CHART OF ANOMALOUS TOTAL MAGNETIC INTENSITY FROM AN ARBITRARY DATUM

The contour interval is 0.5 milligauss. The ship's tracks are shown with light lines. The tracks run largely east-west.

VACQUIER *ET AL.*, PLATE1
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Short Notes

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HORIZONTAL DISPLACEMENTS IN THE FLOOR OF THE NORTHEASTERN PACIFIC OCEAN

Abstract: A total magnetic intensity survey in the northeastern Pacific Ocean revealed a north-south pattern of magnetic anomalies, which is cut through by the Murray, the Pioneer, and the Mendocino faults. The amount of slip along these faults is measured by fitting the magnetic anomaly pattern across the faults. The combined left-lateral displacement across the Mendocino and the Pioneer faults is 1420 km.

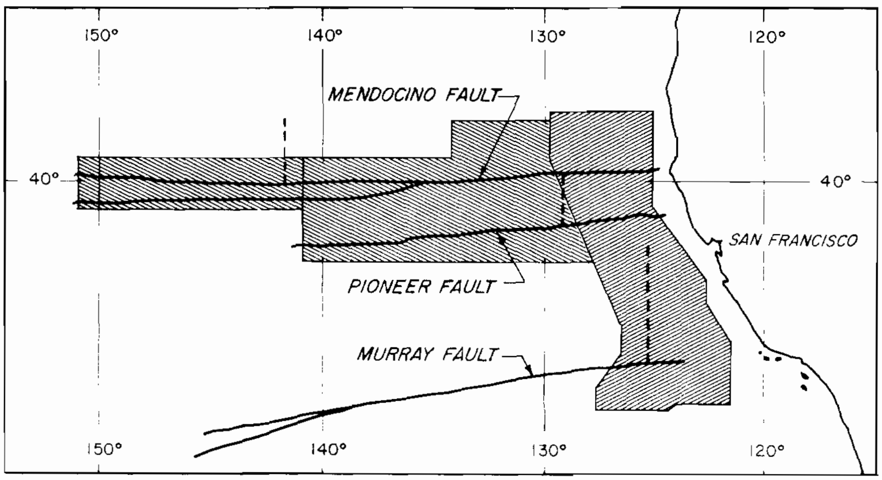

Figure 1. Location of the magnetic survey relative to the Mendocino, Pioneer, and Murray fractures. The dashed vertical line represents the axis of a north–south magnetic anomaly which was continuous before slipping started.

Displacements along strike-slip faults on land have been discussed in the literature. Kennedy (1946) has demonstrated a strike-slip displacement of 65 miles (104km) on the Great Glen fault in Scotland. According to Wellman 1952 the Alpine fault in New Zealand may have slipped 300 miles (480 km). The work of Hill and Dibblee (1953) suggests a right-lateral displacement of 175 miles (320 km) along the San Andreas fault in California since early Miocene time, and 350 miles (640 km) since the Jurassic.

This note presents evidence for displacements of comparable magnitude along some of the transcurrent faults of the northeastern Pacific Ocean.

The geomagnetic surveys first conducted by the Scripps Institution of Oceanography aboard the Coast and Geodetic Survey ship PIONEER and later extended by cruises of Scripps ships have revealed in the eastern Pacific Ocean magnetic anomalies with north–south lineation which are cut by the transcurrent east–west striking faults described by Menard (1959).

