of the Aleutian Arc megathrust system at least 500 miles (800 km) long (Plafker, 1969). Significant tectonic deformation affected a minimum area of 77,000 miles^2 (200,000 km^2) and two subsidiary reverse faults with up to 26 feet (7.9 m) dip slip broke the surface on Montague Island and extended offshore onto the continental shelf to the southwest (fig. 7).

On the continental shelf of the GATP many subbottom faults have been identified on the high-resolution seismic profiles, but few appear unequivocally to rupture the sea floor. Nevertheless, in view of the onshore record of active deformation and the distribution of shallow focus earthquake epicenters on the continental shelf, the likelihood of future fault displacement of the sea floor is a distinct probability.

Because of the uncertainity in epicentral locations, the pattern of historic seismicity (fig. 7) cannot be used to identify seismically active faults. Some improvements in the precision of historic data can be achieved by relocating the old events on a digital computer with improved seismic velocity models (Page, 1975). For example, such techniques have been applied to the Pamplona Ridge earthquake sequence of April 1970 and the Cross Sound sequence of July 1973. The relocated epicenters for the two sequences clearly delineate seismically active faults (fig. 8). The Pamplona Ridge sequence trends about N 20° E, parallel to the submarine ridge; the Cross Sound epicenters align with the WNW trend of the continental slope at the edge of the Fairweather Ground. The absolute accuracy of the relocated epicenters may be no better than 7-10 miles (10-15 km), however, the relative accuracy among the different epicenters is probably 3 miles (5 km) or better. Within the uncertainty of the data, the Pamplona Ridge earthquakes may be associated with movement on one of the faults interpreted from seismic reflection profiles to bound Pamplona Ridge on the east and west. The Cross Sound earthquakes are inferred to mark the eastern extent of a zone of oblique underthrusting along the continental shelf edge in the eastern Gulf of Alaska (Gawthrop and others, 1973).

Onshore networks of sensitive seismographs with a station spacing of 30 miles (50 km) have also proven useful in the delineation of offshore fault trends (Page and Gawthrop, 1973; Gawthrop and others, 1973). In September 1974 the U. S. Geological Survey installed thirteen new seismographs along the Gulf of Alaska from Yakutat Bay to Montague Island for the purpose of better locating earthquake epicenters and defining seismic hazards in the GATP. Preliminary results from this network for the interval September 1974 through May 1975 indicate marked concentrations of earthquake activity in the vicinity of Icy Bay and also offshore in the vicinity of 59°N, 149°W and scattered earthquakes along the continental shelf edge between 144°W and 147°W and along the southeastern shores of Montague and Hinchinbrook Islands. Refined analysis of the existing earthquake data will better resolve the structures responsible for the concentrated activity. Continued seismic monitoring will furnish additional data that will undoubtedly delineate additional seismically active faults.

Tsunamis

Most major earthquakes that involve vertical tectonic displacements beneath the sea are followed by tsunamis (seismic sea waves or "tidal" waves). The earthquake of March 27, 1964, generated one of the larger seismic sea-wave trains of modern times. These waves took 20 lives and caused destruction all along the Gulf of Alaska coast between the southern tip of Kodiak Island and Kayak Island (Plafker, 1969, Plafker and others, 1969). Damage and loss of life were minimized because the initial waves struck at low tide and because much of the coastal belt was tectonically uplifted during the earthquake (fig. 7). The sea waves, which were recorded on tide gages throughout the Pacific Ocean, caused 15 deaths and major damage in British Columbia, Oregon, and California. Recorded run-up heights on steep, rocky coasts along the Gulf of Alaska were as much as 35-40 feet (10.7-12.2 m) above maximum high tides; they were as much as 8 feet (2.4 m) above the high shoreline along the gently sloping outer coast in the area east of Cordova. Tsunami waves with an amplitude of 16-18 feet (4.9-5.5 m) were recorded at Yakataga but the highest of them did not reach to the normal high tide level of about 15 feet (4.6 m).

Future earthquakes involving tectonic deformation of the continental shelf in the eastern Gulf of Alaska may be expected to be accompanied by tsunami waves. Their damage potential will depend to a large degree upon the amount and rate of deformation, the stage of tide, and the effect of bottom configuration on amplification and focusing of the waves. A tsunami comparable to the one that accompanied the 1964 earthquake is probably a reasonable maximum that should be anticipated.

There is no historic record of inundation of the eastern Gulf of Alaska coast by tsunami waves from distant earthquakes.

