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East Pacific Rise: The Magnetic Pattern and the Fracture Zones

It is unlikely that the offsets in the magnetic anomaly pattern are caused by transcurrent faulting.

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Recent studies have revealed several important properties of magnetic anomalies over the mid-ocean ridge system (*1–3*). These anomalies may be conveniently divided into "axial anomalies," which are found over the axial zone of the ridges, and "flank anomalies," which exist over the ridge flanks. The axial zone of the ridges is characterized either by a single large anomaly or by a very striking pattern consisting of several anomalies of nearly constant wavelength, the amplitude being greatest at the crest and decreasing symmetrically on either side (*3*).

Linearity of the anomaly pattern over the axial zone of a ridge appears quite pronounced in areas where the ridge is not intersected by closely spaced fracture zones. The profiles of Fig. 1, from an article by Heirtzler *et al.* (*4*), shows strikingly the linearity of the multiple anomaly pattern over the axial zone of the Reykjanes Ridge (southwest of Iceland). Note in particular the symmetry of the linear anomalies about the central maximum *A*. The axial anomalies of Fig. 1 stop at a shorter distance from the crest than is usual in such patterns. The small width of the axial magnetic pattern is probably related to the small width of the ridge in this region. The anomalies beyond *B* on either side of the crest are considered to be flank anomalies.

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The anomalies over the ridge flanks have longer wavelengths than the axial anomalies, show no diminution in amplitude away from the crest (in some cases there is actually an increase), and generally are not as regular in shape as the axial anomalies. It appears (*5*) that the flank anomalies are also linear, though their linearity is perhaps not always as pronounced as that of the axial anomalies. The longer wavelength (or perhaps one might more properly say the wider spacing) of the flank anomalies is associated with a wider spacing of the bodies that produce the anomalies and cannot be explained merely by the assumption that these bodies are at greater depths than the anomaly-producing bodies of the axial zone.

The relation between the anomaly trends and bathymetry is important. The flank anomalies, while trending parallel to the strike of the ridge and correlating with the regional topography, are quite independent of the local small-scale topography. The axial anomalies are also parallel to the strike of the ridge, and since, generally, the ridge crest topography is also parallel to the strike of the ridge, the axial anomalies can be said to follow the local topography, though they are not directly caused by it.

The similarity of the magnetic anomaly patterns over widely separated parts of the mid-ocean ridge system is remarkable. Any variation, from one crossing of the ridge to another, in the amplitudes of the anomalies recorded appears to be due largely to the variations in the direction and intensity of the earth's magnetic field (mainly related to changes in the magnetic latitude) and the variation in the strike of the ridge. We do not mean to imply that the ridge anomalies are apparent in every single profile across the ridge. Ridge-anomaly patterns tend to break down near the magnetic equator if the ridge trend is north-south because the amplitudes are apparently comparable to the "magnetic noise." They also break down near fracture zones and sometimes over regions of very rough topography.

In this article we do not go into details of the origin of the ridge anomalies. We merely note that the symmetry and linearity, as well as the trend of the anomalies parallel to the ridge strike, indicate that these anomalies are genetically related to the formation of the ridge. We also note that the difference in character of the axial and flank anomalies implies that they do not have identical origins. The flank anomalies are *not* axial anomalies at greater depths. Vine and Mathews (*1*) explain the ridge magnetic anomalies by invoking the "spreading floor hypothesis" of Hess and Dietz. However, we believe that the flankward diminution in amplitude of the axial anomalies and the difference in character between flank anomalies and axial anomalies make their hypothesis untenable, at least in its present form.

Other Properties of the Mid-Ocean Ridge System

The mid-ocean ridge system has other important properties, which we note briefly. Ewing and Heezen (*6*) first pointed out the globe-encircling nature of the mid-ocean ridge system and the close coincidence of earthquake epicenters with an axial valley over a large portion of this system. The ridge crest is offset in many places by fracture zones (*7, 8*), and earthquake epicenters on the fracture zones appear to lie largely between offset portions of the ridge-rise crest (*9*). Seismic refraction studies (*10–12*) have demonstrated that compressional wave velocities in the mantle underlying the axial zone are abnormally low, but that seismic velocities under the ridge flanks are normal. The crust under the ridge flanks is not thicker than that under the ocean basins, and the consequent conflict between results of the seismic refraction studies and gravity measurements is resolved by postulating that the anomalous mantle underlying the ridge axis extends below the normal mantle under the ridge flanks (*13*). The ridge crest also has, typically, high heat flow, while heat flow values for the flank are normal or low (*14*). (We have implied that the East Pacific Rise is part of the mid-ocean ridge system. This is generally accepted in spite of the non-median position of the East Pacific Rise.)