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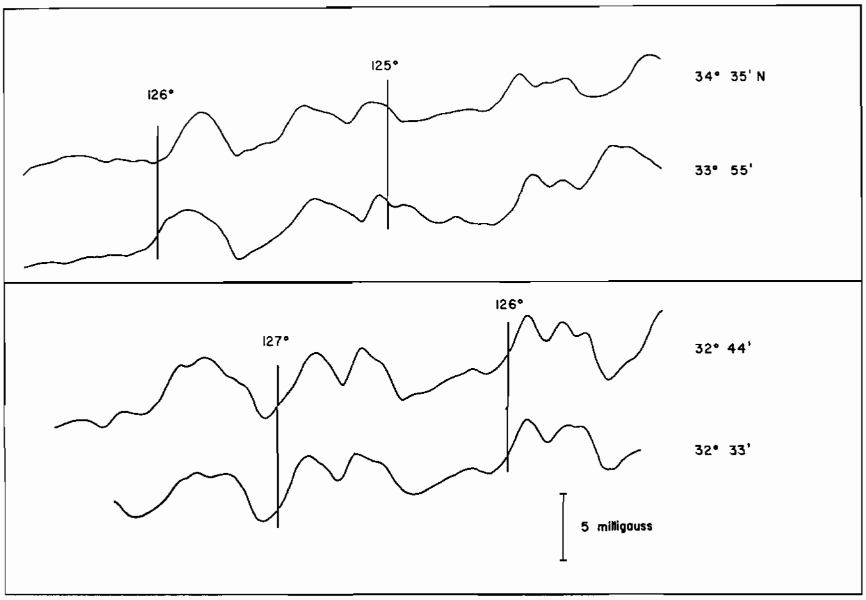


Figure 2. Profiles of anomalous total magnetic intensity north and south of the Murray fault suggesting a right-lateral slip of 84 nautical miles (154 km)

The surveyed area is shown on Figure 1. By matching the magnetic grain north and south of a fault the direction and magnitude of horizontal slip can be measured. This was first done across the Murray fracture zone (Menard and Vacquier, 1958; Mason, 1958) where a right-lateral displacement of 84 nautical miles (154 km) was interpreted (Fig. 2). The displacement along the Murray fault zone suggested an investigation of a possible displacement across the Pioneer fault 300 nautical miles to the north. The cruise of the R/V Horizon in December 1958, undertaken for the express purpose of looking for this displacement, found a left-lateral slip of roughly 3° in longitude (Vacquier, 1959). The cruises of the R/V Spencer F. Baird in August 1959 and April 1960 extended the magnetic survey to the west on both sides of the Pioneer and the Mendocino faults.

The fluxgate ASQ-3A magnetometer was used on all cruises except the last, which employed a proton free-precession magnetometer. The original data are plotted as a magnetic contour chart on Plate 1. Its eastern edge joins the western edge of the contour chart of Mason and Raff (1961, Pl. 1). The normal geographic change of the total magnetic intensity was estimated by smoothing Magnetic Chart No. 1703 published by the Hydrographic Office of the U. S. Navy. Ground-wave Loran positions taken every half hour supplemented by astronomic sights were used for locating the ship. West of 134° W. long., the reception of the ground wave becomes uncertain at night because of the interference of the sky wave. The dead-reckoned course during the night was corrected in the morning as soon as Loran signals became identifiable again. West of 140° W. long. astronomic sights and dead reckoning were the only means of establishing the ship's position. From the spread of the fixes parallel to the track, it is estimated that the average departure of the fixes from the true positions was between 1 and 2 miles. Since short-time fluctuations of the geomagnetic field were not removed from the data, fluctuations of 0.5 milligauss, the contour interval, can originate from this cause during daylight hours. Throughout the two expeditions the ship's average speed was 11 knots.

On Figure 3 profiles of the total magnetic intensity are plotted along the long east-west tracks. The profiles are drawn in their actual positions on the map. Their eastern portion extends across the map of Plate 1 of Mason and Raff (1961). The locations of the Pioneer and Mendocino faults are indicated on Figure 3. The magnetic pattern in the fault zones is too complex to permit contouring with the sparse data. In fact, the contouring of the western portion of the map of Plate 1 depends on the assumption that the magnetic trends are directed north–south as they are on the eastern half of the map where the control is adequate.

East–west magnetic intensity profiles will now be examined for fit of the magnetic grain across the faults without speculation as to origin of the anomalies. The chart of Plate 1 and the profiles of Figure 3 show that as a rule the anomalies strike N.–S. $\pm$ 10°. Occasionally a northwest–southeast trend is observed as well as circular anomalies in the fault zones. The correlation for the measurement of slip depends on the continuity of the north–south trending anomalies. Because the elongate anomalies occasionally terminate where there is no major fault, correlations across the faults cannot be perfect everywhere.