Earthquake recurrence and seismic gaps

Two general approaches are available for deducing the relative susceptibility to major tectonic earthquakes of a continental margin such as the GATP. One is a geologic method in which radiometrically-data displaced shorelines are used to obtain quantitative information on past vertical displacement rates and the recurrence frequency of major tectonic movements which presumably accompany earthquakes. The other is a seismologic method in which the spatial distribution of historic seismicity is used to identify gaps along major tectonic boundaries that are likely to be filled by future events. Both of these methods involve a number of assumptions and uncertainties and neither can predict when an earthquake will occur. However, it may be significant that the two methods independently identify portions of the GATP shelf and slope extending to the east of Middleton Island as a region where one or more major earthquakes are highly probable.

Reconnaissance studies of emergent terraces and beaches along the Gulf of Alaska Coast indicate that the long-term vertical movements occurred as a series of upward pulses that were separated by intervals of stability or even gradual submergence. These upward pulses presumably represent earthquake-related movements similar to the emergence that affected the same coasts during the 1964 event.

The best record of successive uplifts is preserved in a steplike flight of marine terraces at Middleton Island, 50 miles (80 km) off the mainland coast near the edge of the continental shelf. Episodic emergence of the island is recorded by six gently sloping marine terraces that are separated by wave-cut cliffs or rises with average beach-angle elevations of about 13, 45, 75, 98, 131 and 151 feet (4, 14, 23, 30, 40, and 46 m). The 13-foot (4-m) terrace is a marine surface that was uplifted suddenly during the 1964 earthquake. Radiocarbon ages for four of the five older terraces suggest that (1) The last previous uplift was about 1400 years ago; (2) sudden uplifts have occurred at Middleton Island at intervals of 500 to 1400 years (average 800 years) since the island emerged from the sea about 4500 years ago; and (3) the average rate of uplift is about 1 cm/yr, but the rate during the past 1400 years has been one-half that amount (Plafker and Rubin, 1969, and Plafker, 1972). Thus, if the deformation rate is constant, it follows that another tectonic earthquake involving uplift of Middleton Island on the order of an additional 13 feet (4 m) is overdue. Similar data on the displaced shorelines of the Katalla district coast support the conclusion that additional tectonic uplift in that region is needed to keep pace with a long-term late Holocene uplift rates.

Sykes (1971) used a study of historic seismicity along the Alaskan portion of the boundary between the Pacific and North American plates to identify the 125 to 185 mile (200 to 300 km) - long segment lying between the focal regions of the 1964 Alaska and 1958 Lituya earthquakes as a seismic gap that is likely site for a future earthquake larger than magnitude 7.8. On the other hand, Kelleher (1970), using the same seismic data concluded that the gap was not a possible site for such a large earthquake because it was too small and because of the possibility that it could have been filled by the 1899 Yakutat Bay sequence; his data, however, do permit an earthquake as large as magnitude 7.7.

REFERENCES CITED

Bandy, O. L., Butler, A. E., and Wright, R. C., 1969, Alaskan upper Miocene glacial deposits and the Turborotalia pachyderma datum plane: Science, v. 166, p. 607-609.

Bruns, T. R., and Plafker, George, 1975, Preliminary structural map of part of the offshore Gulf of Alaska Tertiary Province: U.S. Geol. Survey open-file report 75-508.

Carey, S. W., 1958, The tectonic approach to continental drift, in Continental drift--a symposium: Hobart, Australia, Tasmania Univ. Geol. Dept. [1956], p. 177-355.

Carlson, P. R., and Reimnitz, Erk, 1975, Study of river effluents and coastal water circulation off the west coast of North America using ERTS-1 data: Geol. Soc. America, Abstract with Programs, v. 5, p. 20.

Carlson, P. R., Bruns, T. R., and Molnia, B. F., 1975, Submarine slides and near-surface faults, northern Gulf of Alaska: U.S. Geol. Survey open-file report 75-504.

Davis, T. N., and Sanders, N. K., 1960, the Alaska earthquake of July 10, 1958; intensity distribution and field investigation of northern epicentral region: Seismol. Soc. America Bull., v. 50, no. 2 p. 221-252.

Eckel, E. B., 1970, The Alaska earthquake March 27, 1964: Lessons and conclusions: U. S. Geol. Survey Prof. Paper 546, 57 p.

Gawthrop, W. H., Page, R. A., Reichle, M., and Jones, A., 1973, The Southeast Alaska earthquakes of July 1973 [abs]: EOS Trans. Am Geophys. Union, v. 54, p. 1136.

Gershanovich, D. E., 1968, New data on geomorphology and recent sediments of the Bering Sea and Gulf of Alaska: Marine Geology, v. 6, p. 281-296.

Gutenberg, Beno, and Richter, C. F., 1954, Seismicity of the earth and associated phenomena: [2nd ed.] Princeton Univ. Press, Princeton, New Jersey, 310 p.

Jordan, G. F., 1958, Pamplona Searidge, 1779-1957: Internat. Hydrog. Rev., May, p. 3-13.

Kelleher, J. A., 1971, Space-time seismicity of the Alaska-Aleutian seismic zone: Jour. Geophys. Res., v. 75, p. 5745.

