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Tectonic setting of the Gulf of Alaska

P. D. Guptill^a, G. E. Brogan^a & T. Turcotte^b

^a Woodward-Clyde Consultants, Orange,
California

^b Woodward-Clyde Consultants, San Francisco,
California

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Tectonic Setting of the Gulf of Alaska

P. D. Guptill

G. E. Brogan

Woodward-Clyde Consultants
Orange, California

T. Turcotte

Woodward-Clyde Consultants
San Francisco, California

Abstract The Gulf of Alaska is a seismically active area within which the boundary between the Pacific and North American plates is located. This active boundary has evolved through a series of shifts from north to south as successive blocks of continental crust were moved into southern Alaska. The present plate boundary includes dominantly strike-slip faulting in the southeastern gulf along the Fairweather and Queen Charlotte fault systems, a complex transition zone of thrust faulting combined with strike-slip faulting in the eastern gulf, and thrust faulting along the Aleutian megathrust in the western gulf. The faults along this complex plate boundary historically have been the sources of major earthquakes in this area; future earthquakes associated with these faults will be of major importance to the development of natural resources offshore and onshore in the Gulf of Alaska area.

Introduction

The Gulf of Alaska is presently a prime target for offshore petroleum exploration. Unfortunately, the gulf contains many natural hazards,

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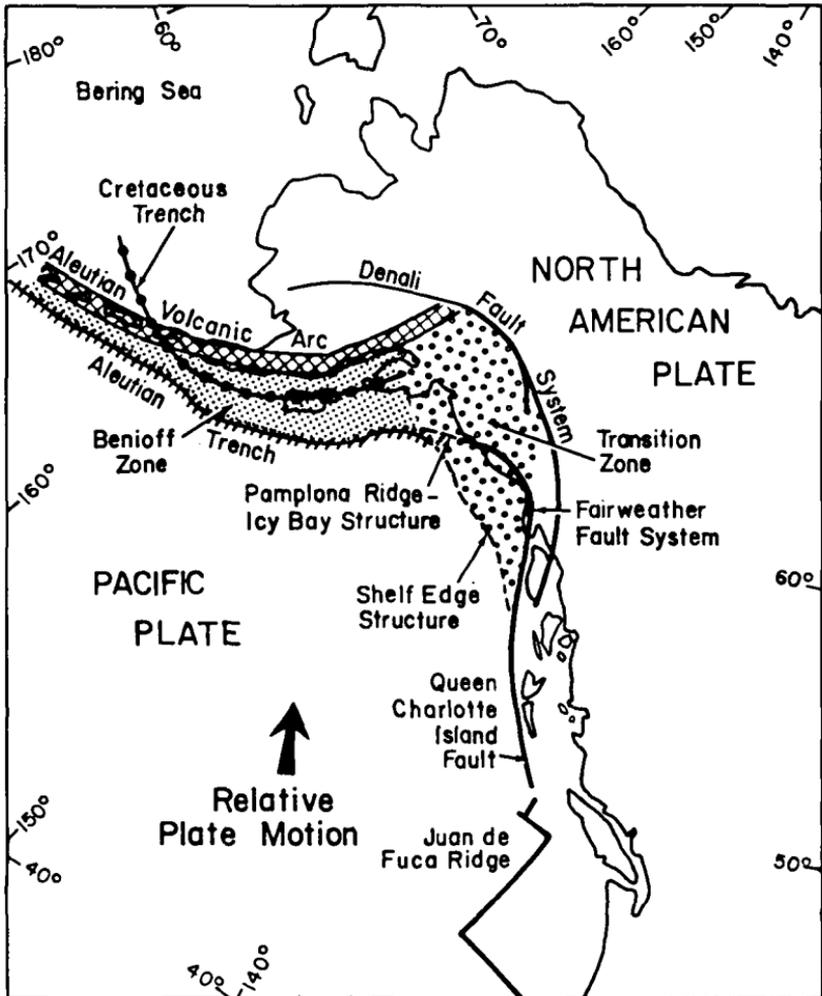
among which earthquake-related hazards are paramount. The potential severity of earthquakes to man-made offshore and onshore facilities, and the potential environmental impacts of petroleum development, demand particular care in design of facilities. The challenge of safe designs must be met in synergistic efforts between design engineers, geologists, and seismologists. One major task is for geologists and seismologists to identify the sources of future earthquakes, and to define them adequately so that engineers can accommodate earthquake effects within their designs.

In the Gulf of Alaska, the general behavior of major seismic sources has been defined from historic interpretation of earthquakes and relative plate motions at the active plate boundary. By evaluating the active tectonics of the Gulf of Alaska, we can understand and predict the general behavior of known seismic sources; this information can be used in developing seismic design considerations. In addition to known seismic sources of the gulf, other sources may be present, especially offshore. This paper summarizes the active tectonics of the Gulf of Alaska as presently known.

Tectonic Setting

Major seismic activity in southern Alaska is associated with the interaction of the Pacific and North American plates along the Aleutian Trench and eastern Gulf of Alaska. In southern Alaska, the boundary between the plates is characterized by two distinctly different styles of tectonic deformation. Along the Alaskan panhandle and eastern Gulf of Alaska north of the Queen Charlotte Islands, the two plates are sliding past each other along major right-lateral strike-slip fault systems. Plafker et al. (1978) have identified the Fairweather and Queen Charlotte Island fault systems as locations of major late Cenozoic dextral faulting, although a complex plate boundary history is suggested between the continental slope on the west and the Denali Fault system on the east (Figure 1).

