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Gulf of Alaska: Magnetic Anomalies, Fracture Zones, and Plate Interaction

ABSTRACT

Recently acquired magnetic data have allowed better definition of the linear magnetic-anomaly pattern in the Gulf of Alaska. Based on anomaly offsets, the Aja fracture zone has been located precisely and three additional fracture zones have been identified. The Aja fracture zone undergoes a change in trend that reflects a major change in spreading direction that occurred about 30 m.y. ago. Along the northwestern margin of the Gulf of Alaska, magnetic anomalies can be traced across the Aleutian trench and up to 50 km into the continental margin; whereas to the northeast, the anomalies lose their identity several tens of kilometers before encountering the continental margin. This latter zone, paralleling the continental margin between 135° W. and 143° W., probably was caused by compressive stresses within the continental margin and oceanic crust related to recent plate convergence along a coupled margin. Also, it may reflect the future location of a transform fault that will short-circuit the present Juan de Fuca Ridge–Aleutian trench transform fault and greatly simplify the plate boundary bordering the Gulf of Alaska.

INTRODUCTION

During the past several years, National Oceanic and Atmospheric Administration (NOAA) ships have collected magnetic data from along 10 east-west tracklines in the northern Gulf of Alaska to delineate the hitherto poorly defined magnetic pattern in this region. Additional magnetic data were collected by the NOAA ship *Oceanographer* in 1971 to supplement the previous trackline information. Emphasis was placed on resolving the oceanic magnetic-anomaly pattern near the continental margin.

A linear anomaly map interpreted from the magnetic data (Fig. 1) was constructed to be compatible with the map of Atwater and Menard (1970, Fig. 1) across the 52d parallel; it is also consistent with trackline magnetic profiles presented by Pitman and Hayes (1968, Fig. 1). The numbering of anomalies follows the time scale established by Heirtzler and others (1968, Fig. 3). Deviations from previous interpretations were made only where warranted by new data.

Salient features revealed are: (1) an abrupt bend in the Aja fracture zone that apparently took place just before the generation of anomaly 8; (2) three fracture zones north of the Aja, two of which were short-lived and terminated by the time of anomaly 13; (3) the continuation of magnetic anomalies 18 to 21 well into the continental slope in the northwestern portion of the Gulf of Alaska; (4) a magnetic "disturbed zone" within the oceanic crust adjacent to the continental margin in the northeastern Gulf of Alaska; and (5) a pair of high-amplitude linear magnetic anomalies within the continental margin adjacent to the disturbed zone.

OBSERVATIONS AND DISCUSSION

Linear Magnetic Anomalies and Fracture Zones

The great east-west fracture zones in the northeast Pacific were generated from offsets along the ancient Farallon ridge and represent the direction of Farallon plate movement relative to the Pacific plate; the Aja fracture zone is the most northerly of these previously described in the literature. Linear magnetic anomalies generated by sea-floor spreading in a reversing geomagnetic field and at right angles to fracture zones are present throughout much of the northeast Pacific (Atwater and Menard,

