STRUCTURE OF CONTINENTAL MARGINS ALONG THE STRIKE-SLIP AND COMPRESSIONAL PLATE BOUNDARIES OF THE GULF OF ALASKA

ROLAND VON HUENE*

RESUMEN

Se infieren los mecanismos tectónicos en los bordes de las placas para modelos tectónicos del Pacífico norte, resultando de tipo transcurrente (transformado) y compresional (convergente). Las observaciones de campo recientes concuerdan con la geometría general de las placas; sin embargo, la configuración de la corteza observada difiere substancialmente de los diagramas y modelos simplistas que utilizan algunos autores. En el borde de tipo transcurrente, la existencia de una gran trinchera rellena con sedimentos implica la intervención de otro proceso además de un cizalle lateral en el contacto entre la corteza oceánica y la continental. En la Trinchera Aleutiana Oriental no hay fallas grandes de sobrescurrimiento o cabalgadura, lo que implica la existencia de algún otro mecanismo para transmitir cizalle desde la zona de Benioff hasta la superficie. En esta región es posible que la zona de Benioff represente un fenómeno sub-cortical y que exista una deformación plástica extendida en la corteza inferior, precisamente encima de la zona de Benioff. Esta situación podría expresarse como una ancha zona de plegamiento en la sección sedimentaria correspondiente.

ABSTRACT

Tectonic mechanisms along the eastern and western Gulf of Alaska continental margins are inferred to be strike-slip (transform) and compressional (converging) plate boundaries in tectonic models of the North Pacific. Recent field observations are consistent with the overall plate geometry; however, the crustal configuration observed departs significantly from the simplistic diagrams and models used by some authors. Along the strike-slip plate boundary, a large buried trench requires that another process beside simple lateral shear is operating at the oceanic-continental crustal juncture. Along the eastern Aleutian Trench an absence of large thrust faults requires other mechanisms of transmitting the shear of the Benioff zone to the earth's surface. In this area it seems that the Benioff zone may be a sub-crustal feature and that extensive plastic deformation occurs in the lower crust just above the Benioff zone. This may in turn be expressed in the overlying sedimentary section as a wide zone of folding.

---

* *U. S. Geological Survey, Menlo Park, California.*

INTRODUCTION

The eastern and western continental margins of the Gulf of Alaska have contrasting morphologies. The eastern margin is only about 50 km wide with a narrow shelf and a narrow slope that ends at an extensive continental rise, whereas the western margin is as much as 250 km wide with a broad continental shelf and a broad continental slope that ends in the Aleutian Trench (Fig. 1). A generally accepted explanation for this contrast is that the eastern margin is dominated by lateral shear related to a strike slip fault (Queen Charlotte-Fairweather fault system) between the continental and oceanic crust (St. Amand, 1957; Southerland-Brown, 1968), whereas the western margin is dominated by lateral compression related to thrusting between the continental and oceanic crust (Aleutian Thench area) (Stauder and Bollinger, 1966; Plafker, 1969). These conditions fit a plate tectonic model well (Atwater, 1970; Hayes and Pitman, 1970) and the basic simple explanation of an interaction between two rigid plates is widely accepted (Fig. 2). In this model, the Pacific plate moves relative to the North American plate along the Queen Charlotte-Fairweather fault in a direction paralleling the plate boundary and the plates move in a direction perpendicular to the plate boundary along the Aleutian Trench. The contrasting morphology, or more fundamentally, the contrast of geologic structure between these two adjacent margins along the same plates provides an opportunity to study structural mechanisms at continental margins by isolating features unique to each of them.

EASTERN CONTINENTAL MARGIN

The structure of the eastern continental margin was known until recently from a moderately dense series of wire-line soundings, and the evidence for the Queen Charlotte-Fairweather fault was only some scattered earthquake epicenters. Despite such uncertainties, the Queen Charlotte-Fairweather fault was used by McKenzie and Parker (1967), Morgan (1968) and Le Pichon (1968) to determine the relative directions of Pacific-North American plate motion. Shor (1962) pointed out a buried trench under the continental rise from seismic refraction measurements. Recently the margin has been crossed by seismic reflection transects (Chase and Tiffin, 1972; Embley and others, 1973) and the Queen Charlotte-Fairweather fault as well as the buried trench have been verified (von Huene and others, in preparation).