Lahr, J. C., Page R. A., and Thomas, J. A., 1974, Catalog of earthquakes in south-central Alaska, April-June 1972: U. S. Geol. Survey open-file report, 35 p.

Lahr, J. C., 1975, Detailed seismic investigation of Pacific-North American plate interaction in southern Alaska: Columbia Univ., New York, Ph.D. thesis, 141 p.

Miller, D. J., 1953, Late Cenozoic marine glacial sediments and marine terraces of Middleton Island, Alaska: Jour. Geology, v. 61, no. 1, p. 17-40.

______1960, Giant waves in Lituya Bay, Alaska: U.S. Geol. Survey Prof. Paper 354-C, p. 51-86.

Miller, D. J., Payne, T. G., and Gryc, George, 1959, Geology of possible petroleum provinces in Alaska, with an annotated bibliography by E. H. Cobb: U.S. Geol. Survey Bull, 1094, 131 p.

Page, R. A., Blackford, M. E., and Bench, B., 1974, Seismicity in the vicinity of Valdez, Alaska (abs.): EOS Trans. Am Geophys. Union, v. 55, p. 347.

Page, R. A., 1974, Evaluation of seismicity and earthquake shaking at offshore sites: Offshore Technology Conf., 7th, Houston, Texas Proc., v. 3, p. 179-190.

Plafker, George, 1971, Pacific margin Tertiary basin, in Future petroleum provinces of North America: Am. Assoc. Petroleum Geologists Mem. 15, p. 120-135.

_____1967, Geologic map of the Gulf of Alaska Tertiary Province, Alaska: U.S. Geol. Survey Misc. Geol. Inv. Map I-484, scale 1:500,000.

_____1969, Tectonics of the March 27, 1964 Alaska earthquake, in The Alaska earthquake, March 27, 1964--Regional effects: U.S. Geol. Survey Prof. Paper 543-I, p. I1-174.

_____1974, Preliminary geologic map of Kayak and Wingham Islands, Alaska: U.S. Geol. Survey open file map 74-82.

Plafker, George, and Miller, D. J., 1957, Reconnaissance geology of the Malaspina district, Alaska: U.S. Geol. Survey Oil and Gas Inv. Map OM-189.

Plafker, George, Kachadoorian, Reuben, Eckel, E.G., and Mayo, L. R., 1969, Effects of the earthquake of March 27, 1964, on various communities: U.S. Geol. Survey Prof. Paper 542-G, 50 p.

Reimnitz, Erk, 1966, Late Quaternary history and sedimentation of the

Copper River Delta and vicinity: California Univ., San Diego, Ph.D. thesis, 160 p.

Richter, C. F., 1958, Elementary seismology: San Francisco, Calif., W. H. Freeman and Co., 768 p.

Sykes, L. R., 1971, Aftershock zones of great earthquakes, seismicity gaps, and earthquake predicition for Alaska and the Aleutians: Jour. Geophys. Res., v. 75, p. 8021-8041.

Tarr, R. S., and Martin, Lawrence, 1912, The earthquakes of Yakutat Bay, Alaska, in September, 1899: U.S. Geol. Survey Prof. Paper 69, 135 p.

Taylor, P. T., and O'Neill, N. J., 1974, Results of an aeromagnetic survey in the Gulf of Alaska: Jour. Geophys. Research, v. 79, no. 5, p. 719-723.

Thomas, B. I., and Berryhill, R. V., 1962, Reconnaissance studies of Alaskan beach sands, eastern Gulf of Alaska: U.S. Bur. Mines Rept. Inv. 5986, 40 p.

Tocher, Don, 1960, The Alaska earthquake of July 10, 1958, Movement on the Fairweather fault and field investigation of southern epicentral region: Seismol. Soc. America Bull., v. 50, no. 2, p. 267-292.

von Huene, Roland, and Shor, G. G., Jr., 1969, The structure and tectonic history of the eastern Aleutian Trench: Geol. Soc. America Bull., v. 80, no. 10, p. 1889-1902.

von Huene, Roland, Lathram, E. H., and Reimnitz, Erk, 1971, Possible petroleum resources of offshore Pacific-margin Tertiary basin, in Future petroleum provinces of North America: Am. Assoc. Petroleum Geologists Mem. 15, p. 136-151.

Winkler, G. R., 1973, Geologic map of the Cordova A-7 and A-8, B-6, B-7 and B-8, quadrangles, Alaska: U.S. Geol. Survey Misc. Field Inv. Map MF-531.

Wright, F. F., 1972, Geology and geomorphology of the central Gulf of Alaska continental shelf, in Rosenberg, D. H., ed., A review of the oceanography and renewable resources of the northern Gulf of Alaska: Univ. of Alaska Inst. Marine Science Rept. R72-23, p. 153.159.