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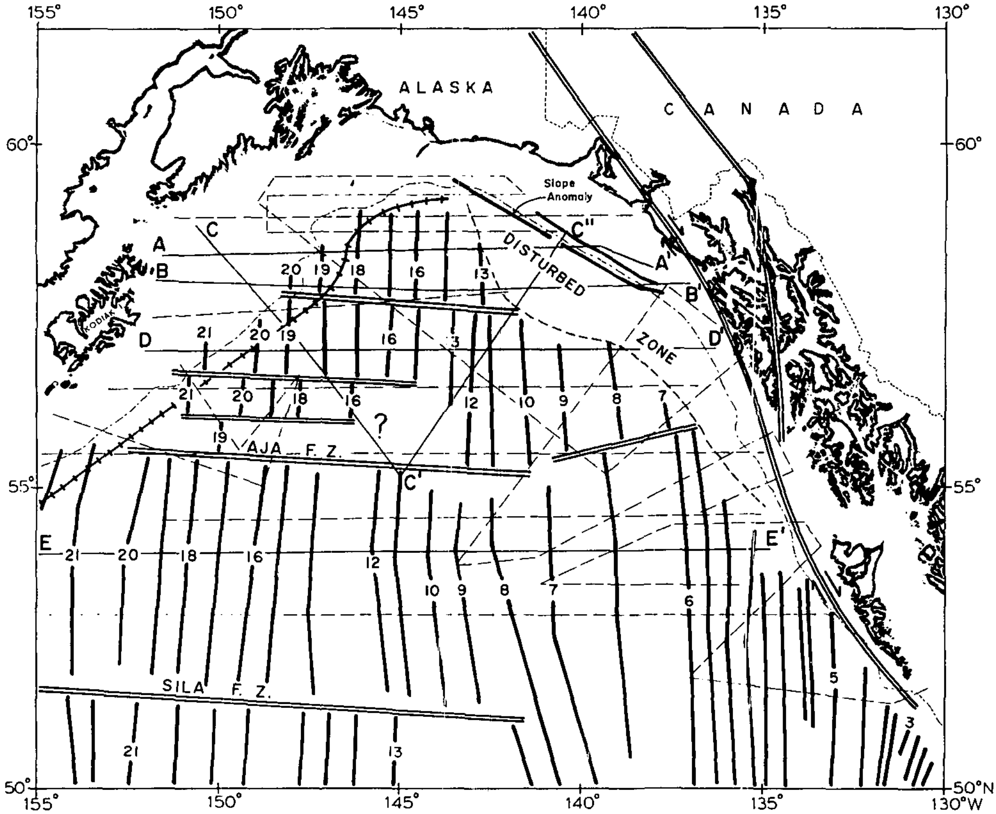


Figure 1. Gulf of Alaska magnetic lineations (heavy solid lines) and fracture zones (double lines). Dashed lines = Ships' trackline. Lettered solid lines = reference profiles shown in Figure 2. Dash-dot line = 1,000-fm isobath. Hachured line = Aleutian trench axis.

1970, Fig. 1). The new data allow a delineation of linear magnetic anomalies in close conjunction with the Aja fracture zone, thus aiding in its precise positioning. Also, on the basis of anomaly offsets north of the Aja fracture zone, several additional fracture zones have been inferred.

Between 152° W. and 142° W., the Aja fracture zone trends slightly southeast. At the time of anomaly 19, the Aja represented a ridge offset of approximately 80 km. By the time of anomaly 12, it had absorbed the ridge offsets of two intermittent transform faults, located 70 and 140 km to the north, and attained an offset of 150 km (see Fig. 1). Because of insufficient data, the magnetic anomaly pattern associated with the termination of the two intermittent fracture zones has not been defined. Also, where trackline information exists, the magnetic signature is poor, which is consistent with observations made about other regions where spreading centers have jumped (see, for example, Malahoff and Handschumacher, 1971).

At approximately 142° W., the Aja fracture zone experiences a marked change in trend of about 25° to the north. The offset of the magnetic anomaly pattern is unaltered through the bend, though it should be noted that the offset had grown to approximately 200 km by the time of anomaly 7 because of a slightly faster spreading rate north of the fracture. The change in spreading direction apparently took place in the interim between the generation of anomalies 9 and 8, or about 30 m.y. ago, assuming the bend (as defined) occurred at a position medial to the location of the offset ridge segments. In other words, a point that best approximates the bend lies equidistant from anomaly 8.5 north of the Aja and its offset equivalent south of the Aja—a relation unique to this position in the anomaly sequence. It should be pointed out that the bend as shown is only an approximation of a feature that probably is considerably more complicated; the magnitude of both the ridge offset and the change in spreading direction at the time of the bend suggest that several large adjustment fractures (Menard and Atwater, 1968) were required to accommodate the change. We have shown the best interpretation of the fracture zone's position before and after the bend based on the available data, and assume that the bend occurs in the center of the undefined portion. Thirty million years ago coincides at least approximately with the termination of the Sila fracture zone and possibly with that of the Sedna and Surveyor fracture zones (see Atwater and Menard, 1970, Fig. 1).