The northern segment of the Queen Charlotte-Fairweather fault has a narrow straight trace along the continental shelf from the northern point where it enters the sea to a point about 400 km south (Fig. 1). Along the remaining 210 km which make up the southern segment, the fault trace descends onto the continental slope and it also curves through a 20° change in strike. The northern and southern segments of the fault also have different structural characteristics. The northern segment is characterized by one or possibly two faults with no associated zone of small scale deformation in the stratified rocks on either side (Fig. 3; upper record, point F). The southern segment, on the other hand, has a wider zone of deformation associated with the irregular relief that characterizes the continental slope there (Chase and Tiffin, 1972) (Fig. 3). The change in strike and wide complex zone of deformation are interpreted as signs of oblique slip whereas the straight narrow trace without associated deformation is interpreted as the most exclusively strike-slip segment. Therefore the strike of the northern segment most nearly defines the direction of movement between the Pacific and North American plates because ideally such a boundary (a transform fault) has only strike slip motion. A pole of rotation constructed from this fault segment and a similar segment of the San Andreas fault in central California, falls at the southern limit of the circle of confidence drawn by Morgan (1968) at a southern tip of land on Newfoundland called Mistaken Point. The relative Pacific-North America plate movement used by most authors and confirmed by this study is shown in figure 2.

The reflection record across the continental slope off the northern segment of the Queen Charlotte-Fairweather fault (Fig. 3) shows sediment on the ocean floor 1 km to 3 km thick. The continental shelf and slope are relatively simple. Locally Pleistocene glaciers moved across the shelf to the shelf break. They deposited great quantities of sediment on the slopes as well as on the adjacent deep ocean floor and glacial periods are responsible for the composite deep sea fans that form the continental rise. These rise sediments have been dated as Pleistocene by tracing the seismic reflectors corresponding to the base of the Pleistocene in DSDP drill hole 178 to the eastern margin. Below the rise is a pre-Pleistocene section that has been depressed to form a trench at the foot of the slope. This buried trench is more pronounced along the slightly oblique-slip portion of the Queen Charlotte-Fairweather fault and is seen in the structure section (Fig. 4) which is based on seismic refraction data (Shor, 1962; Johnson and others, 1973), gravity data (Couch, 1969) and seismic reflection and magnetic data. The trench first pointed out by Shor (1962) involves the oceanic crust and perhaps it is a dynamic feature rather than one caused by static loading. If it were strictly a static feature, it should be deepest where the sediments are thickest; however, a correspondence between degree of crustal depression and thickness of the rise is not apparent. Off Queen Charlotte Island the buried trench is locally absent and in other places nearby, it has expression as a trough on the sea floor (Chase and Tiffin, 1972). Locally it is as large as the eastern Aleutian Trench. The cause of this discontinuous trench along a strike-slip margin is not understood.

WESTERN CONTINENTAL MARGIN

The western margin has been studied more than the eastern margin because it was the site of the great 1964 Alaska earthquake. Observations of the earthquake and the accompanying aftershock sequence, the crustal deformation, and the large tsunami it generated, provided a clearer understanding of tectonic mechanisms.

The western margin contains all the features commonly associated with margins presumed to be formed by underthrusting of oceanic crust beneath the continent. In the vicinity of Kodiak Island, the chain of active volcanoes that parallels the Aleutian Trench forms the backbone of the Alaska Peninsula and the Aleutian Island Arc. These volcanoes rest on early Mesozoic eugeosynclinal deposits and plutons (Fig. 5) (Burk, 1965). Farther seaward, on Kodiak Island, the eugeosynclinal deposits are of Cretaceous and possibly early Tertiary age (Moore, 1968) and they are separated from middle and late Tertiary miogeosynclinal continental shelf deposits by a fault zone. On the continental slope only the Pleistocene sediments have been sampled, however, sediments no older than 0.6 m.y. fill the Aleutian Trench (von Huene and Kulm, 1973). Therefore, in a very broad sense, the seaward progression from older to younger sediment is established and it indicates continental accretion since Mesozoic time.

Crustal structure is consistent with the accretionary evidence from stratigraphy. Seismic reflection measurements and magnetic anomalies indicate that the oceanic crust continues unbroken beneath the continent almost to Kodiak Island (Fig. 6). In some seismic reflection records trench deposits can be traced about 10-13 km beneath the foot of the slope (von Huene, 1972). However, beyond the first 10 km the reflectors become indistinct and there is a corresponding seismic velocity increase from 2 km/sec to as much as 4 km/sec. Since it is known from drill cores and seismic records that the deformed sediments in this part of the slope do not return coherent reflections, this loss of resolution and the increased velocity suggest that intense deformation begins 10 km landward of the trench beneath slumps and large slide blocks. Such a model explains the undeformed sediment commonly found in modern trenches. However, it does not explain some of the 30°-40° slopes that form the landward trench wall because soft undeformed sediment cannot push against the continent and form 1-2 km high folds with such steep limbs. Therefore, piercement and shale diapirism are suggested as mechanism in view of the strong evidence that underthrusting does occur. Evidence for underthrusting has come not only from studies of earthquakes but also from age relationships in the Aleutian Trench area established by the study of DSDP cores. The main points are: 1) Earthquakes recorded near Kodiak over a 10 year period cluster into a landward dipping Benioff zone (Fig. 5); 2) Focal mechanisms of the