The western Gulf of Alaska has developed during a complex history of plate convergence. Geologic evidence, seismicity, and the geomorphic expressions of recent faulting along major faults indicate that the active plate boundary has shifted from interior Alaska southward to the present Aleutian Trench, with the Kodiak Shelf adjacent landward areas



After Naugler and Wageman, 1973

FIGURE 1. Schematic map of Alaska showing the Transition Zone and major tectonic features along the Pacific-North American Plate boundary.

(Figure 2) within the upper plate. The tectonic deformation resulting from boundary shifts is evident more than 400 km northeast of the present plate boundary. At the present plate boundary (the Aleutian Trench), the principal stresses are compressional, causing underthrusting of the Pacific Plate beneath the North American Plate north of the

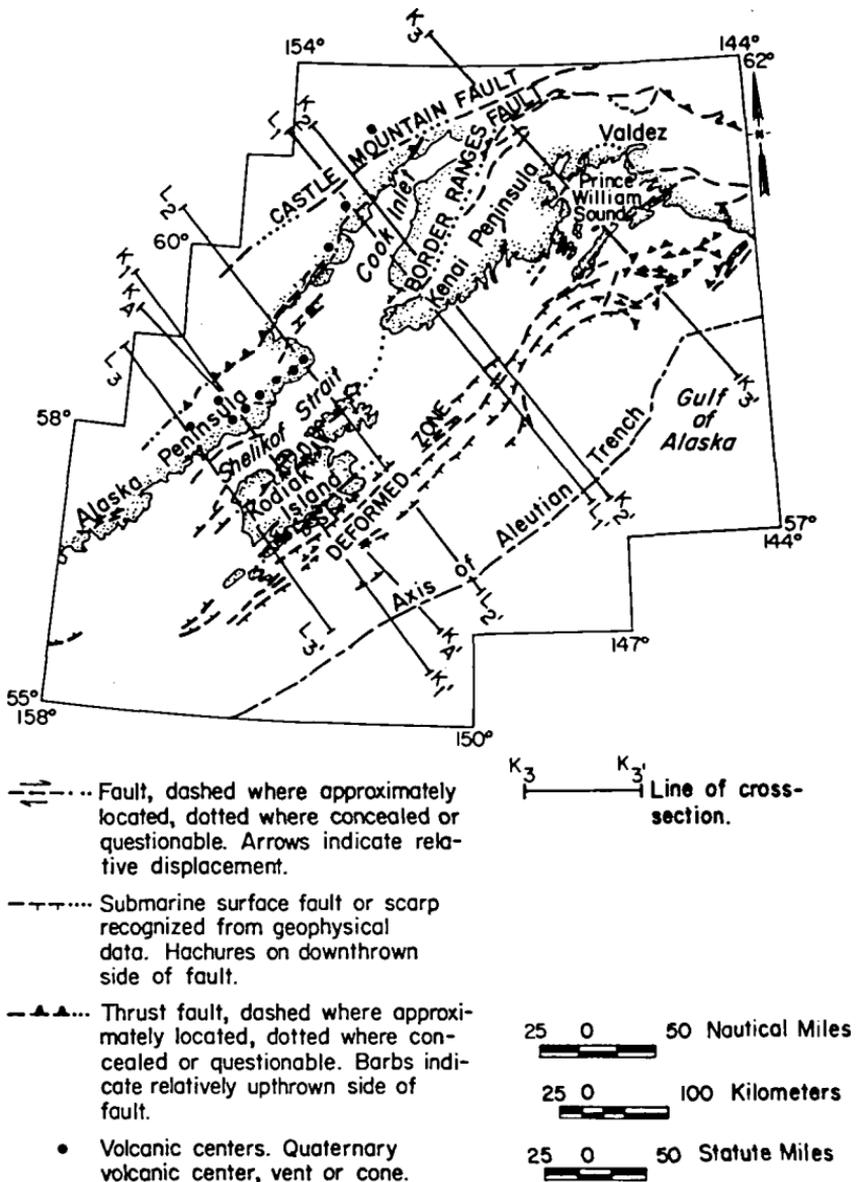
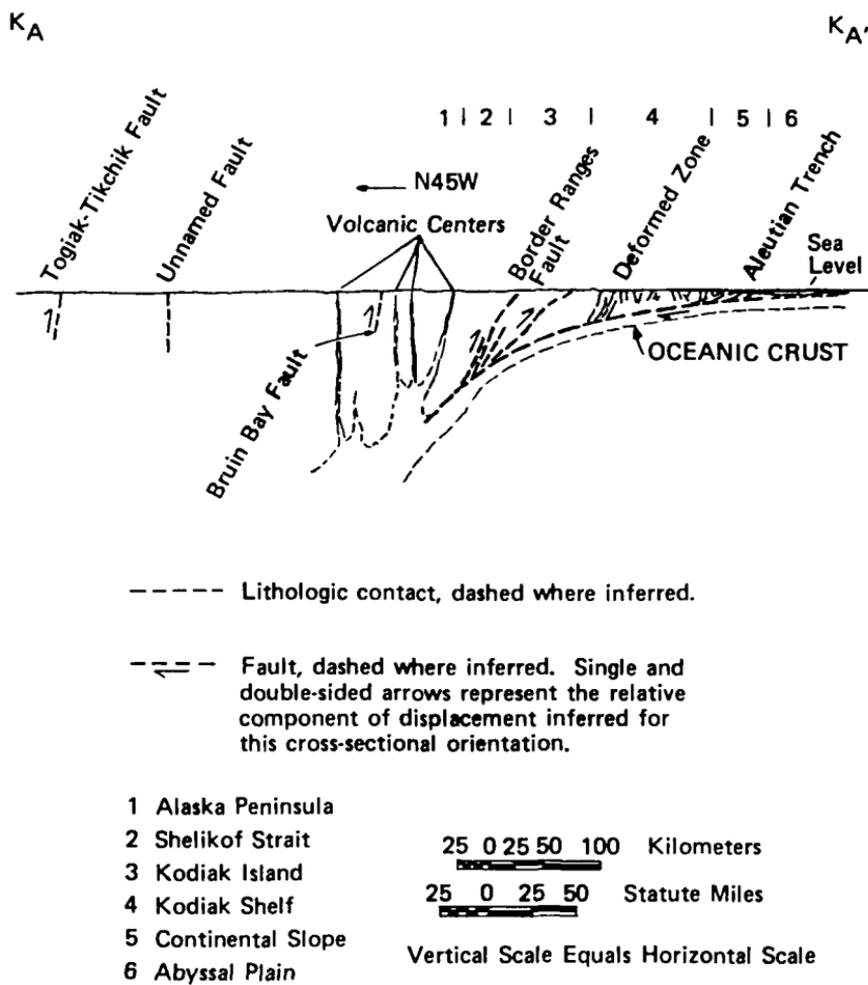


