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Northeast-trending subcrustal fault transects western Washington

by

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TECTONIC SETTING

The north-trending magnetic anomalies of the Juan de Fuca plate are offset along two conspicuous northeast-trending lineaments (fig. 1), named the Columbia offset and the Destruction offset by Carlson (1981). The northeastward projections of these lineaments intersect the continental area of western Washington, hence are of potential significance to the tectonics of the Pacific Northwest region.

Pavoni (1966) suggested that these lineaments were left-lateral faults, and that the Columbia, 280 km in length, had 52 km of offset, and the Destruction, with a length of 370 km, had 75 km of offset. Based on Vine's (1968) correlation of the magnetic anomalies mapped in this area by Raff and Mason (1961), with the magnetic reversal time scale, Silver (1971b, p. 3493) concluded that oceanic crust ranging from 2.5- to 10 m.y. in age was offset 70 km along the Destruction lineament, hence the dislocation was entirely younger than 2.5 m.y. However, a reflection profile across the presumed trace of the Destruction lineament showed no offset of the upper 250 m of the oceanic sediments, indicating that no faulting had occurred for at least 500,000 years (Silver, 1971b, p. 3493).

Hey (1977) proposed that the Destruction and Columbia and other lineaments in the area of the Juan de Fuca and Gorda ridges formed through episodic jumping (propagation) of short transform faults connecting offset segments of the spreading ridges. Provided that successive jumps are in the same direction and occur after equal increments of spreading, the jumps would produce a V-shaped wake consisting of a pair of lineaments intersecting at the ridge.

In a more detailed study, Hey and Wilson (1982) verified that many otherwise mysterious features of the pattern of magnetic anomalies in the area of the Juan de Fuca ridge could be analytically reproduced by a combination of spreading, transform faulting, and ridge propagation. By suitable manipulation of the time and place at which ridge propagation originates, and the propagation direction, rate, and angle, a synthetic pattern very similar to the actual pattern was produced. Their model is--in general terms--verified by the overall similarity of the actual and synthetic patterns. However, the applicability of their hypothesis to the origin of a specific lineament in the Juan de Fuca plate cannot be readily verified unless a corresponding lineament can be found in the Pacific plate.

Hey (1977) further suggested that the lineament identified in figure 1 as YY was the Pacific plate twin of the Destruction lineament. Apparent offset along YY is comparable to that of the Destruction (Pavoni, 1966, p. 174), and the imaginary prolongations of these lineaments and the Juan de Fuca ridge do approximately intersect at a point. In Hey and Wilson's (1982) synthetic pattern the lineaments in the Pacific plate corresponding to the Destruction, the Columbia, and the ancestor of the Blanco fracture zone trend south-southeast, converging toward the southern end of the Juan de Fuca ridge. The actual pattern in this area, complicated by its superposition over the southeast-trending Eickelberg Seamount chain (Barr, 1974), shows disruption northwestward through anomaly 5A by the Blanco fracture zone (Elvers and others, 1973), but the presence of a lineament specifically analogous to the Columbia is not readily demonstrable.

Were the Columbia lineament a fault, the oceanic plate south of it, underlying the Gorda basin and extending to the Mendocino fault (fig. 1) would constitute a separate plate. This area of oceanic crust has been generally referred to as the Gorda plate, but there is little consensus on the position of its northern limit. Bolt and others (1968) suggested that the Blanco fault had broken through to the San Andreas fault, and that this break formed the northern boundary of the Gorda plate. Riddihough (1980) postulated instead that the Gorda plate was bounded on the north by an east-southeast trending fault called the Gorda fault zone intersecting the Gorda ridge at about 42.2° N. latitude. That the oceanic basement of the Gorda basin is highly deformed is apparent from inspection of Raff and Mason's map of magnetic anomalies (1961), which shows clockwise rotation of anomalies of up to 40° from the trend of their counterparts west of the Gorda ridge. However, no offset of anomalies along the eastern part of Riddihough's Gorda fault is apparent. Silver's (1971a) study revealed numerous faults in the Gorda basin, some along the western part of Riddihough's proposed fault, but most trending north to northeast parallel to the magnetic anomalies, perhaps following structural breaks originally formed at the spreading ridge (Atwater and Mudie, 1973). The Gorda basin is seismically active (Bolt and others, 1968). Focal plane solutions for earthquakes within the basin are compatible with Silver's (1971a) conclusion that the basin is deforming mainly through left lateral movement on the north to northeast trending faults (Smith and Knapp, 1980).