1964 Alaska earthquake and its aftershocks give consistent (but not unique) indications of thrusting (Stauder and Bollinger, 1966; Kanamori, 1970); 3) Deformation during the 1964 earthquake and the slower changes in land level between earthquakes are easiest to explain with thrust faulting (Plafker, 1969).

In addition, the study of cores from the Aleutian Trench area provide the following complementary evidence: 1) Uplift of the mountains now circling the Gulf of Alaska began in early or middle Miocene time; 2) A great increase in volcanism about 5 m.y. ago signifies initial development of the chain of volcanoes along the Alaska Peninsula; 3) Sediments now filling the Aleutian Trench are no older than 0.6 ± 0.1 m.y. (von Huene and Kuhn, 1973).

The first two events indicate that the present trench may have developed in early or middle Miocene time and that it probably existed at least 5 m.y. ago; however, the study of cores from the trench has shown that sediments filling it are no older than 0.6 m.y. This difference between the age of initial trench development and the age of sediment now filling it shows that a large quantity of sediment older than 0.6 m.y. is missing and must be incorporated into the continental slope. These combined lines of evidence form as strong an argument in support of underthrusting, rapid tectonism, and incorporation of deep ocean sediment at the western continental margin of Alaska as any that have been made for other margins.

To remain brief, this discussion has concentrated on evidence favoring underthrusting and some unresolved problems have not been discussed. The present evidence is strongly more favorable for underthrusting than other proposed tectonic mechanisms. Disturbing however is the fact that no thrust fault has been observed in seismic records nor is there any place that it appears at the sea floor.

SUMMARY OF EASTERN AND WESTERN MARGIN STRUCTURES

Since the eastern and western margins are boundaries of the same lithospheric plates, they have similar plate tectonic histories. Therefore, the differences between them should result mainly from different tectonic mechanisms. The most obvious is the 100 km difference in their widths (Figs. 4 and 6). The eastern margin is marked by an abrupt 16 km depth change along the crust-mantle boundary, and the continental and oceanic crusts are in sharp contact. This contrasts with the transitional crustal depth change along the western margin where oceanic material is being incorporated into the continent and oceanic crust is perhaps being transformed to continental crust. The western margin has a long history of accretion as shown by the progression of increasingly younger rocks in a seaward direction (Fig. 5). These differences are consistent with the plate models of vertical and gently dipping horizontal plate boundaries.

If the eastern margin is a vertical plate boundary along which deformation is strike slip, then the buried trench is difficult to explain because most trenches are thought to signify descending oceanic crust along a Benioff zone. Depression of oceanic crust along the eastern strike-slip margin is locally as great as the crustal depression under the Aleutian Trench. Isostatic adjustment for the thick Pleistocene continental rise is only a partial explanation because there is poor correlation between sediment thickness and depth of crustal depression. Some type of dynamic mechanism is not only depressing the oceanic crust but it is also uplifting the continental shelf (Fig. 3) (Twenhofel, 1952). Possibly compressional stress oriented subparallel to the margin results from partial coupling adjacent to the Queen Charlotte-Fairweather fault system. Because the oceanic crust in thinner and presumably weaker than the continental crust, its free edge may be crenelated and locally depressed. However, this explanation is largely conjectural until the buried trench is better known. Other examples of trenches along presumed strike slip plate boundaries occur along the western Aleutian Trench and along the Puerto Rico Trench. It seems that more than simple models are required to explain some observations across the eastern margin. In this context it should be noted that the eastern margin is potentially tsunamogenic in spite of the predominately strike-slip tectonic mechanism, because of the major vertical movement that has occurred there.