FIGURE 2. Tectonic elements of the Kodiak region.

trench. The upper plate is only about 5 to 10 km thick near the trench; locally it is disrupted by the strain of compression and tension that has resulted in complex faulting on the continental shelf. Figure 3 is a schematic cross-section illustrating the complexity of the deformation in the upper plate.



NOTE: Structures at depth are inferred.

See Fig. 2 for location of section.

FIGURE 3. Regional tectonic cross-section of the Kodiak region.

The compressive nature of the western Gulf changes in the northern gulf and interior Alaska to strike-slip faulting in the eastern gulf. The change in style of faulting occurs in an area referred to as the transition zone, where both strike-slip and reverse-slip faulting occur, and the plate boundary is not clearly defined by the known surface geology or seismicity data (Figure 1). The transition zone, however, includes the Denali Fault, the Chugach–St. Elias faults and structures in the northern Gulf of Alaska (Figure 4). The northern Gulf of Alaska is most important in the overall tectonic framework of southern Alaska because it contains two major tectonic elements of the transition zone, which directly facilitate the change from underthrusting to strike-slip faulting. These elements include the probable continuation of the Aleutian Trench faulting across the continental shelf through the Icy Bay–Pamplona Ridge trend to the strike-slip faults of the eastern Gulf of Alaska, and oblique underthrusting of the Shelf Edge structure (Figure 1).

Western Gulf of Alaska

The Aleutian volcanic arc lies west of the transition zone with Kodiak Island, the Kenai Peninsula, and the continental shelf forming the southern edge of the North American Plate (Figure 1). The Alaska Peninsula appears to be along a landward continuation of the Aleutian Islands, as indicated by a volcanic arc that extends inland beyond Cook Inlet. The volcanic arc is characteristic of a subduction zone, which is evidenced by an inclined seismic zone (a Benioff zone). Approximately forty active volcanos have been identified along this volcanic arc (Coats, 1962). The Aleutian Trench is well defined bathymetrically southwest of Kodiak Island, and becomes a broad bathymetric low, which continues northeast of Kodiak Island. That bathymetric low is interpreted as the present location of the Aleutian Trench plate interaction (Figure 2). An older boundary or trench, roughly paralleling the trend of the Alaska Peninsula and Alaska Range, is defined by a belt of Cretaceous turbidites and volcanic detritus from the tip of the Alaska Peninsula, northeast through Kodiak Island and the Kenai Peninsula (Moore, 1972). The trend marks the position of a Cretaceous trench, which through accretion became part of the modern upper plate during early Tertiary (Moore, 1972) (Figure 1). Fisher and Magoon (1978)