The Farallon plate started to break up 30 m.y. ago as the Farallon ridge (eastern margin of the Pacific plate) encountered the North American plate (Atwater, 1970). According to models proposed by Atwater (1970, Figs. 6 and 8), this interaction started when the Mendocino transform fault encountered the North American margin, at which time the Farallon plate broke into two separate units. The bend in the Aja fracture zone and the terminations of the Sila, Sedna, and Surveyor fracture zones may reflect a large-scale plate boundary readjustment that followed this initial fragmentation. A greatly simplified ridge structure existed between the Mendocino and Aja transform faults for approximately 20 m.y., or up until the approximate time of anomaly 5 (10 m.y. in age). The nature of the ridge during this interval is best reflected in anomaly 6, which can be identified clearly as a continuous uninterrupted lineation extending more than 2,500 km between the Mendocino and Aja fracture zones. Shortly after the generation of anomaly 5, the Farallon plate started to fragment further because of its diminishing size. The Juan de Fuca complex of rotated and fractured blocks (Peter and Latimore, 1969; Silver, 1971) represents the last, and still active, vestiges of Pacific-Farallon spreading north of the Mendocino fracture zone.

North of the Aja fracture zone, the Farallon ridge was an active spreading center, and at least until the generation of anomaly 7 (about 27 m.y. ago), the youngest identifiable anomaly adjacent to the continental margin. The bend in the Aja fracture zone and the associated reorientation of the magnetic anomaly pattern show that the Farallon plate rotated several degrees counterclockwise before disappearing beneath the North American plate, perhaps to conform better to the orientation of the nearby continental margin.

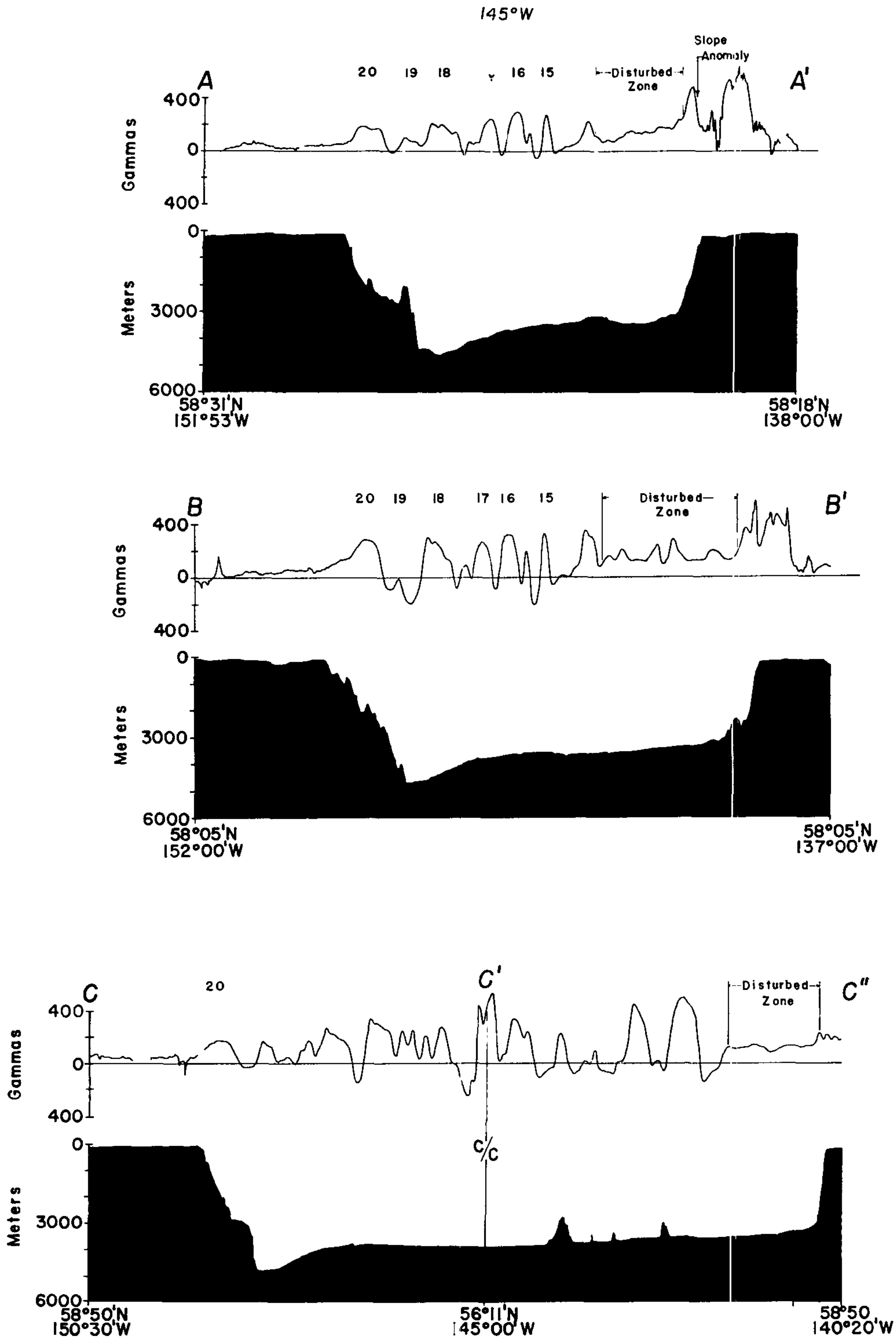
In this region, portions of the Pacific plate younger than anomaly 7 (if ever present) and all vestiges of the Farallon plate have been overridden by the North American plate, thus obliterating any oceanic crustal evidence reflecting the final stages of Pacific-Farallon spreading north of the Aja fracture zone.