The development of a trench along a strike-slip margin raises some question about the tectonic significance of the eastern Aleutian Trench along the western continental margin. Close inspection of the western margin crustal section (Fig. 5) reinforces this question because the oceanic crust can be traced well beyond the Aleutian Trench into the continental slope. This crust is thought to be unbroken under the continental slope because oceanic magnetic anomalies are traced from the ocean floor across the continental slope to the continental shelf (von Huene, 1972). Therefore, the simple model in which oceanic crust slips beneath the continental crust along a zone of thrusting that surfaces at the Aleutian Trench does not fit the observations. Instead, the second oceanic layer (v = 5.0-5.5) thickness increases approximately at the seaward limit of earthquake hypocenters. If the record of earthquakes is complete enough to define a Benioff zone, the Benioff seems to occur only beneath the crust and it does not appear to cross it as a simple shear (Fig. 5). A growing structural arch at the edge of the continental shelf that has locally been uplifted at least 1 000 m (von Huene, 1972) also occurs here. If crystalline rocks of the oceanic crust are tectonically thickened and have contracted laterally, they probably transmit deformation to the overlying sediments across a broad zone. Perhaps the shelf break arch is an indication of the most intense deformation deep in the underlying crust associated with the seaward end of the Benioff zone. If this is so, the Aleutian Trench would only mark the beginning of a structurally complex continental slope and motion along the subcrustal Benioff zone would be dissipated across a broad zone of folding and vertical deformation; no zone of thrusting would crop out as a geologic expression of the Benioff zone. Such a model would explain the absence of intense compressional structures along the adjacent coastal land areas and for that matter along the Aleutian Arc. This model would only apply to an area where accretion occurs and not to non-accretionary margins where oceanic material and even continental crust are consumed.

CONCLUSIONS

Structures along the eastern Gulf of Alaska margin show that the northern segment of the Queen Charlott-Fairweather fault system fits most of the criteria for a strike-slip (transform) plate boundary. The western margin, which contains the Aleutian Trench, fits most criteria of an underthrusting (converging) plate boundary. Therefore, observed structure along north Pacific plate boundaries appears consistent with the geometry of plate tectonic models for the last 20 m.y. However, a buried trench along the eastern strike-slip margin suggests complex secondary processes that are unexplained by the simple juncture of two rigid plates, and it raises some questions as to the origins of trenches. Other examples of trenches along strike slip plate boundaries occur along the western Aleutian Trench and the Puerto Rico Trench. Along the western margin, the simple rigid plate model is even less applicable. Here the Benioff zone may end at a point below the crust and its shear may be transmitted across the crust-mantle boundary at a point approximately below the edge of the continental shelf rather than at the Aleutian Trench. Perhaps the second oceanic layer takes up this thrust motion by tectonic thickening and the overlying sediments may respond to a contraction of the basement by compressional folding deep in the continental shelf and slope. The shelf break arch may indicate the area in which folding is most intense. The Aleutian Trench probably marks the edge of the structurally complex continental slope and it is not the axis of a large thrust fault.