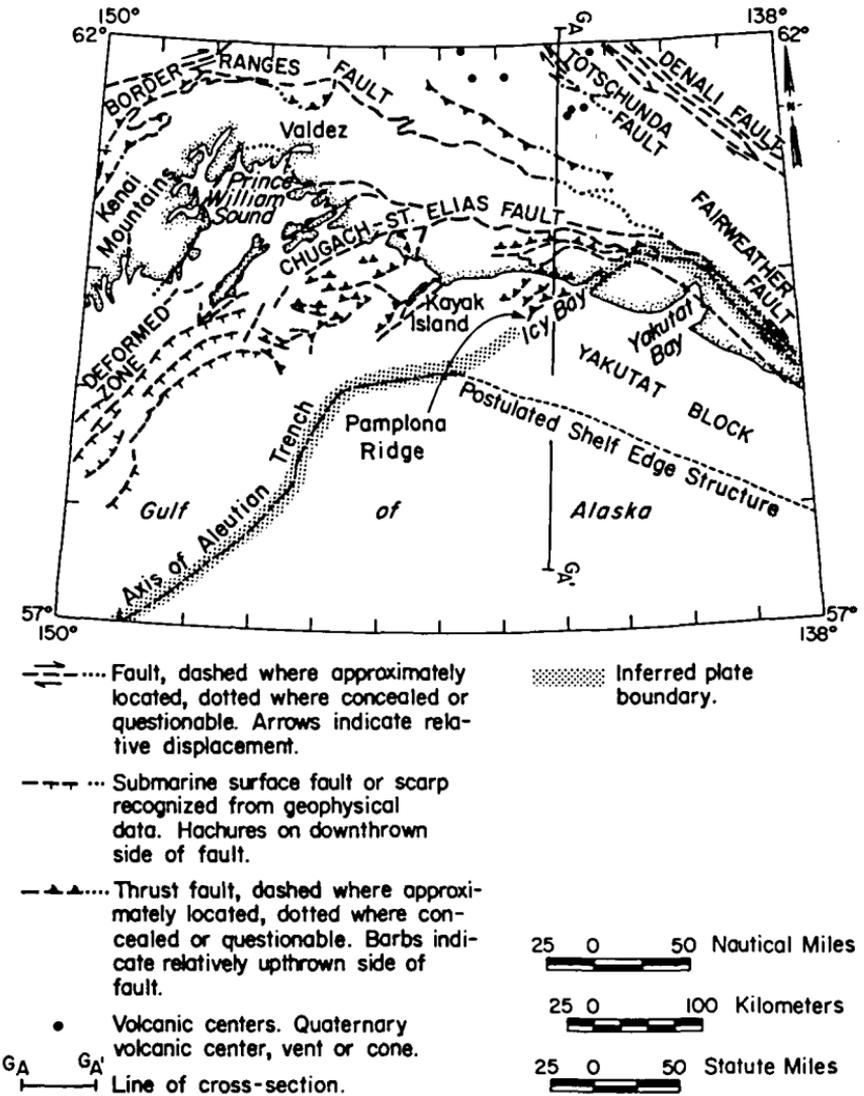


FIGURE 4. Tectonic elements of the Gulf of Alaska region.

summarize data describing the positions and relative ages of shifts of the boundary from the boundary described by Moore (1972) to the present Aleutian Trench. The accretion of thick sediments on the edge of the older trench may have caused the trench to migrate southward, forming a very broad, decoupled thin upper plate which now includes Kodiak

Island, the Kenai Peninsula, and the adjacent outer continental shelf (Figure 2).

The Kodiak shelf includes an area approximately 70 to 150 km wide and 600 km long immediately adjacent to the Aleutian Trench. It extends from the Chirikof Island northeastward to Montague Island. The proximity of the area to the Pacific-North American Plate convergence at the Aleutian Trench subjects the shelf to deformation that is reflected in the local geology of shelf structures and in the historic record of earthquakes. It is clear from geologic and historic observations that the Kodiak shelf is in one of the most highly active tectonic environments in the world, and large earthquakes will continue to occur there in the future.

The seismicity cross-sections shown in Figures 5, 6 and 7 (see also von Huene and Shor, 1969) indicate that the Benioff zone lies at depths

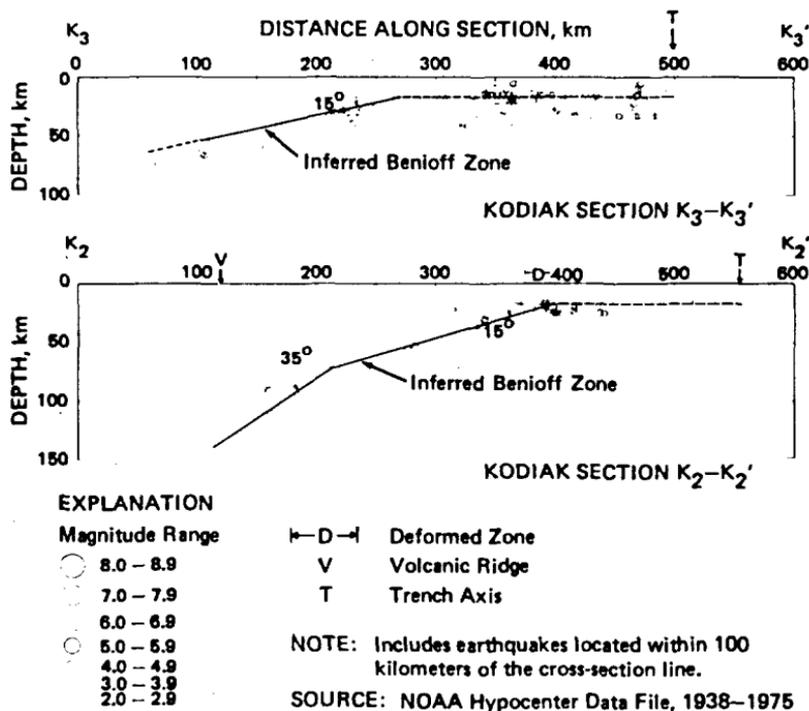


FIGURE 5. Seismicity cross-sections showing the Benioff zone in the Kodiak region.