Magnetic Disturbed Zone and Shelf Anomalies

West of about 143° W., magnetic anomalies 18 to 21 can be traced northward across the Aleutian trench and up to 50 km into the continental slope (Fig. 1). The anomaly field within this slope region appears to originate almost entirely from the underthrusted Pacific plate. As the depth of underthrusting increases beneath the thickening margin, anomaly amplitudes attenuate rapidly, and over the northwestern continental shelf the magnetic field is relatively featureless (Fig. 2).

Along the northeastern margin of the Gulf of Alaska, the magnetic relations differ greatly from those observed to the west. Here a zone of oceanic crust up to 50 km wide and closely paralleling the continental margin is characterized by a relatively smooth magnetic field. On encountering this zone, extending from about 143° to 135° W., characteristic oceanic anomalies abruptly terminate or become distorted and drastically reduced in amplitude. Also associated with the continental shelf in this region is a pair of broad, high-amplitude, positive anomalies that closely parallels a straight-line segment of the continental margin (Fig. 1). The more western of these anomalies occurs slightly downslope of the shelf break and is a more continuous feature, extending from about 143° W. to 138° W.; it is shown in its most characteristic form in Figure 2a. The magnetic smooth zone and a shelf anomaly were noted by Haines and others (1971) from an aeromagnetic survey. They described the shelf anomaly as similar to the slope anomaly along the Atlantic shelf edge of North America (Drake and others, 1963).

Over the past few years, several hypotheses have been advanced to explain the Atlantic slope anomaly and a magnetically smooth zone of oceanic crust adjacent to the Atlantic margin (summarized by Taylor and others, 1968; Emery and others, 1970). Taylor and others


145°W
A
A'
20
19
18
16
15
Disturbed Zone
Slope Anomaly
400
0
400
Gammas
0
3000
6000
Meters
58°31'N
151°53'W
58°18'N
138°00'W
B
B'
20
19
18
17
16
15
Disturbed Zone
58°05'N
152°00'W
58°05'N
137°00'W
C
C'
C"
20
Disturbed Zone
C/C
58°50'N
150°30'W
56°11'N
145°00'W
58°50'
140°20'W