East Pacific Rise in Northeast Pacific

Figure 2 shows the similarity of two magnetic anomaly profiles obtained over widely separated portions of the mid-ocean ridge system (the South Mid-Atlantic Ridge and the Pacific Antarctic Ridge) and a profile obtained recently off British Columbia by the research vessel *Vema*. Off British Columbia the *Vema* traversed the northern portion of the Ridge and Trough province, which has been extensively surveyed by scientists of the Scripps Institution of Oceanography and the Navy Electronics Laboratory. Very high values for heat flow were obtained by Von Herzen (*15, 16*) just north of the Mendocino fracture zone between the continental slope and 130°W. In the same area Raitt (*7*) detected low mantle velocities under a thin crust. Measurements made west of 140°W showed normal mantle velocities and low or normal heat flow. Between 40° and 50°N the topography of the Ridge and Trough province consists of strikingly linear segments. A belt of epicenters roughly follows the topographic trends. Menard (*7, 11*) recognized these features as typical of a mid-ocean ridge crest. He further pointed out that the whole floor of the northeast Pacific Ocean slopes toward the west and is actually the western flank of the continuation of the East Pacific Rise.

When it is recognized that the Ridge and Trough province is actually the crest of the East Pacific Rise, the remarkable similarity between the three magnetic anomaly profiles of Fig. 2 is explained. The profile obtained over the South Mid-Atlantic Ridge on cruise 2 of the *Zapiola* was recorded at a magnetic latitude lower than that of the other two profiles, hence the anomalies have smaller amplitudes; otherwise the only important difference between these profiles is the sudden disappearance, in the *Vema* cruise-20 profile, of the ridge anomaly pattern at the beginning of the continental slope.

Vacquier *et al.* (*17*), Mason and Raff (*18*), and Raff and Mason (*19*) have presented extensive magnetic maps of this general area. The pattern that we have described—linear anomalies having large amplitudes and short wavelengths over the axial zone and longer wavelengths, over the flanks—may be recognized in their published maps and profiles for latitudes north of the Mendocino fracture zone. This pattern of parallel linear anomalies appears to continue as far west as the western edge of the East Pacific Rise. It has been followed by Vacquier westward to 170°W (north of the Mendocino fracture zone), where it apparently disappears. Peter and Stewart (*20*) have recently presented a magnetic anomaly map for the region between 45° and 55°N and 155° and 159°W which shows that this pattern extends as far north as the Aleutian Trench. While there are deviations from the main north-south trend, especially in the Ridge and Trough province, near the continent, the essential unity of the magnetic pattern and its close spatial relationship with the East Pacific Rise, north of the Mendocino escarpment, indicates a genetic relationship.

The coincidence of the maximum amplitude of the axial magnetic anomalies with the topographic crest makes it possible to follow the ridge crest north of the Mendocino fracture zone from point *A* in Fig. 3 to point *F* in Figs. 3 and 4. The axis of the rise is clearly offset between *B* and *C* and between *D* and *E* (Figs. 3 and 4) along what appear to be fracture zones (*21*). It is between these offset portions of the crest that the earth-

