Transform Faults, Oceanic Ridges, and Magnetic Anomalies Southwest of Vancouver Island

Abstract. *The San Andreas Fault and a large fault off British Columbia are interpreted as examples of the recently proposed "transform faults." They are joined by a short, isolated length of oceanic ridge striking N20°E, with an associated "window" of young crust. The displacement along these faults is estimated at 400 kilometers.*

In recent years much evidence has been found for large horizontal shear motions in the crust. Offsets have been noted across faults, across submarine fracture zones, and on lines of disturbance across magnetic anomaly maps. Similar contemporary motions are observed to accompany earthquakes. Two puzzling features are that many of the dislocations terminate abruptly and that recent seismic activity is often confined to short parts of fracture zones.

A recent paper (*1*) attempted to explain this anomalous behavior by pointing out that conventional discussions of fault mechanisms such as that given by Anderson (*2*) have tacitly assumed that the faulted medium is continuous and conserved, but if new crust is created on ridges and old crust is destroyed in trenches or mountains this assumption is not true, and other kinds of faults can be envisaged in addition to normal, thrust, and transcurrent types. If plates in the crust move horizontally relative to one another, a class of strike-slip faults called transform faults can exist which have a different behavior from conventional transcurrent faults.

On transcurrent faults shear motion continues indefinitely, but in transform faults it ends abruptly by transformation into extension across a rift or compression across a mountain belt or thrust. A fault which terminates suddenly in mid-ocean ridges at both ends may be called a ridge-ridge type of transform fault. Paradoxically, the offset of one ridge relative to another across a transform fault is not altered during the faulting as it would be by transcurrent faulting, and the motion of transform faults is in the reverse direction to that expected if the fault were regarded as transcurrent. The behavior of transform and transcurrent faults is compared in Fig. 1.

The San Andreas fault was cited as a possible example of a dextral, ridge-ridge, transform fault, and the great "marine dextral transcurrent fault" described by Benioff (*3*) off the British Columbia coast was spoken of as a transform fault of a different type. It is convenient to call the latter fault the Queen Charlotte Islands fault. The locations of the ends of these faults at A, B, C, and D in Fig. 2 have been taken as precisely as possible from Benioff's figures 4 and 16 and are given in my Table 1 with the locations of some points in my Fig. 3. It was suggested that a short length of mid-ocean ridge joins the adjacent ends, B and C, of these two faults. It will be convenient to call this the Juan de Fuca Ridge and to use the term *ridge* for all mid-ocean ridges including the East Pacific Rise.

The motion of the floor of the Pacific northward relative to North America (*3–5*) should have created new young crust in the vicinity of the Juan de Fuca Ridge off Vancouver Island and Washington.

Menard (*6*) has already identified a young mid-ocean ridge in this area. The new interpretation does not change its location, but differs in two respects. Menard regarded the ridge as the northern end of the East Pacific Ridge with a northwest strike, but the Juan de Fuca Ridge is here considered to be an isolated ridge with a strike of N20°E, separate from the East Pacific Ridge off Southern California, although linked to it by the San Andreas transform fault.

The map of total magnetic field anomalies published by Raff and Mason (*7*) covers the region of the Juan de Fuca Ridge, and any interpretation should obviously be compatible with the magnetic observations. In order to follow the discussion, one should take the original anomaly map and superimpose on it the lines shown in Fig. 3.

Raff and Mason had realized that this region is unusual, for they stated that "most of the area on the map from 41°N lat. to 49°N lat. looks like angular pieces of crust that have slipped and rotated with respect to neighboring pieces." The block stands out for which the points P, B′, Q, R, C′, S, and P have been chosen as the boundary. This block has intense parallel anomalies bounded by steep gradients. The anomalies strike N20°E, whereas the usual strike in the rest of the mapped area is north-south. These anomalies are arranged symmetrically about the axis B′C′.