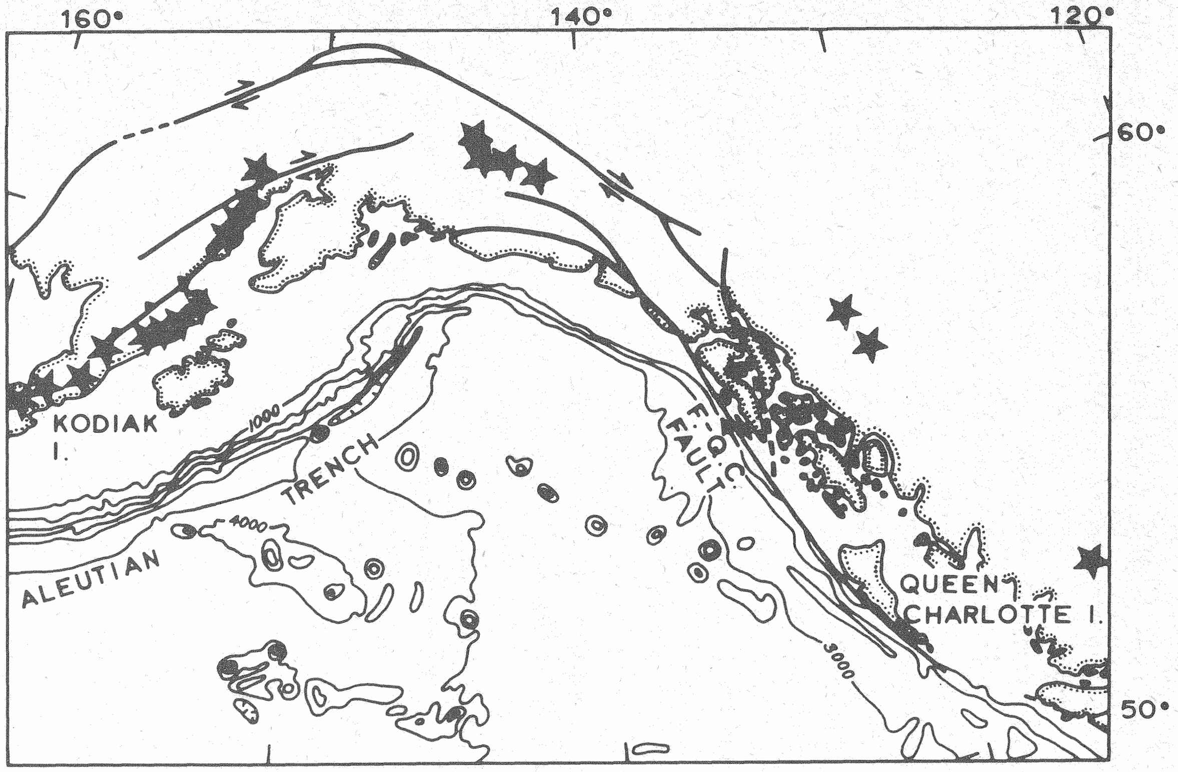

Figure 1. Map of the Gulf of Alaska showing the Aleutian Trench, the Queen Charlotte-Fairweather fault system, and volcanoes (stars).

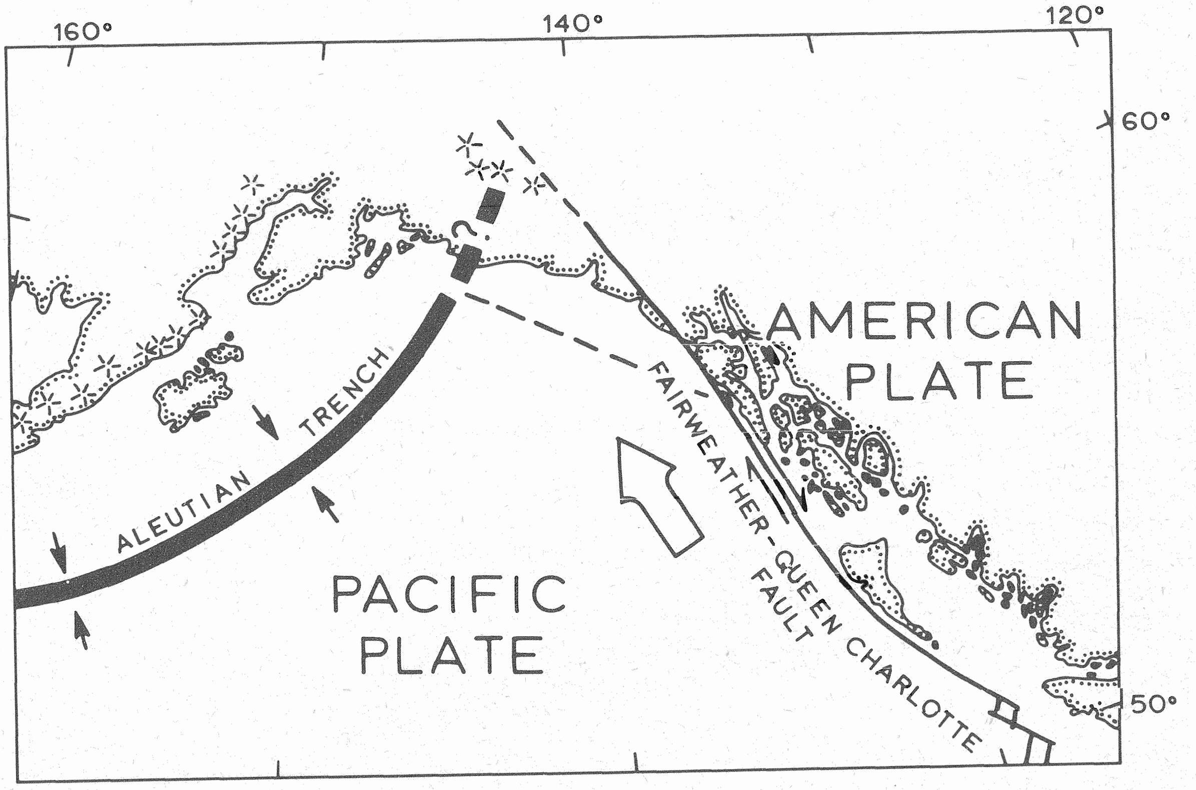

Figure 2. Diagram indicating relative motion between the North American and Pacific plates. The eastern margin has predominantly strike-slip motion and the western margin marks a zone of compression where plates converge.