Some insight into the likelihood of there being an independent Gorda plate can be gained through comparison of the Neogene spreading history of the Gorda and Juan de Fuca ridges. At about 7 Ma, the clockwise rotation of the ridges abruptly slowed (Carlson, 1981) and until 5.3 Ma, the Pacific, Juan de Fuca, and Gorda plates apparently spread from a common pole (probably located near 50° S., 160° W.). After 5.3 Ma, clockwise rotation of the Juan de Fuca ridge abruptly accelerated, then slowed again at 3.8 Ma (Carlson, 1981). Rotation of the Gorda ridge accelerated about 4.4 Ma, and then slowed again at 3 Ma (Carlson, 1981). The asynchroneity of these changes in rotation rate suggests decoupling of the Gorda and Juan de Fuca plate about 5 Ma (about 4.9 Ma, according to Hey and Wilson, 1982, p. 178). Since 3.5 Ma, the Juan de Fuca ridge has spread approximately 0.58°/m.y. about a pole at 18° S., 157° W. (Hey and Wilson, 1982, p. 17).

The internal deformation of the Gorda plate frustrates attempts to calculate the Pacific-Gorda pole of rotation. And like the Juan de Fuca ridge, spreading at the Gorda ridge has probably been complicated by one (Hey and Wilson, 1982) or more propagating rifts. At present, the Gorda ridge forms three segments (Riddihough, 1980), best defined by discontinuities in the linearity of the Escanaba trough, the graben marking the current axis of spreading (Moore, 1970; Atwater and Mudie, 1973). The southern (S) and central (C) segments trend approximately north, perpendicular to the Mendocino fracture zone. The northern (N) segment trends east-northeast, perpendicular to the Blanco fracture zone. The overlap of the northern part of segment C and the western Brunhes normal anomaly implies recent northward propagation of segment C at the expense of segment N.

Spreading could be orthogonal to all segments of the Gorda ridge, or oblique to all, or orthogonal to some and oblique to others. If spreading were orthogonal to the ridge segments, the differences in recent spreading rates (segments S and C spread at roughly 2 1/2 cm/y and segment N at 5 1/2 cm/y, according to Riddihough, 1980) require that the oceanic plate east of Gorda N converge southward toward the plate east of Gorda C. The same sense of convergence is implied by the bending and clockwise rotation of the southwestern parts of the magnetic stripes of the Gorda basin (fig. 1). Deformation of the Gorda basin can be viewed as flexural slip folding and clockwise translation of numerous elongate strips of oceanic crust. The east-west extension required by this process could compensate for the reduced spreading rate at Gorda ridge segments S and C. Continuation of this style of deformation to the present implies some degree of convergence between the Gorda plate and the eastward extension of the Pacific plate south of the Mendocino fault, possibly indicating that in the aggregate the Gorda plate moves toward an azimuth between that of the Mendocino and Blanco fracture zones.

The extreme possibilities are as follows: A point at the northern end of the Gorda ridge and on the Gorda plate could be moving (a) 5 1/2 cm/y (as measured by Riddihough, 1980) to 114° azimuth (parallel to the nearby active segment of the Blanco fault, as mapped by Silver, 1971a); or (b) 6 cm/y to roughly 090° azimuth (parallel to the Mendocino fracture zone, orthogonal to Gorda ridge segments S and C, and oblique to segment N). The movement transmitted to regions to the east includes this component, which is due to spreading, and also a component of unknown magnitude due to east-west extension within the region immediately east of the ridge. This addition seems necessary to account for the continuation of the active trace of the Blanco fault eastward past the northern end of Gorda ridge segment N.

At the same time, a point on the Juan de Fuca plate immediately north of this location would move 5.9 cm/y to 121.5° azimuth (on the basis of the post-3.5 Ma pole and rate of rotation for Pacific and Juan de Fuca spreading as given by Hey and Wilson, 1982). Hence, referring to the vector solution (fig. 3), the Gorda plate must move between 0.8 and 3 cm/y north to northeast relative to the Juan de Fuca plate. Adding a nominal amount to the Gorda spreading rate to account for extension east of the Gorda ridge shifts the direction of relative motion to the east.