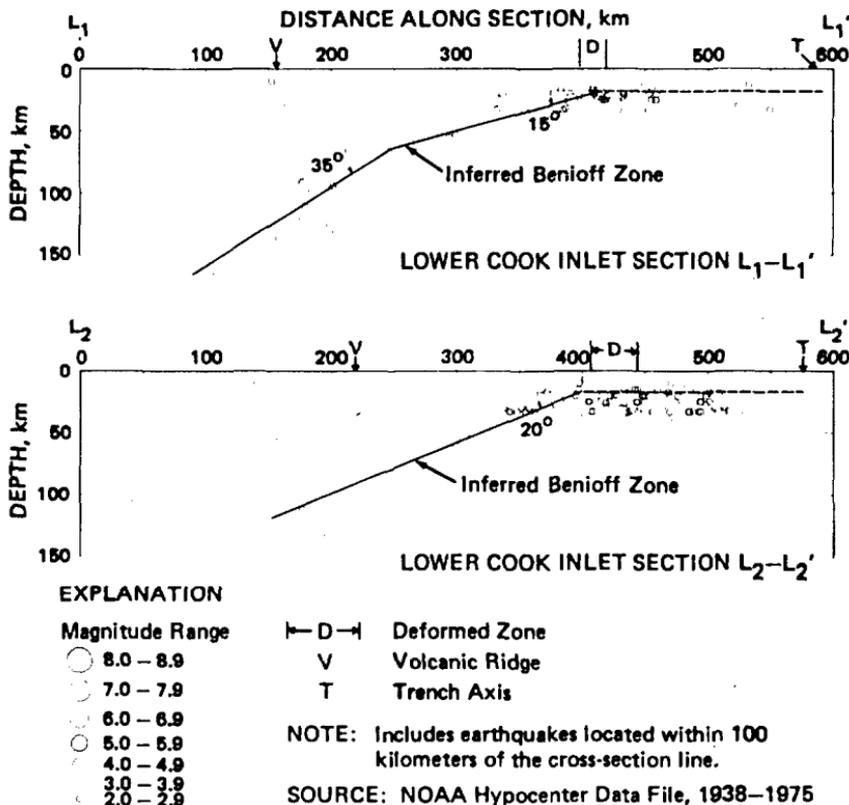


FIGURE 6. Seismicity cross-sections showing the Benioff zone in the Lower Cook Inlet region.

of between approximately 20 to 70 km beneath the Kodiak shelf and Kodiak Island. The shallower seismicity and the known structure of the continental shelf and slope suggest that the plate interaction is not a simple megathrust under the Kodiak shelf, but that the entire shelf is in a zone of crustal shortening; major crustal deformation is present in the Deformed Zone (Figures 2 and 3) of the southern coast of Kodiak Island and the area from the edge of the shelf to the base of the continental slope (von Huene, 1972; von Huene et al., 1976).

At the shelf edge, the shelf sediments are arched upward. This arching is either in response to underthrusting of the Pacific Plate beneath the continental shelf (von Huene, 1972) or to the rebound of the lower density crustal material being subducted. Shoreward from the

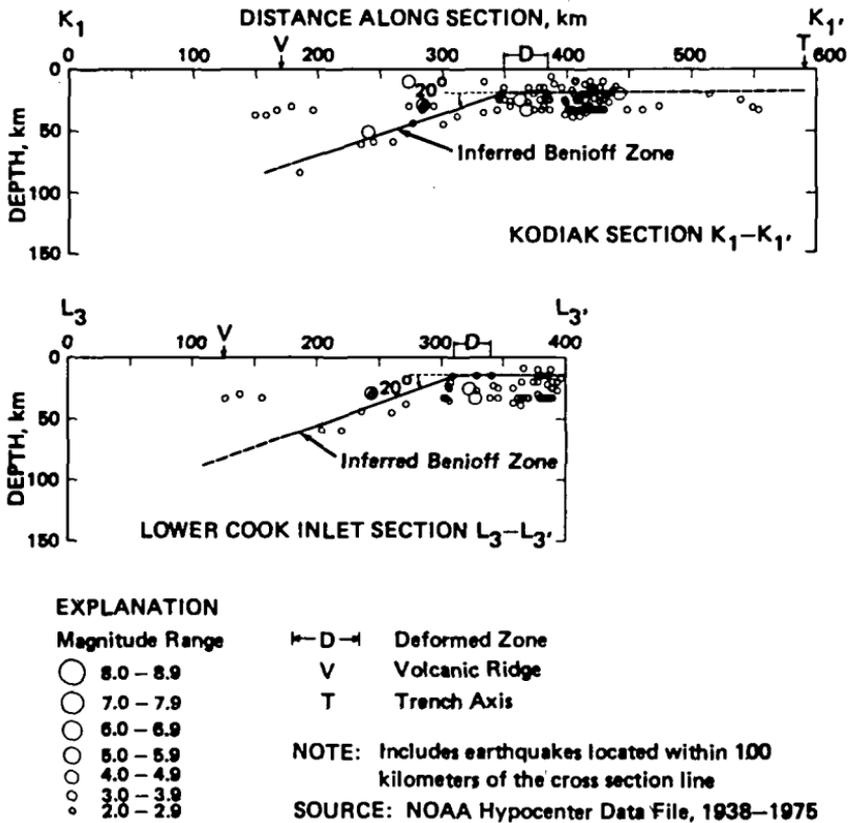


FIGURE 7. Seismicity cross-sections showing the Benioff zone in the Lower Cook Inlet and Kodiak regions.

arch, the shelf is downward warped and arched again near the deformed zone at Kodiak Island (Figure 2). The deformed zone appears to be a major crustal discontinuity, although a lack of continuity between individual surface structures has been noted (von Huene et al., 1976).

The southward migration of the subduction zone and the accretion of sediments complicate the structure of the megathrust such that faults may break through the upper plate. The seismicity cross-sections (Figures 5, 6, and 7) show that the position of the deformed zone corresponds closely to a change in dip of the Benioff zone from near horizontal to approximately 10–20°. This change in dip may be associated with the heavy concentration of shallow-focus earthquakes along the line of the deformed zone and may result from the megathrust splaying upward through the deformed zone.

Sections K_1 , L_2 , L_3 (Figures 6 and 7) depict a striking lack of intermediate-depth (greater than 70 km) earthquake activity when compared with seismicity to the northeast and to the southwest. This lack of intermediate-depth earthquakes appears to be associated with an abrupt change in the trend of the volcanic arc adjacent to the northeast end of Kodiak Island (Figure 2), which is also associated with a change in the dip of a lower portion of the Benioff zone. The aftershock zone of the 1964, M 8.4, Prince William Sound earthquake terminated abruptly in the vicinity of Chirikof Island along a line almost perpendicular to the arc. Several investigators, notably Mogi (1968), Sykes (1971), Stauder (1972), Engdahl (1971), and Kelleher (1970), have shown that the aftershock zones of large earthquakes occurring along the Aleutian arc generally terminate abruptly, and that the arc appears to be segmented into "blocks." Engdahl (1971) and Spence (1977) have found that the ends of the aftershock zones in the western and central Aleutians correspond to submarine canyons that are transverse to the arc, and with offsets in the otherwise smooth curve of the volcanic arc. Spence (1977) also found that the offsets in the volcanic line at longitudes 180° and 173° W correspond with slight changes in the dip of the Benioff zone at depth.