Figure 4 represents our interpretation of the magnetic data as slips along the Pioneer and Mendocino faults. The profiles north of Lat. 38°45′ N. have been translated eastward 3°05′, which amounts to 145 nautical miles (265 km). The profiles north of Lat. 40° N. have been translated eastward by an additional 13°42′ (640 nautical miles or 1160 km). The total displacement across both faults is thus 780 nautical miles (1425 km). The correlation of some of the magnetic features across the faults is shown on Figure 4 by dashed lines. To make the goodness of fit more obvious, the northernmost profile of Figure 4 has been drawn again as a dotted line between the profiles south of the Pioneer fault.

Possible origins for the observed magnetic-anomaly pattern are discussed by Mason (1958) and by Mason and Raff (1961). There is of course an infinity of possible distributions of magnetic rocks that will yield the same magnetic anomaly. However, certain types of distributions can be excluded because they would require the presence of rocks possessing unreasonable magnetic properties. To have a reasonable magnetic-polarization contrast, the bodies of rock causing the north-south trending anomalies should be at least 2 km thick. Some of these anomalies are sufficiently sharp to place the top of the magnetic rock no deeper than 6 km from sea level (1.5 km below the sea floor). A likely origin of the magnetic pattern is the intrusion of more strongly magnetic material into the basaltic crust. That the large magnetic anomalies are not directly related to the known topography is demonstrated by the anomaly caused by the 200-fathom relief of the Pioneer Ridge which is no more than one-tenth of the anomalies due to intrusives or extrusives in this fault zone, some of which are as large as 8 milligauss. Plate 1 shows a crossing of the Pioneer Ridge centering at 38°40′N. lat., 130°25′W. long., where no large magnetic anomaly was encountered.

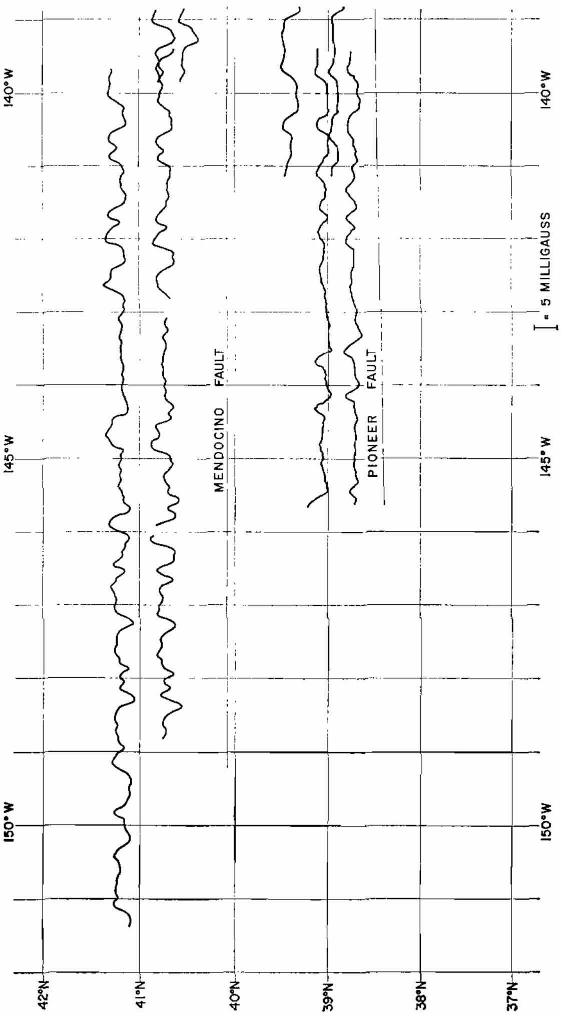
Evidence of the extension of the oceanic faults into the continent is weak and contradictory. Its lack of definiteness compared to that of the magnetic data in the ocean suggests that the geotectonics of the continental crust are influenced by the slips along the transcurrent oceanic faults without directly taking part in these displacements. Thus, the geologic expression of the Mendocino fault is that it lines up with the southern termination of the Cascades Range. From the geophysical point of view, James Affleck of the Gulf Research and Development Company (Personal communication) writes:

"There is evidence from magnetics that the Mendocino feature may extend eastward from the coast for at least 100 statute miles (160 km). There is no direct evidence of horizontal displacements, but strong lineaments and changes of magnetic character are present."