Although the choice of the boundary (and hence of the displacements) is subject to some uncertainty, the sides QR and SP of the block have been chosen to mark the limits of the
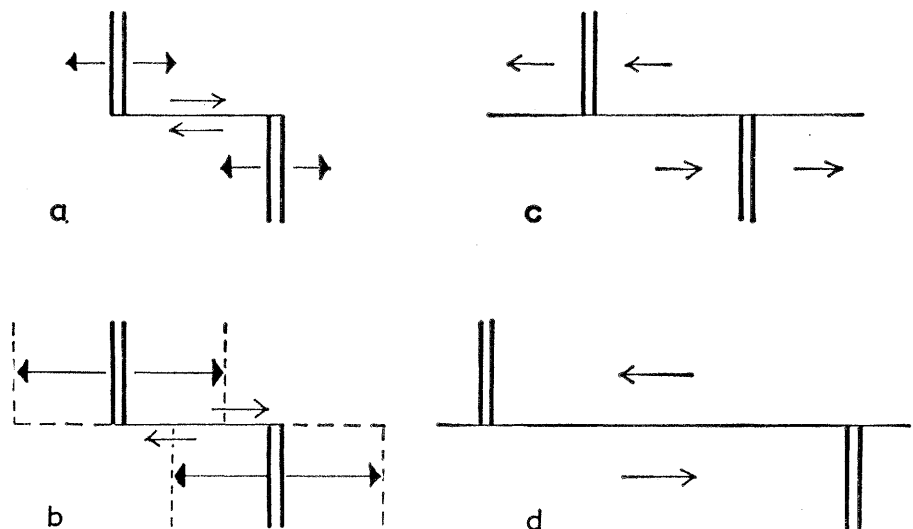

Fig. 1. (*a*) Dextral ridge-ridge type transform fault connecting two expanding ridges. (*b*) Fault shown in 1*a* after a period of movement. Note that motion has not changed the apparent offset. (*c*) Sinistral transcurrent fault offsetting a ridge, with offset in the same sense, but motion in the opposite sense to the transform fault in 1*a*. (*d*) Fault shown in 1*c* after a period of motion. Note that the offset has increased. Open-headed arrows indicate components of shearing motion. Solid-headed arrows indicate ocean floor spreading from the ridge axis.

anomalies which strike N20°E. They lie at equal distances of 175 km on either side of B′C′, which is the axis of symmetry.

This block may be a piece of mid-ocean ridge between two transform faults and B′C′ may be its central rift and axis. It meets the criteria for a ridge on the following bathymetric, magnetic, and seismic grounds.

1) Menard mapped the area as part of a mid-ocean ridge. Although he chose a northwesterly strike for the ridge, he marked the line B′C′ on his large physiographic map by linear topographic ridges and valleys, and he wrote that the region "shows strong evidence of comparative youth" and that it is divided into "long, thin ridges which trend northeast or north" (5).

2) On the magnetic anomaly map the line B′C′ is parallel to the local trend of the anomalies (N20°E) and has been chosen because the anomalies are symmetrically arranged with it as an axis.

3) Within the limits of error in locating faults from scattered earthquake epicenters, the points B′ and C′ can be taken to represent the bounds of earthquake activity instead of B and C. At B′ and C′ the transform faults end by being transformed into the ridge. The cause of the accompanying change in seismicity will be discussed later.

4) Menard also reported high heat flows in an area immediately to the south.

The rough bilateral symmetry exhibited in the magnetic anomalies seems to follow as a corollary of Vine and Matthews' (8) proposal that the floor of the ocean is built of strips of lavas and intrusives alternately magnetized with normal and reversed po-

larity. Because ocean basins have a rough bilateral symmetry shown, for example, in the symmetrical relationships of some pairs of ocean islands and ridges (9), it is to be expected that the strips on the ocean floor should also be formed at an approximately uniform rate on each side of the rift. At any time the pair of strips being formed along the rift would be made of similar rocks and would be magnetized in the same field, and so should give similar anomalies. It would be a matter of great interest if samples could be obtained from these anomalies and their age and direction of magnetization measured and compared with those from surrounding regions having a different strike. The magnetic anomalies are discussed further in an accompanying report (10).

The position of the major faults is a matter of interest. Concerning the position of the Queen Charlotte Islands fault, nothing can be added to Benioff's proposal except that it has been slightly shifted to end at B′ instead of B. The inactive extension B′Q is required if the concept of transform faulting is correct. Benioff's position for the fault and the location of its extension do not conflict with the magnetic anomalies.