The segmentation of the arc into "blocks," the dip of the shallow Benioff zone, and the volcano-trench gap width may influence the magnitude of earthquakes that occur at different locations along the arc.

Eastern Gulf of Alaska

The eastern Gulf of Alaska is characterized by major strike-slip faulting from Yakutat Bay southward along the coast. The main tectonic structure in the area is the active Fairweather Fault (Figures 1 and 4), which ruptured for its entire known length during the 1958, Magnitude 7.9, Yakutat earthquake. The fault is parallel to the direction of Pacific Plate motion relative to the North American Plate. From teleseismic data, the focal mechanism of the 1958 earthquake has been determined to be right-lateral strike-slip (Stauder, 1960). At the south end of the Fairweather Fault, where it projects offshore near Cross Sound, it is interpreted to connect with the Queen Charlotte Fault. The Queen Charlotte Fault continues southward across the continental shelf and may coincide with the edge of the continental shelf far south of Cross Sound. The Queen Charlotte Fault is the probable source of the 1949 Queen Charlotte and 1972 Sitka earthquakes.

Inland from the Fairweather–Queen Charlotte faults, another major strike slip-fault trends roughly parallel to the Pacific Plate motion; that is the Denali Fault system (Figure 1). No large historic earthquakes are known along this fault system, but clear offsets of geologic units and abundant geomorphic evidence attest to the youthful right-lateral strike-slip nature of these faults.

In addition to the Fairweather–Queen Charlotte and Denali fault zones, several authors have suggested that the base of the continental shelf west of the Fairweather Fault is an active member of the tectonic elements governing the eastern Gulf of Alaska (Page, 1975; Plafker et al., 1978; Perez and Jacob, in preparation). The geometric configuration of the shelf edge and the tectonic plate motion require convergence between the North American and Pacific plates along the shelf edge, which is slightly oblique to the motion of the Pacific Plate.

Transition Zone

Available geologic data indicate that the behavior of the transition zone between strike-slip motion to the east and subduction to the west is complex and poorly defined. Packer et al. (1975) review several possible solutions to the problem of a transition zone, although evidence is lacking to select a preferred model. Subsequent accumulation of geologic data from the offshore area in the Gulf of Alaska suggests that the North American Plate and the Pacific Plate are at least partially decoupled in the Gulf of Alaska at the shelf edge (Page, 1975; Bea, 1976), as well as along the Fairweather Fault. The resultant strain in the northern Gulf of Alaska is characterized by oblique slip, likely on a continuation of the Aleutian Trench structure across the continental shelf to Icy Bay (Figure 4). These shelf structures are interpreted to represent southernmost tectonic elements in the transition from the compressional environment in the western gulf to strike-slip plate motions in the eastern gulf.

The existence of the transition zone has been inferred by seismological studies, but a complex picture emerges from these data. Stauder and Bollinger (1966) showed that the aftershocks of the 1964, M 8.4, Prince William Sound earthquake in the Kodiak Island area all had focal mechanisms compatible with a low-angle thrusting in a northwesterly direction, which is associated with subduction of the Pacific Plate (Figure 8). To the east, at Prince William Sound, the focal mechanisms

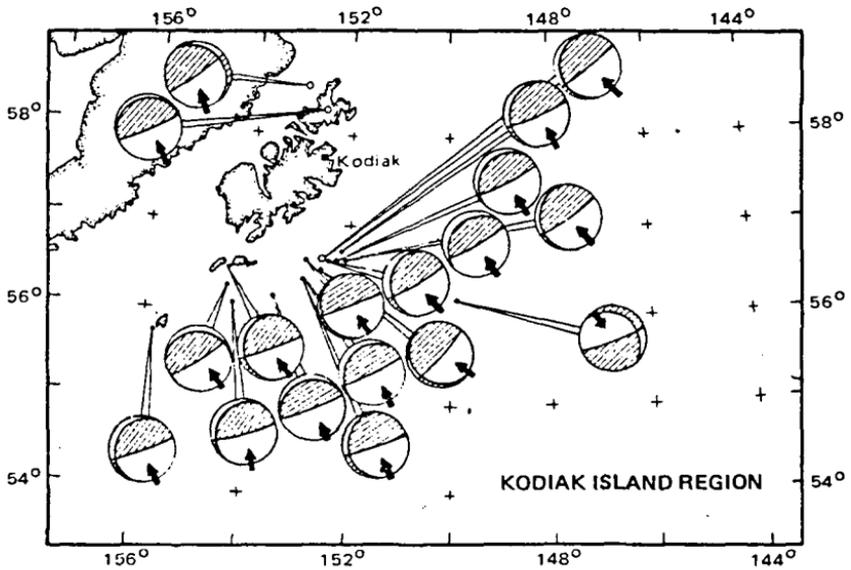


FIGURE 8. Focal mechanisms of aftershocks in the Kodiak Island region following the great Alaska earthquake of March 27, 1964. Shaded areas represent compression; arrows represent horizontal compressive stress orientation. (After Stauder and Bollinger (1966).

of aftershocks are inconsistent in orientation and mode of faulting (Figure 9). Strike-slip faulting is combined with normal and shallow-dipping thrust fault mechanisms in that area. The orientations of these focal solutions vary in general conformity with the regional structural trends, changing trend from their alignment with the underthrusting slab in the northwest to align with the strike-slip fault systems in the east and southeast.