Quite possibly the real rates and directions lie within these extremes. If so, a north- to northeast-trending left lateral fault between the Blanco and Juan de Fuca plates seems required. Movement on this fault would probably result in concurrent counter-clockwise rotation of the Blanco fault (fig. 1). The Blanco fracture zone and the Blanco fault, located on the basis of bathymetry (figs. 1 and 2), vary somewhat from the position commonly picked on the basis of the magnetic anomaly pattern. The bathymetric location (which is shown on fig. 1) is similar to Silver's (1971a, p. 2971) location of a segment of the fault on the basis of air-gun profiles, hence is probably valid. As shown in figure 1, the Blanco has two bends, one located east of the intersection with the Gorda ridge, the other west of the intersection with the Juan de Fuca ridge. Figure 2 shows the bathymetry on which the interpretation of the eastern intersection and bend is based. The western bend is much more obscure because of the more subdued submarine topography and because of complications in the anomaly pattern resulting from radical shift in trend of the Blanco about 4.9 Ma (Hey and Wilson, 1982).

The bends probably reflect changes in plate movements that occurred somewhat less than 2 Ma, judging from age of the magnetic anomalies at the bends. Prior to that time the trend of the Blanco was more northwest than at present;

subsequently it rotated counterclockwise to its present west-northwest trend. This rotation is compatible with breakup of the Juan de Fuca plate and left-lateral movement on the Columbia lineament (fig. 4). Adjustment of the Blanco to the new orientation entails a combination of overthrusting or shearing off of plate corners and local spreading.

SEISMICITY

Unlike the Blanco fault, the Columbia lineament is not seismically defined by numerous earthquakes, judging from recent compilations of northeastern Pacific seismic activity (Tobin and Sykes, 1968; Couch and others, 1974). The Blanco fault is revealed by localization along it of numerous earthquakes, large and small. Fault plane solutions of the larger earthquakes along the Blanco suggest right-lateral strike-slip movement on the Blanco or a fault parallel to it with the P-axis in the northwest quadrant (Couch, 1980). Fault plane solutions for the two large earthquakes with locations northeast of the Blanco fault and near the Columbia lineament (fig. 2) indicate that there the P-axis lies in the northeast quadrant, with one of the conjugate pair of nodal planes striking parallel to the lineament.

Farther northeast the epicenter of the moderate earthquake of Nov. 8, 1960 (Tobin and Sykes, 1968) plots directly on the Columbia lineament (fig. 2). Continuing northeast (fig. 5), the epicenters of the 1939, magnitude 5.8 subcrustal earthquake, 1946, magnitude 6.3 subcrustal earthquake, 1949, magnitude 7.1, 70 km-deep earthquake, and 1965, magnitude 6.5, 57 km-deep earthquake plot along or near the projection of the Columbia lineament into the Puget Sound area of Washington.

The fault plane solution for the 1949 earthquake indicates either (1) overthrusting on a fault striking N.76°W., dipping 12° south, with a component of right-lateral shear, or (2) left-lateral strike-slip movement on a fault striking N.49°E., dipping 83° to the northwest, with a component of under-thrusting (Hodgson and Storey, 1955, p. 68). Three solutions have been published for the 1965 earthquake (Algermissen and Harding, 1965; Isacks and Molnar, 1971; and Chandra, 1974), only one of which (alternate solution of Chandra, 1974, p. 1537) shows movement on a nodal plane subparallel to the Columbia lineament.

Continuing northeast, the epicenter of the 1872 earthquake, as located by Malone and Bor (1979), plots near the projection of the lineament (fig. 5). Their location for this earthquake is based on fitting of isoseismals to observed attenuation curves, assuming that the earthquake had magnitude of 7.4 and was 60 km deep.

DISCUSSION

Recent compilations of epicentral data in western Washington (Crosson, 1983, p. 9, 10) do not show concentration of earthquakes--either crustal or subcrustal--along the northeastward projection of the Columbia lineament. Nor is the lineament itself revealed by the bathymetry of the ocean floor west of the continental slope. This area is largely blanketed by Pleistocene sediments composing the Astoria fan (see Von Huene and Kulm, 1973). Seismic profiles across the lineament (in Kulm and others, 1973) show that these sediments are essentially flat-lying and little disrupted.