Nothing on land corresponds to the Pioneer fault. This fault may be regarded as a sliver of the Mendocino fault zone.

The Murray fault to the south marks the northern boundary of the drowned Basin and Range topography of the continental borderland (Shepard and Emery, 1941). South of the Murray fault the continental borderland shows evidence of right-lateral strike-slip faults parallel to the San Andreas fault, suggesting that the latter belongs to a fault zone a part of which is under water. On the continent the Murray fault lines up with the Channel Islands and the Transverse Ranges of California, where all horizontal displacements measured by geological methods are left lateral. This direction is opposite to the 154-km right-lateral slip found in the deep ocean by the magnetic survey. However, all magnetic and bathymetric evidence of the Murray fault stops east of 124°W. long., making a gap of 4° between the eastern end of this fault at sea and the Channel Islands.

The presence of this gap makes it possible to reconcile the opposite directions of displacement by assuming an absence of genetic relationship between the displacements at sea and on land. This explanation may be unlikely, but it follows directly from the assumption,


140°W
145°W
150°W
42°N
41°N
40°N
39°N
38°N
37°N
MENDOCINO FAULT
PIONEER FAULT
= 5 MILLIGAUSS

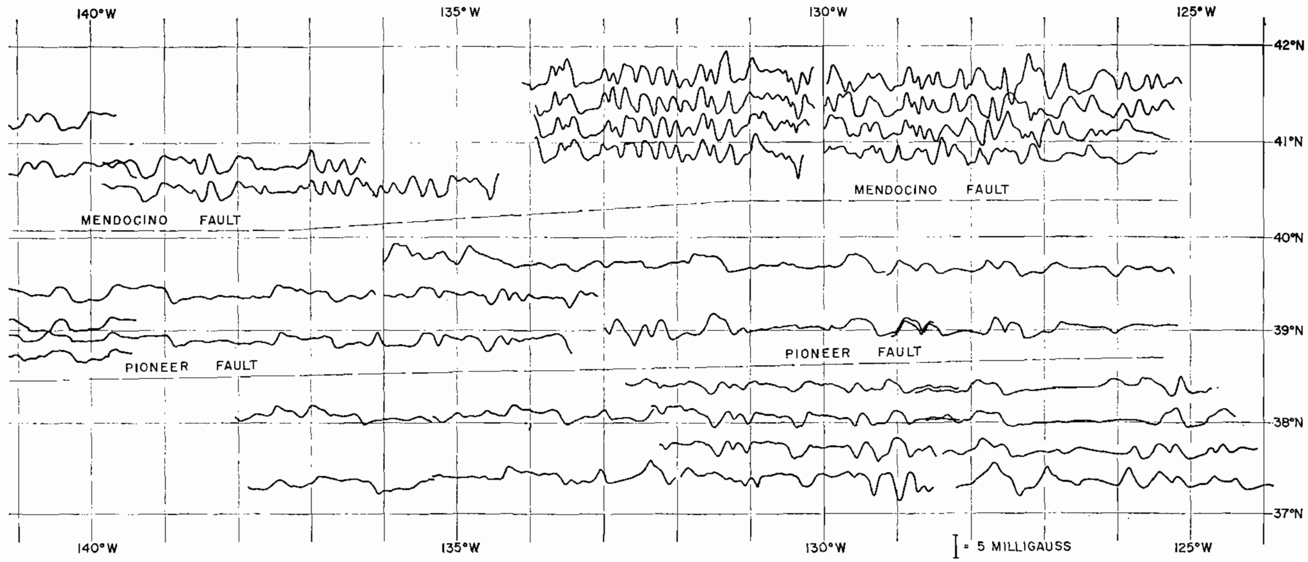


Figure 3. Profiles of anomalous total magnetic intensity along the long east-west tracks. The location of the profiles is approximately that of the corresponding tracks of Plate 1