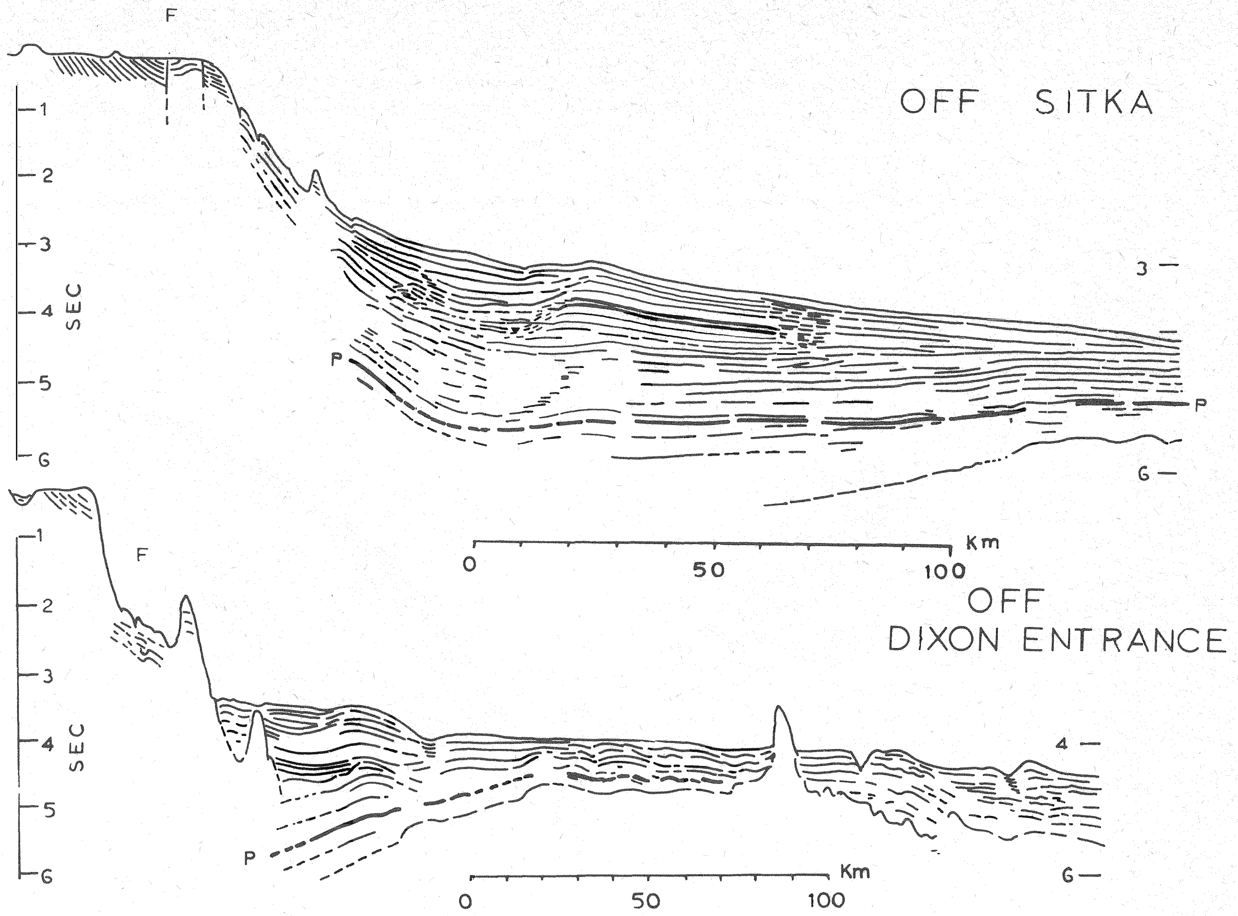

Figure 3. Tracings of seismic reflection records. Heavy reflector marked with letter "P" indicates base of Pleistocene sediments: letter "F" indicates Queen Charlotte-Fairweather fault system. Vertical exaggeration of upper and lower records is 14 and 20 respectively.