Benioff and Tocher (11) have suggested that the northern, submarine extension of the San Andreas fault is a straight extension continuing the strike of the fault as measured on land near San Francisco, but the location of epicenters is too scattered to make this certain, and bathymetric and magnetic maps lend no support to that view. On the other hand, Shepard and Emery (12) followed Matthews in considering the extension to bend and follow the coastline closely from Point Arena (38°50′N lat.) to Punta Gorda (40°15′N lat.) where they were so much impressed by the Gorda submarine escarpment that they suggested that the fault turned to follow it out to sea. Menard and Dietz (13) have now associated the Gorda escarpment with the Mendocino fracture zone which may be part of a different and older system. On the other hand an equal deflection of the fault to the right would swing it along the continental slope as far as point W, whence a curved disturbance in the anomaly map extends to Y where it joins a strong, straight disturbance which continues toward C′ as far as the edge of the mapped anomalies. Exactly the

same path is clearly shown on Menard's physiographic map and in the south fits Shepard and Emery's Chart IV. The trace follows part of Menard's Cascadia Channel. The epicenters plotted by Tocher and shown on Fig. 3 fit this curved line better than a straight one. Therefore, on magnetic, bathymetric, and seismic evidence this line is proposed as the extension of the San Andreas fault. Its present activity ends at C′, but, if it is a transform fault, an inactive trace should extend farther, and C′S has been selected for that part for reasons which follow. An obvious precedent for re-
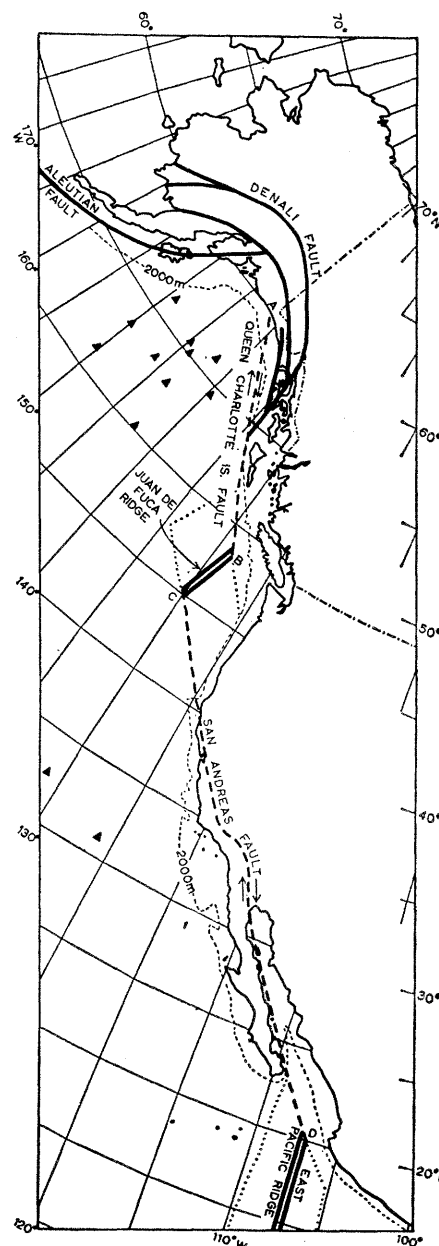

Fig. 2. Sketch map showing the location of some of the principal faults off the west coast of North America. The black triangles are guyots. [After Benioff and St. Amand and Wilson]

garding the whole submarine part of the San Andreas fault as curved is the curvature of the fault in Southern California.

The width of the Juan de Fuca Ridge normal to B′C′ is approximately 350 km but the total displacement on the San Andreas fault since the forma-tion of the Juan de Fuca Ridge should be measured in the average direction of the strike of the fault. According to Benioff this is a line joining Point Arena to C. This displacement is 400 km (250 miles). This estimate is nei-ther precise nor dated, but it lies with-in the limits proposed by Hill and Dibblee (14), who suggested 175 miles since early Miocene with more doubt-ful possibilities of 225 miles since Late Eocene, 320 miles since Cretaceous, and 350 miles since Precambrian, and by Crowell (15) who gives a displace-ment of 175 for Oligocene rocks and perhaps "still more" for older ones. The displacement of the Queen Char-lotte Islands fault parallel to its aver-age strike would also be about 400 km.