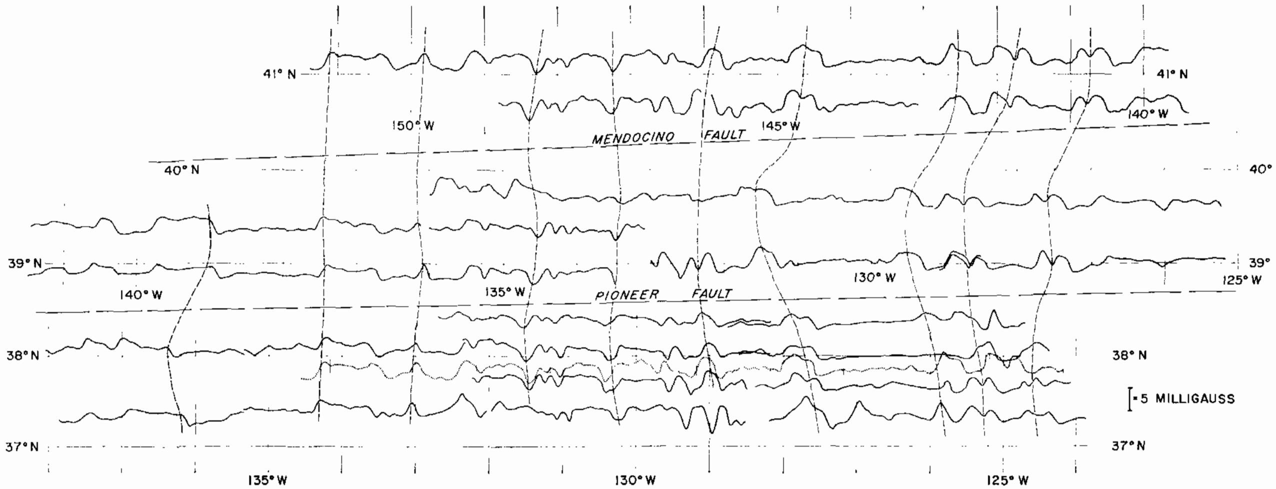


Figure 4. Interpretation of the anomalous total magnetic intensity profiles of Figure 3 in terms of left-lateral displacement of 265 km along the Pioneer fault and 1150 km along the Mendocino fault.

which again may be unlikely although still possible, that the displacements along oceanic faults propagate into the continent at the time they happen. If this time is ancient, both magnetic and geologic evidence for the slips gets largely wiped out on the continent. Furthermore, geologists do not usually look for slips of 1400 km. The absence of definite extension of the oceanic faults into the continent can be explained by the motion along the San Andreas fault zone which separates the ocean from the continent. The land east of the San Andreas fault is now slipping to the south at the rate of 5 cm per year. Since the Jurassic it has moved 560 km (Hill and Dibblee, 1953), roughly the distance between the Mendocino and the Murray faults. There is no need to be disturbed about the discrepancy between the displacements of the Murray fault at sea and the faults on land at about the same latitude unless one insists that the oceanic faults are younger than the San Andreas fault. This is contrary to present-day evidence; the San Andreas fault is seismically active, whereas the oceanic faults are seismically dead west of 130° W. long. Also, mild heat-flow anomalies seem to cross the Mendocino escarpment as though it did not exist (R. P. Von Herzen, personal communication), indicating quiescent conditions in the last 100,000 years at least.

Recalling again that the present discussion has postulated without proof the extension of the oceanic displacements into the continent at the time of their formation, a limit to their age is set by the age of the San Andreas fault—namely, they must have stopped moving some time in the Cretaceous. At 1 cm per year, the average rate of motion along the San Andreas fault, the slip along the Mendocino fault must have taken another 100 million years. The rocks that give us the magnetic lineations that permit us to measure the lateral displacements along the transcurrent faults are thus still older and must have been laid down in Paleozoic time or earlier. They have not been disturbed appreciably since that time either mechanically or by intrusions or extrusions, or we would not have been able to read the magnetic record of the motions. Thus, except for the motions along the transcurrent faults, it is likely that the floor of the eastern Pacific Ocean between 30° and 45°N. lat. has been relatively quiescent since some time in the Paleozoic. This interpretation could be directly confirmed by dating paleontologically and geochemically the material from a deep boring in the ocean floor.