Presently, the area between Prince William Sound and Icy Bay is considered to be a seismic gap, which is an area that has not experienced a large earthquake as recently as adjacent portions of the plate boundary. Several large earthquakes occurred in the area at the turn of the century (Tarr and Martin, 1912), and a recurrence of such events is apparently now due. The St. Elias earthquake of M 7.7 in 1979 has partially filled this gap (Lahr et al., 1979). That earthquake resulted from reverse faulting east of Prince William Sound. Other large earthquakes should be expected to fill the gap in the future. Because of the lack of instrumental earthquake data, seismologic studies have not been able to define the nature of the transition zone in this area in detail.

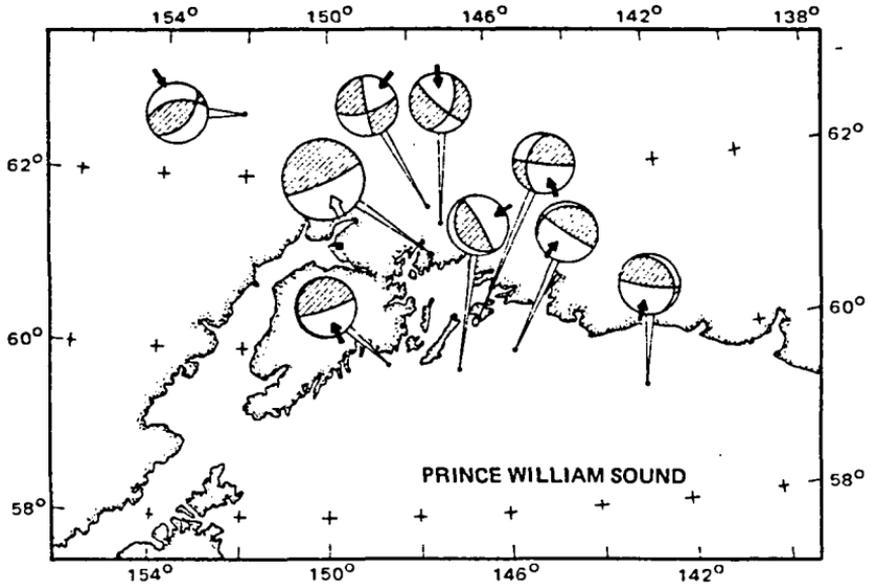


FIGURE 9. Focal mechanisms of aftershocks in the Prince William Sound region following the great Alaska earthquake of March 27, 1964. Shaded areas represent compression; arrows represent horizontal compressive stress orientation. (After Stauder and Bollinger (1966).

The onshore geology indicates a series of thrust faults in the St. Elias area with strike-slip faults in the interior of Alaska, suggesting a structural transition from underthrusting on the west to strike-slip on the east. The northern Gulf of Alaska contains the elements that translate the underthrusting of the Aleutian Trench to the Fairweather Fault. Apparently, the northward motion of the block west of the Fairweather Fault is interrupted in the northern Gulf of Alaska and absorbed by a zone of folding and underthrusting from the northern continuation of the Aleutian Trench past Pamplona Ridge to Icy Bay. Although the tectonic setting suggests a Benioff zone beneath the gulf, the lack of seismic events makes this interpretation inconclusive at this time. This Pamplona Ridge–Icy Bay trend is interpreted as the relatively youthful Pacific–North American Plate collision boundary. The Fairweather Fault, Pamplona Ridge–Icy Bay structure, and the shelf edge structure postulated by Page (1975) bound a relatively stable block referred to as the Yakutat Block by Plafker et al. (1978) (Figures 4 and 10).