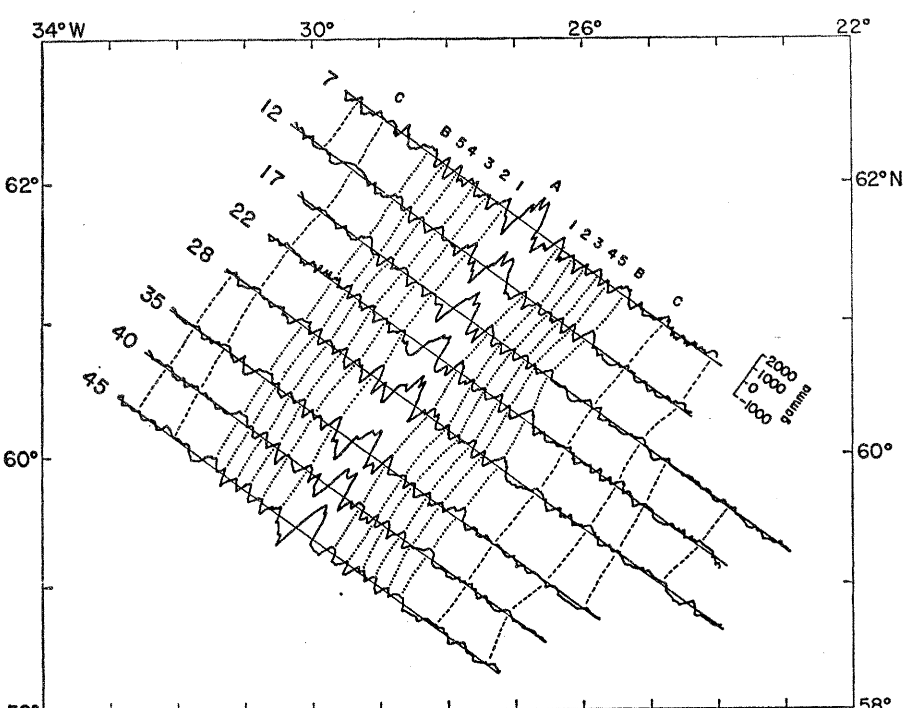

Fig. 1. Eight total-intensity magnetic anomaly profiles obtained over a section of the Reykjanes Ridge (southwest of Iceland) demonstrate the striking linearity of anomalies found over the axial zone of the ridge. A regional anomaly has been substracted from the observed values. Note the symmetry about the central anomaly (*A*). The central anomaly has a peak-to-peak amplitude greater than 2500 gammas. On the far side of each of the two anomalies labeled *B* are somewhat poorly developed anomalies of longer wavelength, which generally show less regularity and linearity than the axial anomalies.