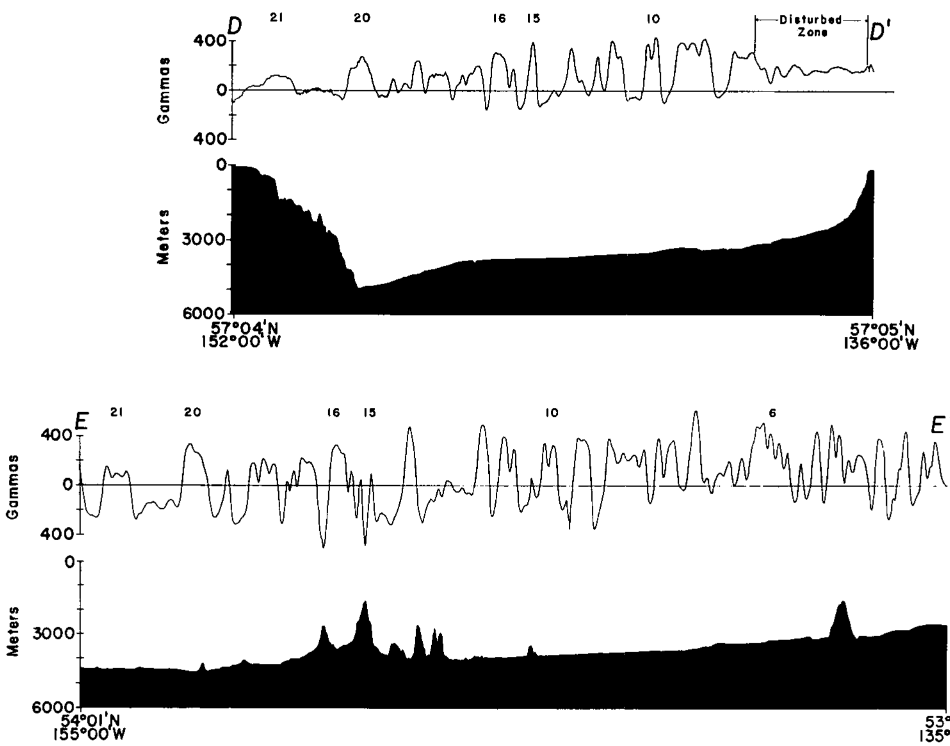


Figure 2. Bathymetry and associated magnetic anomaly field (IGRF) along selected tracklines in the Gulf of Alaska (see Fig. 1).

(1968) feel that the slope anomaly reflects an intrusion emplaced along the continental margin, and that the oceanic smooth zone resulted from regional metamorphosis that destroyed the magnetization of the basaltic layer 2. Emery and others (1970) relate both phenomena to geomagnetic field events recorded on the basaltic layer 2 during its generation by sea-floor spreading. They believe the slope anomaly reflects spreading during an Early Permian period of normal polarity that coincided with the initial rifting of the European and North American land masses, and the smooth zone represents crust generated during the ensuing Kaiman reversed magnetic interval. The parallelism of these magnetic features and their proposed ages are not inconsistent with the geometry and history of spreading in the Atlantic as presently conceived; thus, relating their origin to fundamental spreading processes is an attractive alternative.

The same cannot be said of the relations observed along the northeast Gulf of Alaska margin. Here it is virtually impossible to relate the magnetic smooth zone to a magnetic quiet interval for a number of reasons, including the age of the adjacent oceanic crust, the general shape of the zone, and the fact that the anomalies lose their identity at different positions along the anomaly sequence. Based on the above considerations and also continental margin relations discussed in the following paragraphs, the smooth zone appears to represent Tertiary oceanic crust whose original magnetic character has been distorted. Thus, regional metamorphism, invoked by Taylor and others (1968) to explain the Atlantic smooth zone, may find more credence when applied to the Gulf of Alaska disturbed zone.

Also it is highly unlikely that the shelf anomalies are in any way related to original spreading (extrusive) processes. The Gulf of Alaska continental margin has probably undergone considerable large-scale deformation because of the vast amounts of oceanic crust subducted beneath it (Atwater, 1970). Indeed, the shelf region here is probably composed almost entirely of material incorporated into the margin during the lengthy periods of subduction. The anomalies thus appear to represent either dike intrusion or a basement ridge complex formed during margin deformation. It may be significant that these anomalies occur only where the margin is coupled. This suggests that they are not the result of plate interaction but were produced after the margin became coupled. This argument favors recent dike intrusion.