If the motions along oceanic faults do not propagate into the continent at the time of their occurrence, then nothing can be said about their age, and the preceding discussion is discarded. It can be imagined that somehow the oceanic crust carrying the magnetic pattern can slip under the continental mass without disturbing appreciably the continent's geology and isostasy. The oceanic crust would be depressed under the continent, which would cause smoothing out of the geomagnetic field as noted by Heezen (Heezen and Tharp, 1959) in the Atlantic Ocean as one proceeds shoreward over the continental slope and shelf. The same happens along the west coast of North America as shown by unpublished observations by workers at the Scripps Institution of Oceanography, except that the band of smooth field is much narrower along the Pacific margin, as one would expect it to be.

The discovery of slips of the order of 100 km in the ocean floor suggests looking for such displacements on the continents by reviewing geological and geophysical evidence. As a start, James Affleck (Personal communication) has examined for that purpose over 1 million square miles of aeromagnetic surveys. He found that there are numerous magnetic trends related to major tectonic features. Some of these can be followed for several hundred miles. In addition, offsets in anomaly-trend systems commonly suggest horizontal displacements but generally only of the order of 10 miles. In general, geomagnetic measurements indicate that the crust is more complex in continental areas than under the oceans. In evaluating the evidence from land magnetic surveys one should remember that surveys for oil exploration are confined to sedimentary basins.

The displacements along strike-slip faults in the ocean floor are thus of the same magnitude as the distances through which continents have been presumed to drift to accommodate physiographic and paleomagnetic data. Except for Carey (1958), who invokes a several-fold expansion of the whole Earth, continents are pictured in the literature as rigid plates drifting without distortion through the viscous ocean floor. Now we have evidence for the rigidity of the upper part of the oceanic crust that carries the magnetic pattern, which is just as good as the evidence for the rigidity of continents exemplified by the fit obtained by Carey (1958) between the coasts of Africa and South America along the 2000-m isobath. Since it is most unlikely that the magnetic or the physiographic correlations are accidental, the resolution of this paradox will be an important advance in geophysics.

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References Cited

Carey, S. Warren, 1958, Continental drift: A Symposium: Univ. Tasmania, Hobart, Tasmania, p. 177–355

Heezen, B. C., and Tharp, M., 1959, Floors of the oceans I: North Atlantic; Geol. Soc. America Special Paper 65, 122 p., map

Hill, M. L., and Dibblee, T. W., Jr., 1953, San Andreas, Garlock, and Big Pine faults, California: Geol. Soc. America Bull., v. 64, p. 443–458

Kennedy, W. Q., 1946, The Great Glen fault: Geol. Soc. London Quart. Jour., v. 102, p. 41–76

Mason, R. G., 1958, A magnetic survey off the west coast of the United States between Latitudes 32° and 36°N and Longitudes 121° and 128°W: Geophys. Jour., v. 1, p. 320–329

Mason, R. G., and Raff, A. D., 1961, Magnetic survey off the west coast of North America, 32° N. to 42° N.: Geol. Soc. America Bull., v. 72, p. 1259–1266

Menard, H. W., 1959, Minor lineations in the Pacific Basin: Geol. Soc. America Bull., v. 70, p. 1491–1496

Menard, H. W., and Vacquier, V., 1958, Magnetic survey of part of the deep sea floor off the coast of California: Office of Naval Research, Research Reviews, June, p. 1–5

Shepard, F. P., and Emery, K. O., 1941, Submarine topography off the California Coast: Geol. Soc. America Special Paper 31, 171 p.

Vacquier, V., 1959, Measurement of horizontal displacement along faults in the ocean floor: Nature, v, 183, p. 452–453

Wellman, H. W., 1952, The Alpine fault in detail: New Zealand Jour. Science and Technology, sec B. v. 33, no. 5, p. 409–414

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