In Fig. 3 some other areas are marked by irregular anomalies. Their pattern in the area RC′YR led to the suggestion that SC′, the extension of the San Andreas fault, should be curved. RC′ is a mirror image of SC′ about B′C′, the axis of symmetry, and RY is displaced from SC′. No other detailed discussion of these com-plex patterns will be attempted, but four factors seem likely to have con-tributed to the formation of these ir-regular areas. (i) Raff and Mason's map indicates other faults which have not been discussed here. (ii) The San Andreas fault is curved. (iii) R. G. Mason has pointed out to me in pri-vate discussion that other short lengths of ridge may exist and that they may have given rise to additional new crust. (iv) The geometry of transform faults and ridges is such as to allow, and in some cases to require, the for-mation of new crust associated with the faults in addition to that on the ridge. This geometry may also help to explain the distribution of earthquakes.

In Fig. 4a two transform faults join two ridges orthogonally. In this case the faults can fail by pure shearing, and the opening of the rifts along the ridges can be purely tensional. Break-ing in tension is quite different from breaking in shear and presumably gives rise to different and much weaker forms of earthquakes. With this type of pattern mid-ocean ridges might show seismicity only where crossed by fracture zones (that is, transform faults).

In Fig. 4, b and c, two transform faults join two ridges at obtuse angles. In the case represented by Fig. 4b the tensional forces parallel the faults, which are therefore pure shears, but the ridge has a motion which com-bines rifting and shearing. In this case the pattern of earthquakes over the ridge and the faults would not be so distinct and all parts of a long mid-ocean ridge might have some earth-quakes with a greater concentration on the fracture zones.
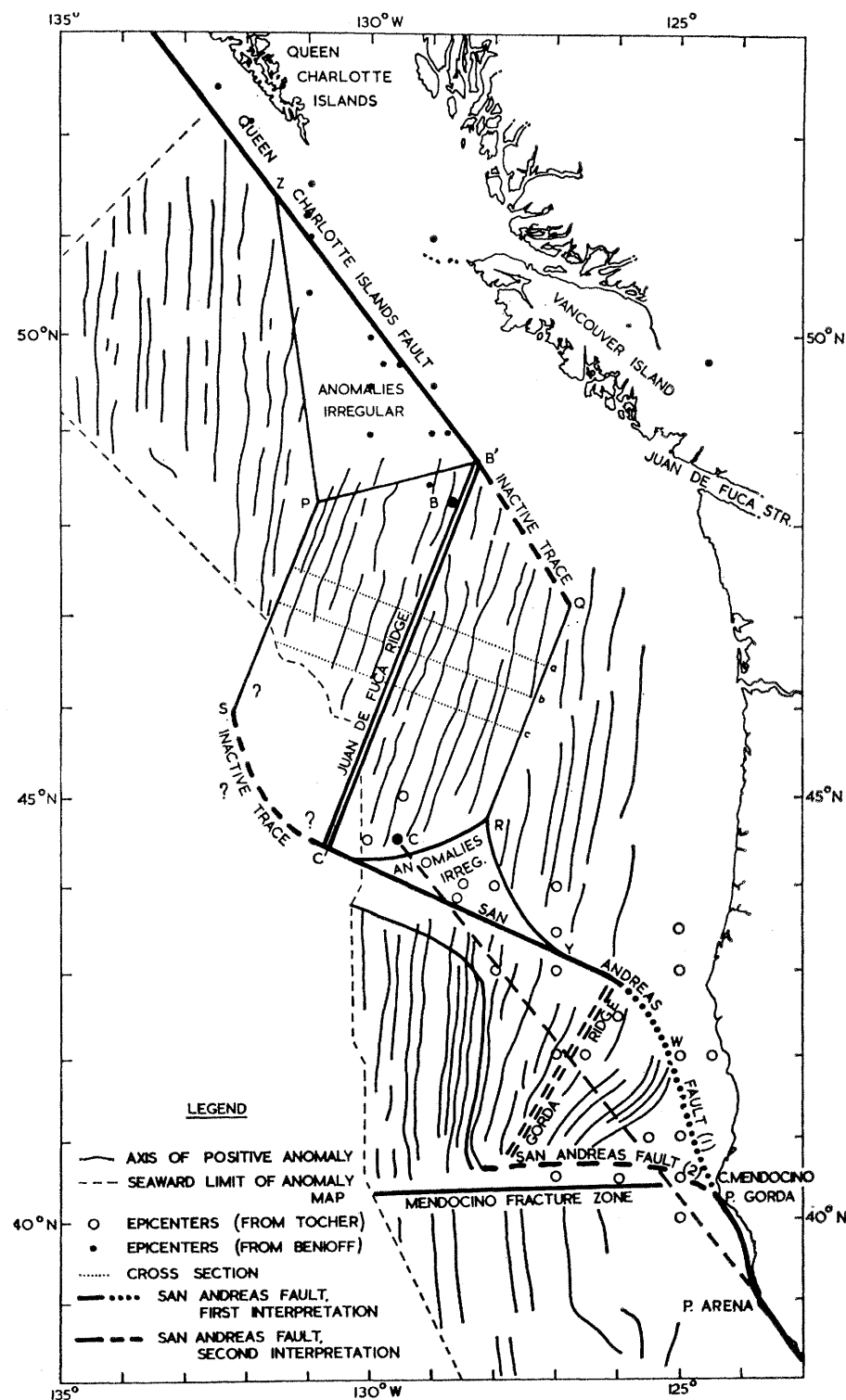