Recent History of Plate Interaction

Plate interactions in the Gulf of Alaska have been complicated during Tertiary and recent times by two plates that are no longer present. The Farallon plate and the ancient northerly moving Kula plate (Pitman and Hayes, 1968; Grow and Atwater, 1970; Atwater, 1970) once lay between the Pacific and North America plates. As these plates were consumed, a complex sequence of changing plate-boundary conditions occurred along the Pacific margin of the North America plate (Atwater, 1970) leading to the present geometry (Fig. 3).

In the present model of this region, a great ridge-trench transform fault, or system of transform faults, extends from the Juan de Fuca ridge complex to the Aleutian trench (Wilson, 1965; Tobin and Sykes, 1968) and marks the boundary between the Pacific and North American plates. This system consists of several distinct parts, including the Queen Charlotte Islands fault, the Fairweather and Totschunda faults (Richter and Matson, 1971), and parts of the Denali fault system. These will be referred to collectively as the Queen Charlotte Islands fault system. Theory requires a transform in this location to accommodate the lateral displacement between the Pacific and North America plates.

Convergence of the two plates occurs along the Aleutian volcanic arc (McKenzie and Parker, 1967; Isacks and others, 1968). Associated with the Aleutian arc is an active zone of intermediate-depth earthquakes (70 to 170 km) that extends north to the Denali fault system (Fig. 3; Tobin and Sykes, 1966). Shallow seismic activity occurs between the arc and its related submarine trench to the south but terminates in an easterly direction at about 146° W. This location coincides approximately with the easternmost bathymetric expression of the Aleutian trench (Fig. 3), suggesting that active underthrusting is negligible east of 146° W. Consequently, much of southeastern Alaska between this eastern limit of underthrusting and the southern extension of the Denali fault system appears to be largely coupled to the Pacific plate (Richter and Matson, 1971). Assuming the rest of Alaska is rigidly attached to the North America plate, a transition of the plate boundary from one of strike-slip displacement (the Queen Charlotte Islands fault system) to one of underthrusting (the Aleutian arc subduction zone) must be occurring within the continental crust of southeastern Alaska. This results in an unstable situation in which subduction of continental crust is required in order that a narrow zone of deformation, typifying most plate boundaries, be maintained throughout the transition. Subduction of continental crust is considered by many to be physically untenable owing to its buoyancy and hyperfusible petrologic make-up (for example, Dietz and Holden, 1970). Thus, to allow for the present differential motion between the Pacific plate and the North America plate, crustal shortening by internal deformation must be occurring to relieve horizontal compressive stresses and complete the plate boundary transition. This zone of compression should lie between the eastern limit of active subduction along the Aleutian trench and the system of transform faults farther east.

Based on a late Miocene or early Pliocene disappearence of the northern-moving Kula plate (Atwater, 1970) and recent uplift and deformation in the Alaska area (Stonely, 1967; Plafker, 1969), Richter and Matson (1971) propose that the decoupling of the continent along the Denali fault system may have occurred as recently as 10 m.y. ago. This resulted in a portion of southeastern Alaska becoming fixed to the leading edge of the Pacific plate. Richter and Matson (1971) further propose that the Totschunda and Fairweather faults represent the beginning of a new transform fault, short-circuiting the southeast section of the Denali fault system in an attempt to better accommodate the present-day plate motions.