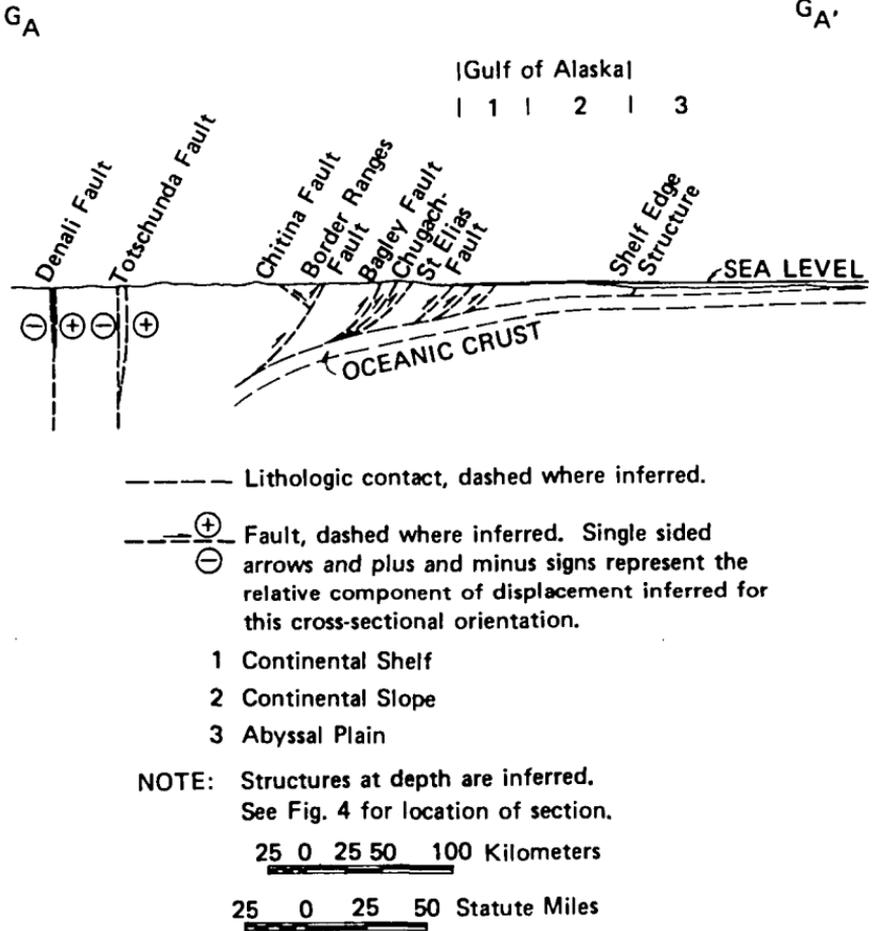


FIGURE 10. Regional tectonic cross-section of the northern Gulf of Alaska region.

Leading Plate Edge

The northern Gulf of Alaska has been relatively unknown tectonically. Recent research such as that by Plafker et al. (1975) and Carlson (1976) has shown two youthful structural trends transecting the shelf; these are along the trend through Kayak Island and along the trend through Pamplona Ridge-Icy Bay. These trends are apparently major zones of crustal shortening, where the motion along strike-slip faults northeast of the continental shelf in the gulf has been translated to thrust faulting and

asymmetrical folding perpendicular to the line of motion for the Pacific Plate. The central Gulf of Alaska and the continental shelf southeast of the Pamplona Ridge–Icy Bay structure appear to be relatively undeformed, with bedding essentially horizontal. Based on the distribution of zones of deformation on the continental shelf and mainland Alaska, it appears that the Pamplona Ridge–Icy Bay structural trend is the leading southern edge of the North American Plate.

Along the Pamplona Ridge–Icy Bay structure, a series of well-developed parallel folds traverse the continental shelf obliquely through the Gulf of Alaska. Locally, anticlines are flanked on the southeast by north-dipping reverse faults (Plafker et al., 1975). The structural style of the Icy Bay trend is similar to the Kayak Island trend, although the flanks of the folds are not as steep as those of the Kayak Island trends, and they have not been severely uplifted and exposed to erosion (Bruns and Plafker, 1976). Considering the anomalies in bathymetry along the same northeast–southwest trend of these folds, a similar structural trend appears to branch to the shelf edge (Plafker et al., 1978; Rogers, 1977) and may tie into the shelf edge structure postulated by Page (1975) and Bea (1976).

The Pamplona Ridge–Icy Bay structural trend is a zone of crustal weakness that has been deformed in response to active compression of the North America and Pacific tectonic plate collision. In adjustment to that compression, the crust has experienced shortening in a zone traversing the shelf that is similar to the zone of deformation traversing the shelf parallel to Kayak and Middleton islands. Given the current geophysical data, it is possible to assume development of a major crustal structure underlying the area; however, no evidence of a Benioff zone marking a plate boundary has been identified there.

Shelf Edge Structure

At the base of the shelf in the eastern Gulf of Alaska, the structurally stable continental shelf off Yakutat Bay has been warped into a shelf-edge arch, which may result from oblique underthrusting at the base of the continental slope along the shelf edge structure proposed by Page (1975). Seismic refraction data of Bayer et al. (1977) suggest that oceanic crust may be located 7–12 km beneath the Gulf of Alaska area. If so, the nearly horizontal surface may indicate the location of the plate

boundary Benioff zone beneath the Gulf of Alaska. A critical element in testing the existence of this boundary is the shelf edge structure. Page (1975) and Bea (1976) have both suggested that a major tectonic structure exists at the base of the continental slope from the eastern end of the Aleutian Trench to south of Cross Sound, parallel to the coast, and to the edge of the continental shelf. In the context of plate tectonics, such a fault would represent the southernmost expression of the plate boundary. Several lines of evidence support the existence of this shelf edge structure; these are summarized in the following paragraph.

Although instrumental records define few events, Page (1975) has shown that a Magnitude 6.7 earthquake in 1973 and its aftershocks align at the base of the continental slope west of Cross Sound. Analysis by Page of the main event shows that the relative motion involved oblique underthrusting toward the northeast. The relative motion suggested by that earthquake is consistent with the relative motion suggested by regional tectonics, where the Pacific floor would be thrust obliquely beneath the continental shelf (Page, 1975). Also, evidence of arching at the shelf edge in the northern Gulf has been defined by Plafker et al. (1975) and by Rogers (1977) as similar to the arching at the edge of the Kodiak shelf above the active Aleutian Trench. The arching may result from underthrusting at the base of the continental slope. This relationship suggests that parts of the eastern Gulf of Alaska shelf edge have been influenced by underthrusting in the past; this is likely to continue into the near future.

Conclusion

Southern Alaska is a highly active seismic area where large earthquakes have been associated with major tectonic structures. Many of these structures are well defined by tectonic models and seismicity; however, the transition zone and parts of the eastern gulf are poorly understood with regard to their earthquake potential because of the lack of detailed geologic and seismologic data in these areas. Several significant structures with earthquake potential exist in the offshore area; these structures and other data suggest a megathrust may exist beneath the continental shelf in the Gulf of Alaska. Such a megathrust, if it exists, could strongly influence seismic design for offshore and coastal facilities. Conservative assumptions can be postulated regarding the earthquake

potential of these earthquake structures, which are not well defined, but additional data are needed in order to better address the problems of the engineering designer, who must accommodate the tectonic setting in his design.

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