Fig. 3. Sketch map showing the proposed interpretation of the Juan de Fuca Ridge with its relation to other faults and the magnetic anomalies. It should be compared with the map of anomalies in Raff and Mason (7).
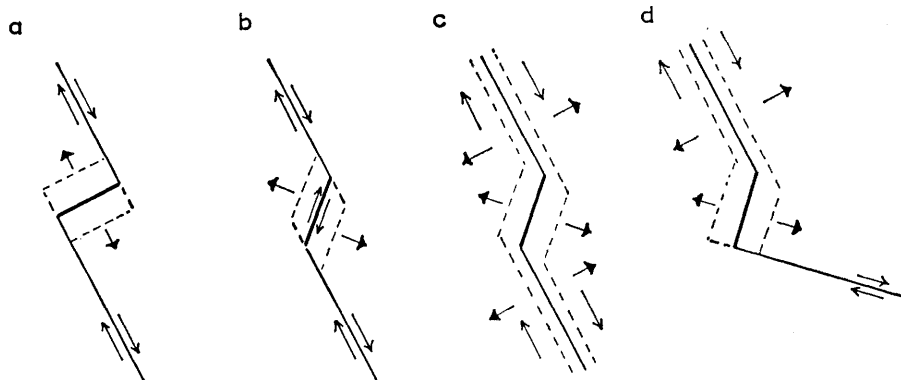
Fig. 4. Diagram illustrating variations in the transform of mid-ocean ridges to transform faults, depending upon the angles of junction and directions of motion.

14. M. L. Hill and T. W. Dibblee, Jr., *Bull. Geol. Soc. Am.* **64**, 443 (1953).
15. J. C. Crowell, *Intern. Geol. Congr. 21st, Rept. Session,* (1960), part 18, p. 45.
16. E. H. Bailey, W. P. Irwin, D. L. Jones, *Calif. Div. Mines Geol. Bull. 183* (1964).
17. H. H. Hess, in *Colston Symposium on Marine Geology* (University of Bristol, Bristol, England, in press).

In Fig. 4c the tensional forces are perpendicular to the ridge producing purely tensional rifting across it which requires the faults to open as well as to shear. In this case there could again be a complete lack along the ridge of any earthquakes due to shearing. It is suggested that this is an idealization of the case which we have been discussing. It can account for the lack of seismicity along the ridge, the uniformity of the anomalies, and the existence of areas of irregular anomalies. Obviously a full explanation of the irregular anomalies will require more consideration, but the motion in Fig. 4c agrees with that favored by Bailey, Irwin, and Jones for the San Andreas fault (*16*).