Origin of the Disturbed Zone

The magnetic disturbed zone paralleling the Alaskan continental margin between 143° W. and 135° W. probably is related to the deformation occurring in the nearby continent. Both appear to extend from the Queen Charlotte Islands fault to the eastern limit of underthrusting along the Aleutian trench. Furthermore, transmission of compressive stresses acting

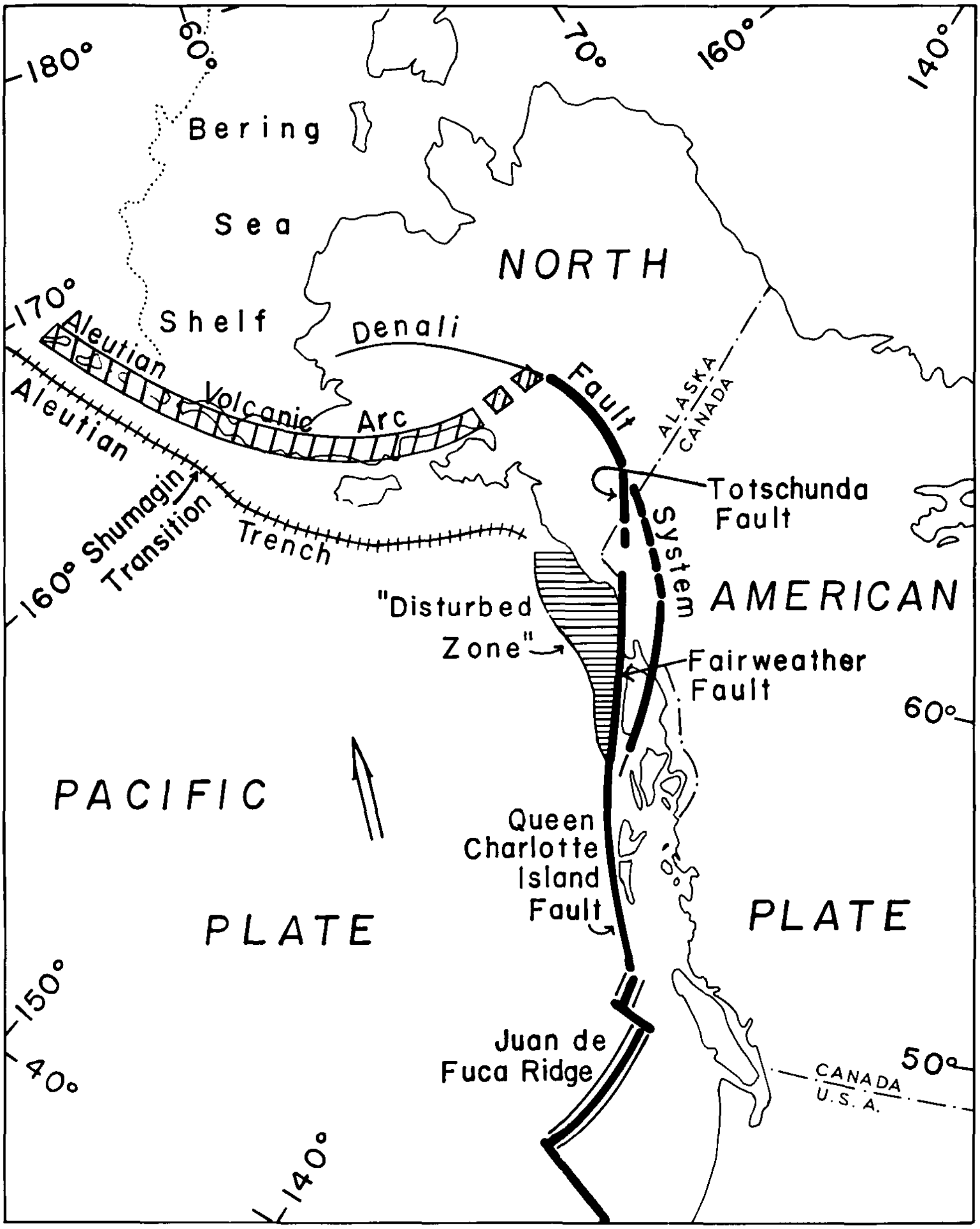


Figure 3. Sketch map of northwestern North America showing major tectonic features along Pacific–North America plate boundary (in part after Tobin and Sykes, 1968; Richter and Matson, 1971). Arrow indicates present motion of Pacific plate relative to North America plate.

within the continent across a coupled margin to the adjacent oceanic crust could be anticipated. The location and shape of the disturbed zone support this conclusion and suggest that the crust here is being subjected to a compressional stress with a component of right-lateral shear.