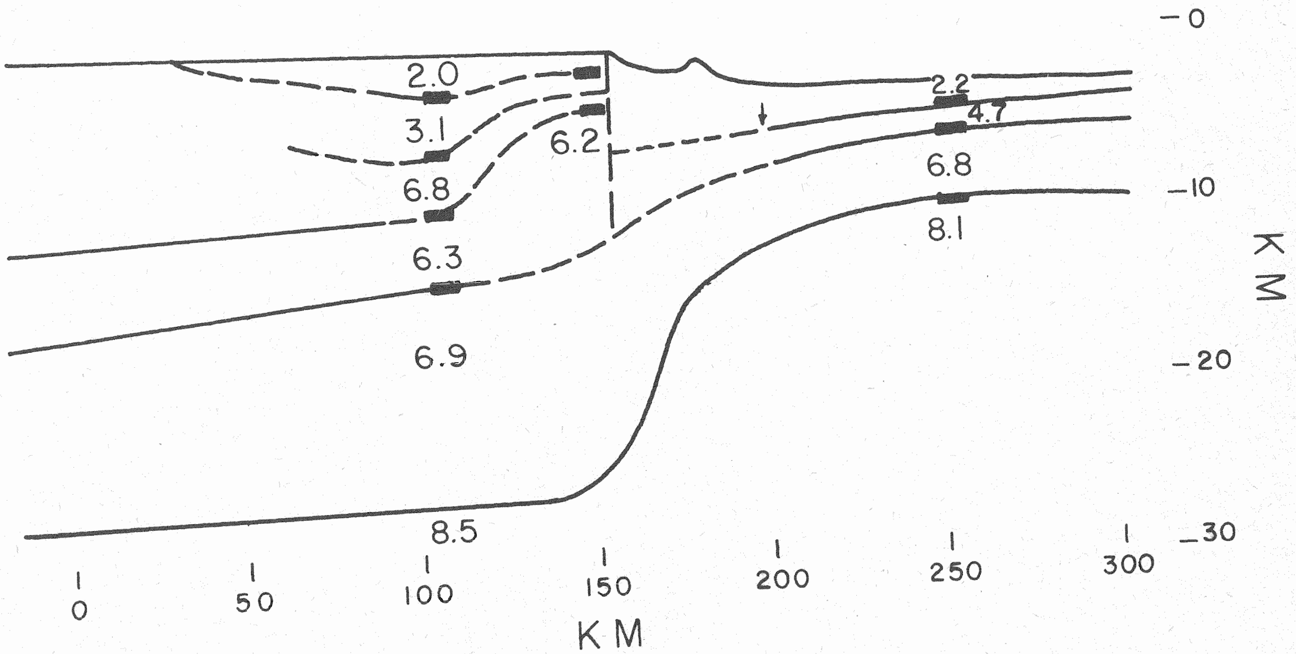

Figure 4. Crustal section across the eastern margin near Dixon Entrance based on seismic refraction records (Shor, 1962; Johnson and others, 1972), gravity (Couch, 1969) and unpublished seismic reflection, gravity and magnetic observations.

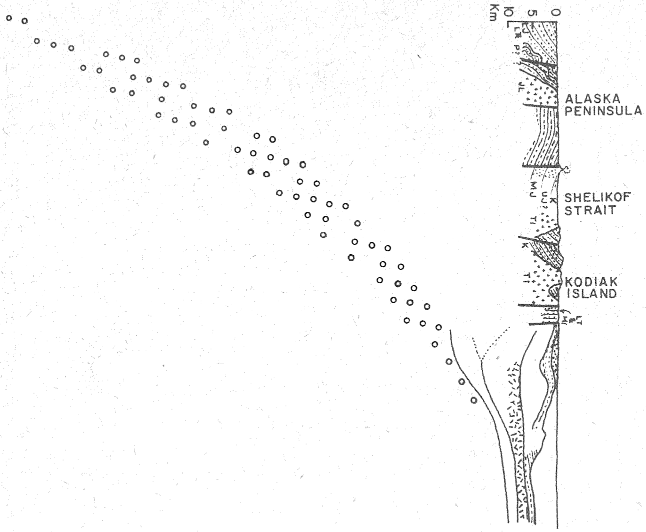

Figure 5. Diagram of structure across the Alaska Peninsula, Kodiak Island and the Aleutian Trench, and earthquake hypocenters from the latitude of Middleton Island to the southern end of Kodiak Island. Geology generalized from Burk (1965), Moore (1968), and seismic refraction data from Shor and von Huene (1972). The Benioff zone, shown diagrammatically, is constructed from a 10 year record of earthquake hypocenters relocated by Tobin and Sykes (1966).