Figure 4d illustrates a still more complex case in which neither are the transforms between faults and ridges orthogonal, nor are the faults parallel with one another. Transform junctions at acute angles would introduce compression along faults as well as shearing. In practice many more complexities can be expected.

If this interpretation is correct the whole floor of the Pacific Ocean from the East Pacific Ridge has been moved northward towards the Aleutian Trench, bearing the Mendocino and other, older fracture zones with it. Therefore, they are not related to structures on the continents with which they happen at present to be aligned.

R. G. Mason, from a study of magnetic anomalies, and H. H. Hess, from a consideration of measured heat flow, have both independently proposed to me in discussion that there may be another young and growing ridge between the Mendocino fracture zone and the Juan de Fuca Ridge. This neat solution also explains the epicen-

ters along the Mendocino and Gorda escarpments (which are not shown by Tocher or in Fig. 3). It has been added as an alternative in Fig. 3 and named the Gorda Ridge, but does not affect the other arguments.

The manner in which seismic activity in the eastern Pacific is concentrated on those parts of the fracture zones lying between apparently offset lengths of the East Pacific Ridge suggests that the Mendocino and other fracture zones parallel with it may themselves be transform and not transcurrent faults, as has heretofore been supposed. If this is so, the offsets in the patterns of magnetic anomalies are not due to displacement by faulting, but are an inheritance from the original shape of the first rift in the floor of the Pacific with which they are connected. According to Menard (*6*), this is the East Pacific Ridge. According to Hess (*17*), it is the Darwin Rise. In either case a new interpretation is needed.

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References and Notes

1. J. T. Wilson, *Nature* **207**, 343 (1965).
2. E. M. Anderson, *The Dynamics of Faulting* (Oliver and Boyd, Edinburgh, ed. 2, 1951).
3. H. Benioff, in *Continental Drift*, S. K. Runcorn, Ed. (Academic Press, New York, 1962), chap. 4.
4. P. St. Amand, *Bull. Geol. Soc. Am.* **68**, 1343 (1957).
5. H. W. Menard, *ibid.* **66**, 1149 (1955.)
6. ———, *Marine Geology of the Pacific* (McGraw-Hill, New York, 1964).
7. A. D. Raff and R. G. Mason, *Bull. Geol. Soc. Am.* **72**, 1267 (1961).
8. F. J. Vine and D. H. Matthews, *Nature* **199**, 947 (1963).
9. J. T. Wilson, *ibid.* **198**, 925 (1963).
10. F. J. Vine and J. T. Wilson, *Science*, this issue.
11. D. Tocher, *Bull. Seismol. Soc. Am.* **46**, 165 (1956).
12. F. P. Shepard and K. O. Emery, *Geol. Soc. Am. Spec. Papers 31* (1941).
13. H. W. Menard and R. S. Dietz, *J. Geol.* **66**, 266 (1952).

Magnetic Anomalies over a Young Oceanic Ridge off Vancouver Island

Abstract. *The recent speculation that the magnetic anomalies observed over oceanic ridges might be explained in terms of ocean-floor spreading and periodic reversals of the earth's magnetic field may now be reexamined in the light of suggested reversals during the past 4 million years and the newly described Juan de Fuca Ridge.*

Surveys of the earth's total magnetic field have been made along closely spaced lines over large areas in the northeastern Pacific Ocean (*1*). These show a surprisingly regular, linear pattern of anomalies, often hundreds of kilometers long and tens of kilometers wide, and usually aligned approximately north-south. Vine and Matthews (*2*) have suggested that these anomalies, together with the central magnetic anomaly observed over certain oceanic ridges, might be explained in terms of ocean-floor spreading (*3*) and periodic reversals of the earth's magnetic field. The idea proposes that as new oceanic crust is formed over a convective upcurrent in the mantle, at the center of an oceanic ridge, it will be magnetized in the ambient direction of the earth's magnetic field. If the earth's field reverses periodically as ocean-floor spreading occurs, then successive strips of crust paralleling the crest of the ridge will be alternately normally and reversely magnetized, thus producing the linear anomalies of the northeastern Pacific. These anomalies are not obviously parallel to any active oceanic ridge, but it seems