The deposits of the continental slope and shelf are deformed and faulted, but in general the folds and faults trend north-northwest, parallel to the continental margin (Snavely and others, 1977). West of Oregon, both the upper and lower slopes are folded and faulted. West of Washington, the upper slope is characterized by folds and seaward-dipping thrusts (Barnard, 1978). The transition zone between these areas of differing structural style trends northeast and intersects the lower slope at about 46.5° N. (Barnard, 1978). The structural transition was attributed to differing rates of underthrusting of the continental slope to the north and south (Barnard, 1978). There is also a morphological transition zone on the lower slope at about 45° N. North of this latitude the lower slope is characterized by ridge and basin topography, whereas to the south the slope is marked by a steep escarpment (Kulm and others., 1973, p. 980).

The subcrustal extension of the Columbia lineament, if extrapolated northeastward, intersects the Cascades in the vicinity of Glacier Peak (fig. 4). Hughs and others (1980) theorized that a subcrustal fault with this approximate trend lay below the Glacier Peak volcano. Their suggestion was based on the observation that the Cascade volcanic chain was segmented, and that some volcanoes--such as Glacier Peak--that developed over the segment boundaries are chemically distinguishable from volcanoes within the segments. Volcanism probably began at Glacier Peak after about 0.7 Ma, according to Tabor and Crowder (1969), and it may be significant that individual vents are aligned north-northeast, sub-parallel to the Columbia lineament.

To sum up, (1) the disruption of magnetic anomalies along the Columbia lineament, (2) the probable discordance in spreading directions of the Juan de Fuca and Gorda ridges, (3) the apparent rotation of the Blanco fault zone, (4) and the focal plane solutions of earthquakes along the lineament, indicate that the Columbia lineament is a major fault. Morphologic and structural changes along the slope and shelf and the segmentation of the Cascade chain at the latitude of their intersection with the lineament support this conclusion.

On the other hand, lack of seismic definition of the lineament, and the possible absence of deformation of young sediments of the Astoria fan in the vicinity of the lineament militate against the fault hypothesis. Further study of these aspects of the problem is required.

With that reservation, the evidence suggests that 5 Ma or less, the Gorda plate broke away from the Juan de Fuca plate. Subsequent movement of the Gorda with respect to the Juan de Fuca has in part been accommodated by left-lateral displacement on a fault along the Columbia lineament. Quite possibly that movement accelerated concurrent with the beginning of the major deformation of the Gorda plate, which began about 2 1/2 Ma (Silver, 1971a).

The Columbia fault probably extends below the North American plate, where it bounds the subducted extensions of the Juan de Fuca and Gorda plates. The fault apparently does not extend upward into the overlying North American plate.

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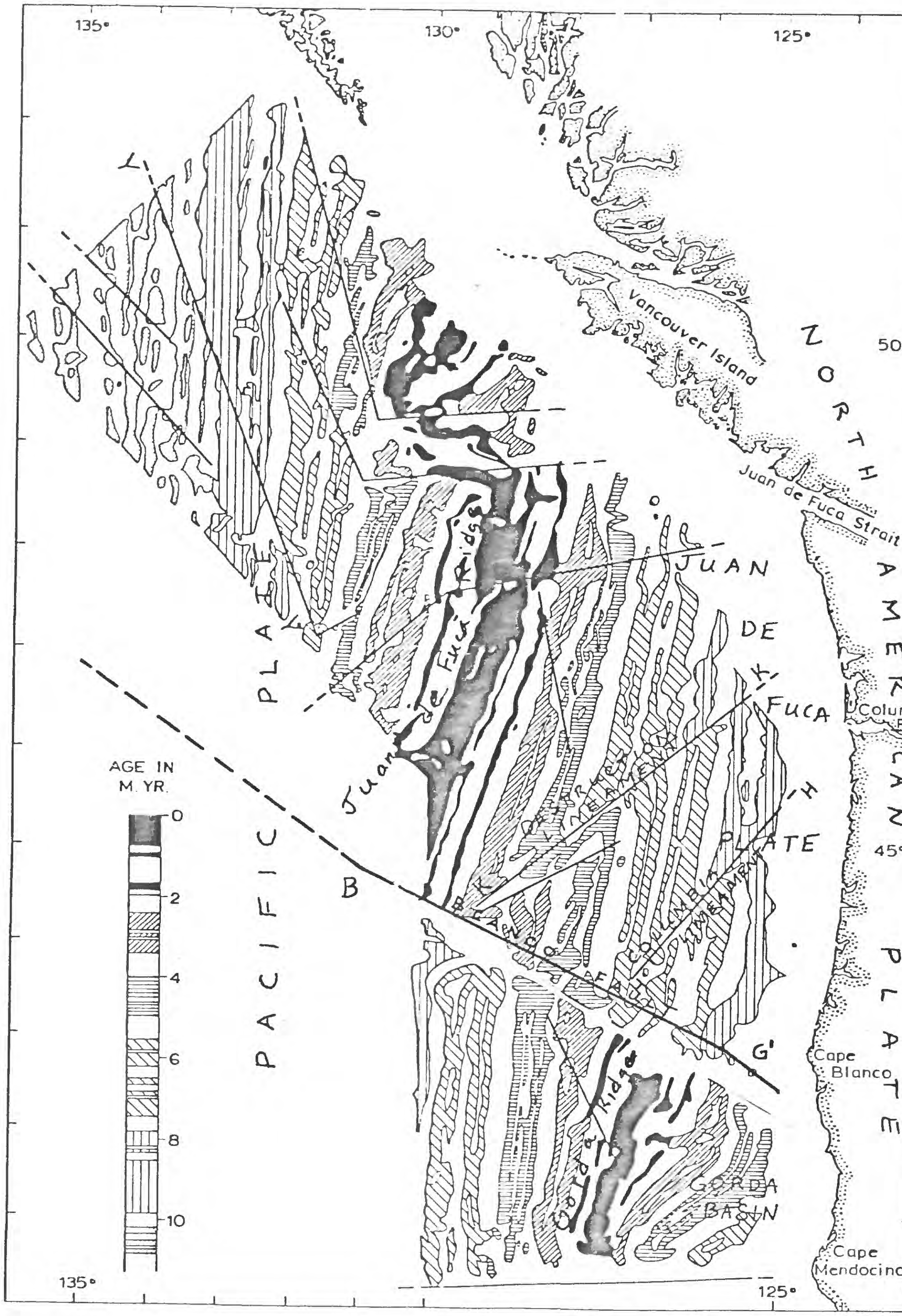