The manner in which crustal deformation can lead to destruction of the magnetic anomaly field is difficult to assess at present. Some form of regional metamorphism related directly or indirectly to crustal compression may have reduced greatly the effective magnetization of rock within the magnetized layer. One possibility is hydrothermal alteration of fractured rock. Luyendyk and Melson (1967), on examining rocks dredged from the mid-Atlantic ridge, found that hydrothermal alteration of "oceanic" tholeiitic basalts resulted in a breakdown of the high-susceptibility magnetic oxides (titano-magnetite and ilmeno-haematite) to sphene and other minerals, thus decreasing the susceptibility and remanent magnetism.

Eastern Aleutian Trench

Implied in this discussion is that west of 145° W., underthrusting and subduction are relieving compressional stresses resulting from plate convergence. This does not appear to be wholly correct. In a recent seismic reflection study of the continental margin off Kodiak Island (including the Aleutian trench between about 152° W. and 145° W.), von Huene (1972) concluded that the presumed megathrust producing the Benioff zone of earthquakes does not come to the surface as a simple shear zone at the trench but that there is a diffuse zone of deformation across the whole continental margin. In his interpretation, the trench in this region appears relatively unimportant as a structural feature, with its only significance being that it marks the beginning of a broad zone of compressional deformation; thus, the northwestern termination of the disturbed zone and the beginning of shallow seismic activity associated with the Aleutian trench does not mark a prominent boundary between a coupled margin and a well-developed subduction zone. The transition is a gradual one, with a broad zone of deformation occurring along the continental margin perhaps as far as the Shumagin transition (von Huene and Shor, 1969), at about 160° W. The Shumagin transition marks the location where the Aleutian arc system narrows significantly as it leaves the Bering shelf and becomes entirely an oceanic feature.

West of the Shumagin transition, the Aleutian arc appears to represent a well-developed subduction zone with virtually all plate convergence accommodated efficiently by underthrusting and resorption of the Pacific plate. Between 160° W. and 146° W., the Pacific plate is apparently partially coupled to the continental margin. Here, horizontal crustal shortening seems to be accomplished by broad compressive deformation as well as underthrusting and subduction, further complicating a region inherently complex because of its lengthy history as a zone of plate convergence. Between about 146° W. and 135° W., where compressive stresses appear to be transmitted across the continental-oceanic crustal boundary, there is no evidence for subduction in the surface of the crust.

Present-Day Plate Motion and the Disturbed Zone

On examining the orientation of the disturbed zone, a conspicuous and perhaps significant relation is noted. The seaward limit of apparent deformation conforms with a straight-line extension of the Queen Charlotte Islands fault and also encounters the continental margin in the northernmost Gulf of Alaska with an orthogonal relation to the presently active portion of the Aleutian trench. It compels one to speculate that this represents the eventual plate boundary (transform fault) that will accomplish a stable transition from the Queen Charlotte Islands fault structure to the Aleutian trench subduction zone, assuming present-day plate motions persist. This would seem a simple solution to the complex situation that exists today, consequently one might ask why this short-circuiting has not occurred already. The answer may be tied in with the fact that "thin" rigid plates of lithosphere have significant vertical dimension (generally considered to be about 100 km) when compared with surface crustal features, and processes occurring at depth may not always be reflected in the surface geology. For the present geometry of the crust (surface of the lithosphere) to exist at all, tectonic activity in this region must be dominated by motions within the deeper portions, and probably major bulk, of the lithosphere. The present plate geometry appears to result from recent large-scale plate reorganizations that have produced an unstable surface configuration but as yet have not become dominated by it. Complications in the form of surface drag from sialic continental crust resisting subduction apparently have not become sufficiently critical to require a repositioning of the plate boundary oceanward. This should occur when the compressive stresses acting near the surface reach deep enough into the lithosphere to impede its motion, resulting in a recoupling of southeastern Alaska to the North America plate. The Fairweather and Totschunda fault systems may represent an initial stage of this repositioning.

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