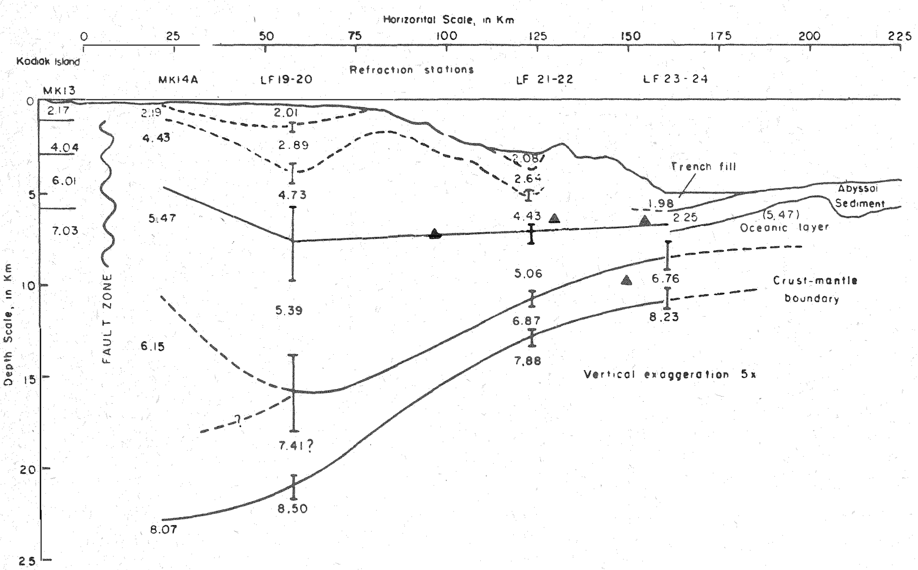

Figure 6. Crustal section near Kodiak from von Huene (1972) based on data in Shor and von Huene (1972).

BIBLIOGRAPHY

ATWATER, Tanya, 1970. Implications of plate tectonics for the Cenozoic tectonic evolution of western North America. *Geol. Soc. Amer. Bull.*, 81(12): 3513-3536.

BURK, C.A., 1965. Geology of the Alaska Peninsula-Island arc and continental margin, pts. 1-3, *Geol. Soc. Amer. Memoir 99,* 250.

CHASE, R.L., and TIFFIN, D.L. 1972. Queen Charlotte fault-zone, British Columbia, *Proc. Internat. Geol. Congress, Montreal,* 17-27.

COUCH, R.W., 1969. Gravity and structures of the crust and subcrust west of Washington and British Columbia, *Ph.D. dissertation, Oregon State Univ., Corvallis.*

EMBLEY, R.W., J.I. EWING and A.B. WATTS, 1973. Sediment distribution and continental margin structure in the Gulf of Alaska, *Trans. Amer. Geophys. Union,* 54, 336.

HAYES, D.E., and W.C. PITMAN, 1970. Magnetic lineations in the North Pacific, *in* Hayes, J.D., ed., Geological Investigations of the North Pacific, *Geol. Soc. Amer. Memoir,* 126: 291-314.

JOHNSON, S.H., R.W. COUCH, M. GEMPERLE and E.R. BANKS, 1972. Seismic refraction measurements in southeast Alaska and western British Columbia, *Canad. Jour. Earth Science,* 9(12): 1756-1765.

KANAMORI, Hiroo, 1970. The Alaska earthquake of 1964, Radiation of long-period surface waves and source mechanism, *J. Geophys. Res.*, 75(26): 5029-5040.

LE PICHON, X., 1968. Sea-floor spreading and continental drift, *J. Geophys. Res.*, 73: 3661-3697.

McKENZIE, D.P., and R.L. PARKER, 1967. The North Pacific, an example of tectonics on a sphere, *Nature,* 216: 1276-1280.

MORGAN, W.J., 1968. Rises, trenches, great faults, and crustal blocks, *J. Geophys. Res.*, 73: 1959-1982.

PLAFKER, George, 1969. Tectonics of the March 27, 1964, Alaska earthquake, *U.S. Geol. Survey Prof. Paper 543-1,* 74 pp.

ST. AMAND, P., 1957. Geological and geophysical synthesis of the tectonics of portions of British Columbia, the Yukon Territory, and Alaska, *Geol. Soc, Amer. Bull.*, 68, 1343.

SHOR, G.G., 1962. Seismic refraction studies off the coast of Alaska 1956-1957, *Geol. Soc. Amer. Bull.*, 52: 37-57.

STAUDER, William and G.A. BOLLINGER, 1966. The focal mechanism of the Alaska earthquake of March 28, 1964, and its aftershock sequence, *J. Geophys. Res.*, 71: 5283-5296.

SOUTHERLAND-BROWN, A., 1968. Geology of the Queen Charlotte Islands, British Columbia, *British-Columbia Dept. Mines and Petr. Res. Bull.*, 54, 226 pp.

TWENHOFEL, W.S., 1952. Recent shore-line changes along the Pacific coast of Alaska, *Amer. Jour. Science,* 250: 523-548.

VON HUENE, R.E., and L.D. KULM, 1973. Tectonic summary of Leg 18, in Kulm, L.D., R.E. von Huene, et al, Initial Reports of the Deep Sea Drilling Project, Vol. XVIII, Washington.

VON HUENE, R., 1972. Structure of the continental margin and tectonism at the eastern Aleutian Trench, *Geol. Soc. Amer. Bull.*, 83: 3613-3626.