Figure 1. Magnetic anomalies in the northeastern Pacific (Raff and Mason, 1961; Vine, 1968). Location of Blanco fault and its inactive extensions (dashed lines) based on interpretation of bathymetry (Scripps Institution of Oceanography, 1973). Bends in Blanco fault at B and G' discussed in text.

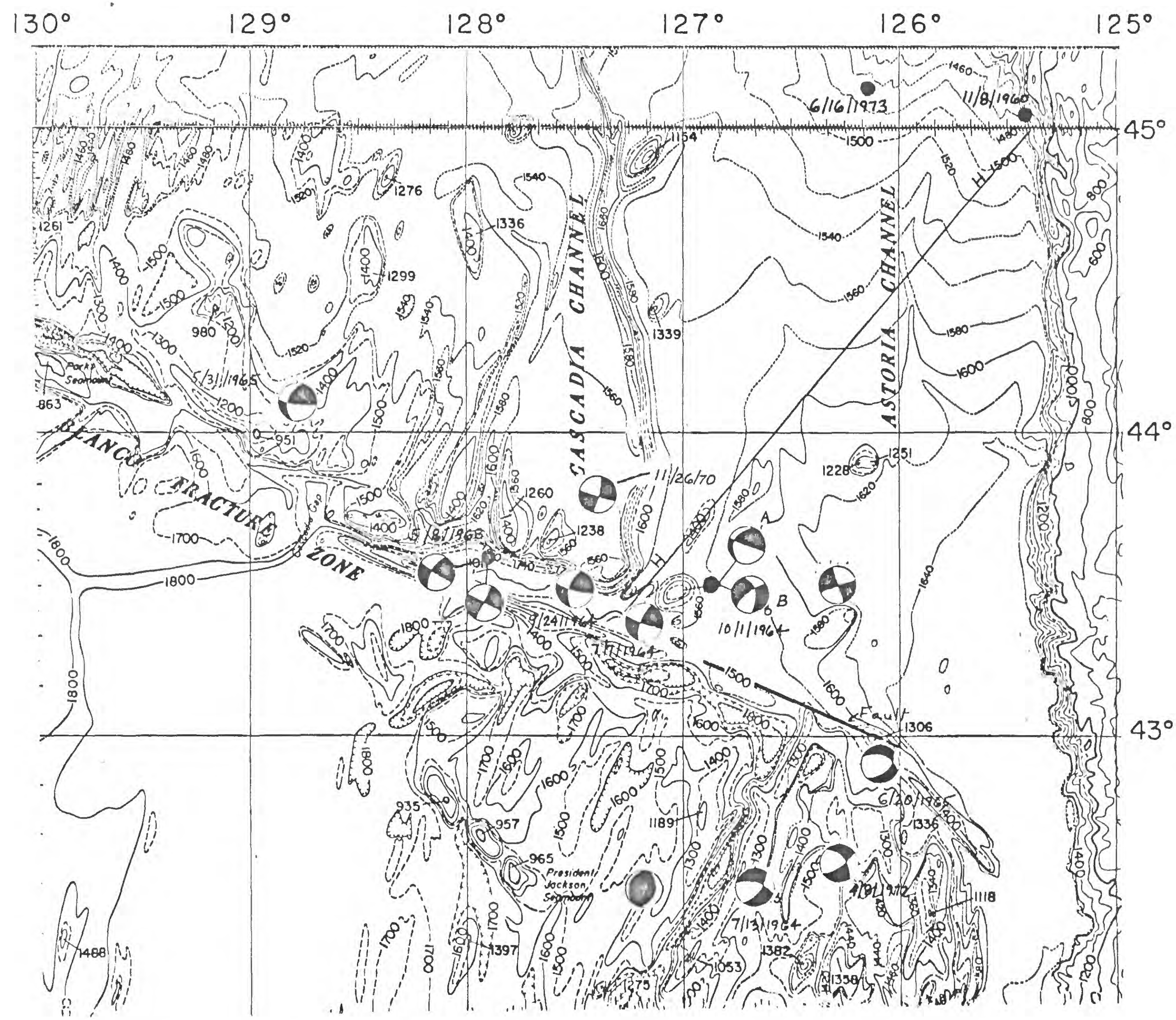

Figure 2. Bathymetry at intersection of Columbia lineament and Blanco fault (fracture zone) (from Scripps Institution of Oceanography, 1973). Fault (solid line) at southeastern end of Blanco fracture zone from Silver (1971a). Solid dots and "beachball" projections of fault plane solutions denote earthquakes discussed in text (from Chandra, 1974, and compilation by Couch, 1980).

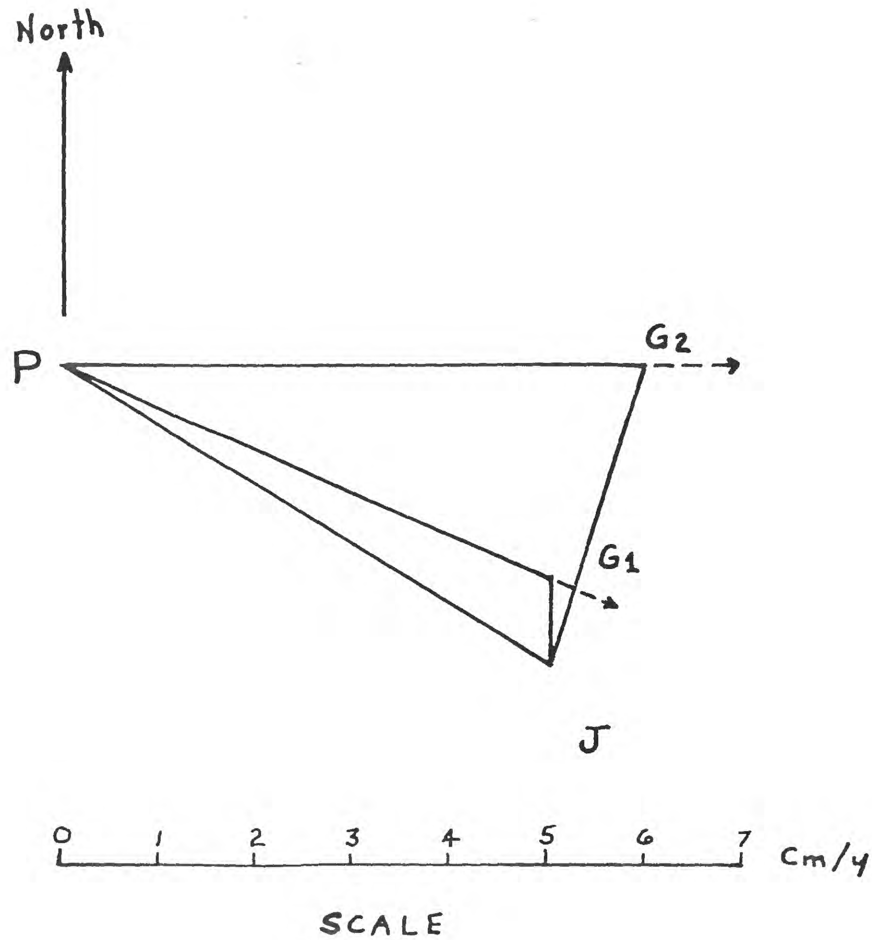

Figure 3. Plane vector representation of movement of Gorda plate (G), Juan de Fuca (J) and Pacific plate (P) at northern end of the Gorda ridge, assuming (G1) Gorda plate moves parallel to nearby Blanco fault, or (G2) Gorda plate moves parallel to Mendocino fracture zone.

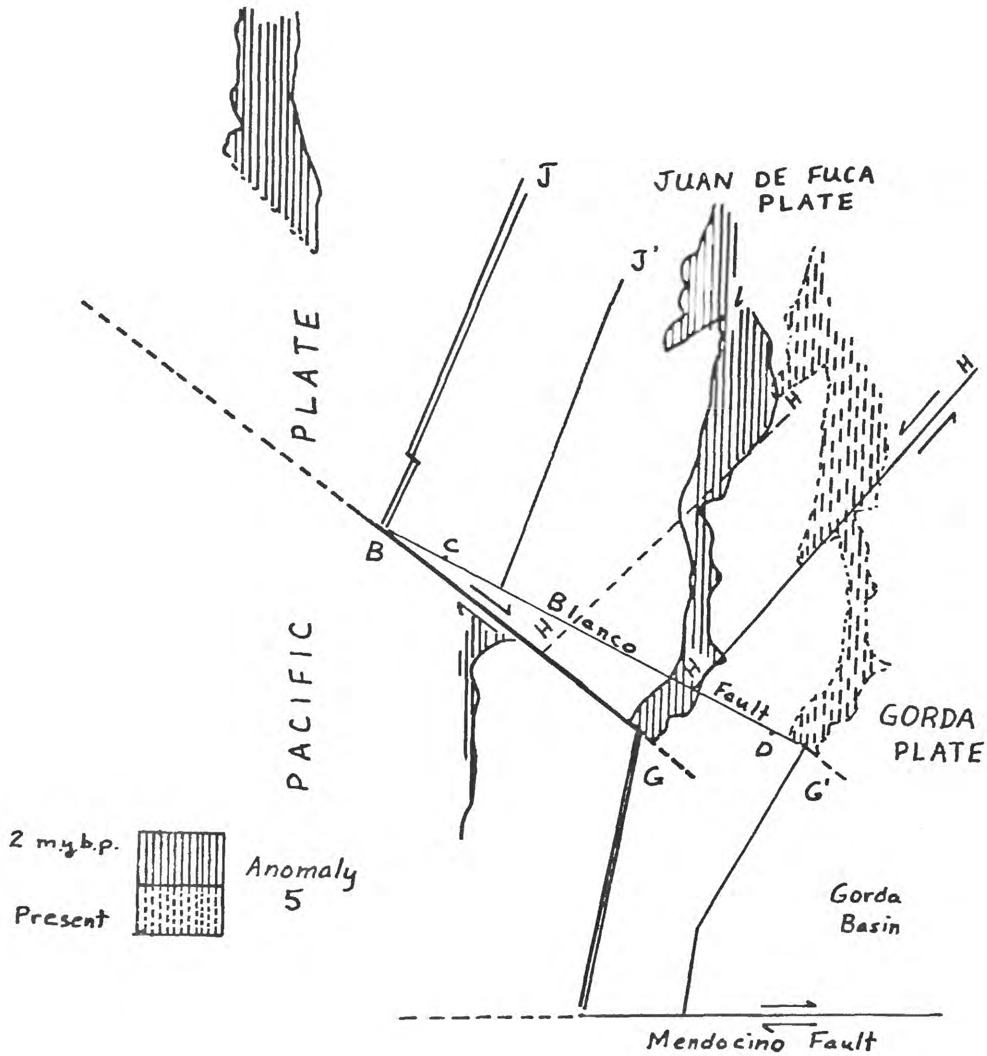

Figure 4. Reconstruction of Pacific-Juan de Fuca plate geometry 2 m.y. before present assuming movement of Gorda plate subsequent to that time was subparallel to Mendocino fault. North American plate ignored. At 2 Ma, Blanco fault connected ends of spreading ridges B and G. Anomaly 5 shown for reference. With Pacific plate fixed, spreading moves G to G', and Juan de Fuca plate breaks at HH, offsetting Anomaly 5 as shown. C is present intersection of Juan de Fuca ridge with Blanco, and D is present intersection of Gorda ridge with Blanco. Anomaly J, formed 2 m.y. ago in Juan de Fuca plate, moves to J' (present).

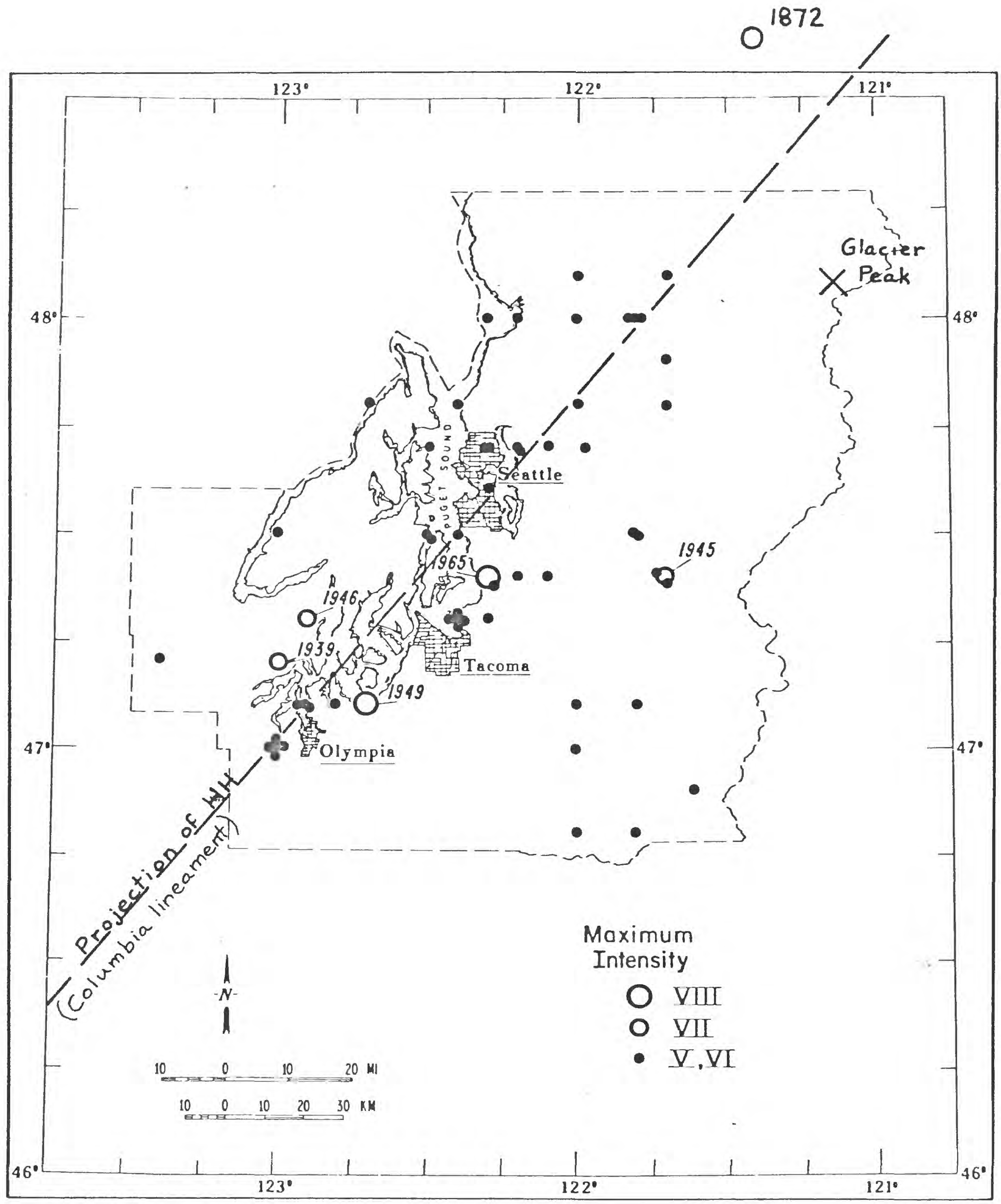

Figure 5. Epicenters of historical earthquakes with intensity greater than V (Modified Mercalli scale) in Seattle area (from U.S. Geological Survey, 1975). Projection of Columbia lineament, location of 1872 earthquake (from Malone and Bor, 1979) also shown.