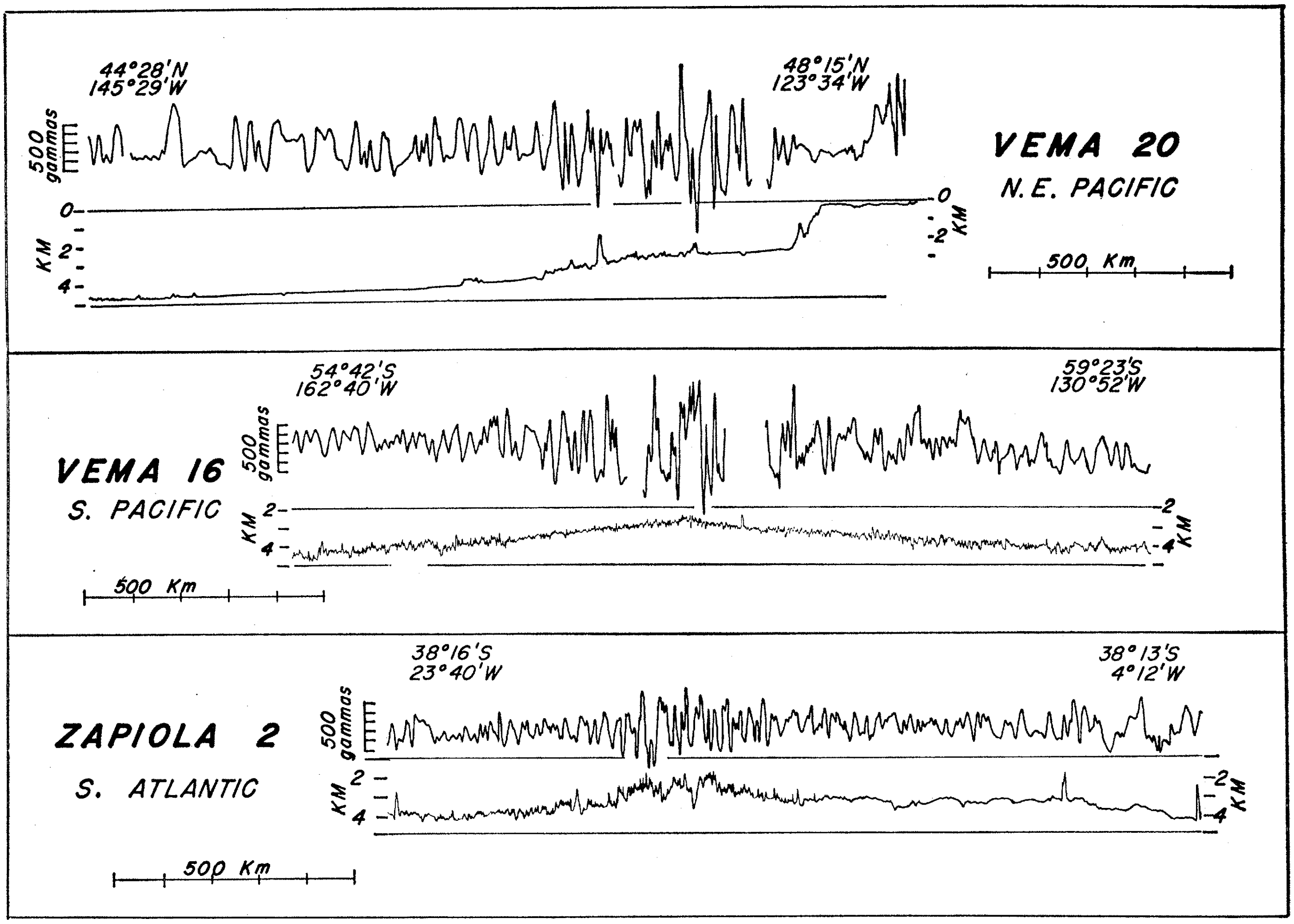

Fig. 2. Three profiles of topography and total-intensity magnetic anomaly across the mid-oceanic ridge (topographic vertical exaggeration, 40 to 1). The *Zapiola* cruise-2 track is normal to the trend of the ridge. The *Vema* cruise-20 and cruise-16 tracks make angles of about 30 to 40 degrees with the ridge trend.

quake epicenters occur most frequently. Between *C* and *D* the magnetic and topographic patterns are undisturbed and earthquake epicenters are very rare. This seems to support the observation that the zone of seismic activity is limited to the portions of the offsets between the crests of the rise (*9*). Note that between 40° and 50°N the earthquake epicenters (Fig. 3) are related to the East Pacific Rise, and that south of 40°N the earthquake epicenters (not shown in Fig. 3) pass on to land and are associated with the San Andreas fault system.

All the geophysical measurements obtained over the East Pacific Rise north of the Mendocino fracture zone indicate a structure similar to the one described for the mid-ocean ridges (*3, 11–13*). The important difference is that the eastern flank of the rise is under the continent. Figure 5 shows a schematic crustal cross section of the East Pacific Rise north of the Mendocino fracture zone. The anomalous upper mantle continues as a low-density zone under the flank; the flank is thus in a state of isostatic compensation. A progressive flankward thickening of the crust is inferred from previous work in other mid-ocean ridge areas (*11, 12*). The general magnetic pattern is obtained from the *Vema* cruise-20 profile. It could also be inferred from Vacquier's published profiles and maps.

Offset of East Pacific Rise at Mendocino Zone

South of the Mendocino fracture zone the crest of the East Pacific Rise is not present in the oceanic area (*7*). On the basis of matching magnetic anomaly patterns, Vacquier and others (*17*) have concluded that, south of the Mendocino fracture zone, the magnetic pattern is offset to the east by about 1600 kilometers (this value includes the offset across the Pioneer fracture zone) with respect to the area to the north of the Mendocino fracture zone. A critical question is whether the East Pacific Rise is also offset by this distance. All the bathymetric and geophysical evidence does point to such an offset. Menard (*7*) has noted that the greater depths found south of the Mendocino escarpment would be in accord with a horizontal offset of a gently sloping surface, the East Pacific Rise (in Fig. 4 note the position of the 5000-meter contour north and south of the Mendocino fracture zone). Thus, north of the Mendocino fracture zone the area between 127° and 129°W lies on the crest of the rise, but south of the fracture zone it lies on the lower flank. Between these meridians the magnetic anomalies south of the fracture zone clearly have longer wavelengths than those to the north of it; south of the fracture zone heat flow is low or normal (*15*) and the mantle velocities are normal (7, 22). All these geophysical parameters indicate that, south of the Mendocino fracture zone, we are on the lower flank of the East Pacific Rise. Consequently one would expect the crustal section south of the fracture zone to be identical to the western part of the section shown in Fig. 5 and offset to the east by a large distance, with the crestal zone underlying the continent. A crustal model for this region presented by Thompson and Talwani (23) differs slightly from Fig. 5 in that in their model the anomalous mantle under the continent terminates below the continental slope. By postulating extension of the anomalous mantle beyond the continental slope and a slightly thinner crust than they envision, we can reconcile their model with that of Fig. 5. A crustal model proposed by Dehlinger and Couch (22) for the Mendocino fracture zone on the basis of seismic and gravity data obtained along meridian 127°W is not in conflict with the crustal and mantle structure described above.

So far we have assumed that the anomalous mantle is at a shallow depth merely by analogy with other mid-ocean ridges. Independent support for its shallowness derives from two

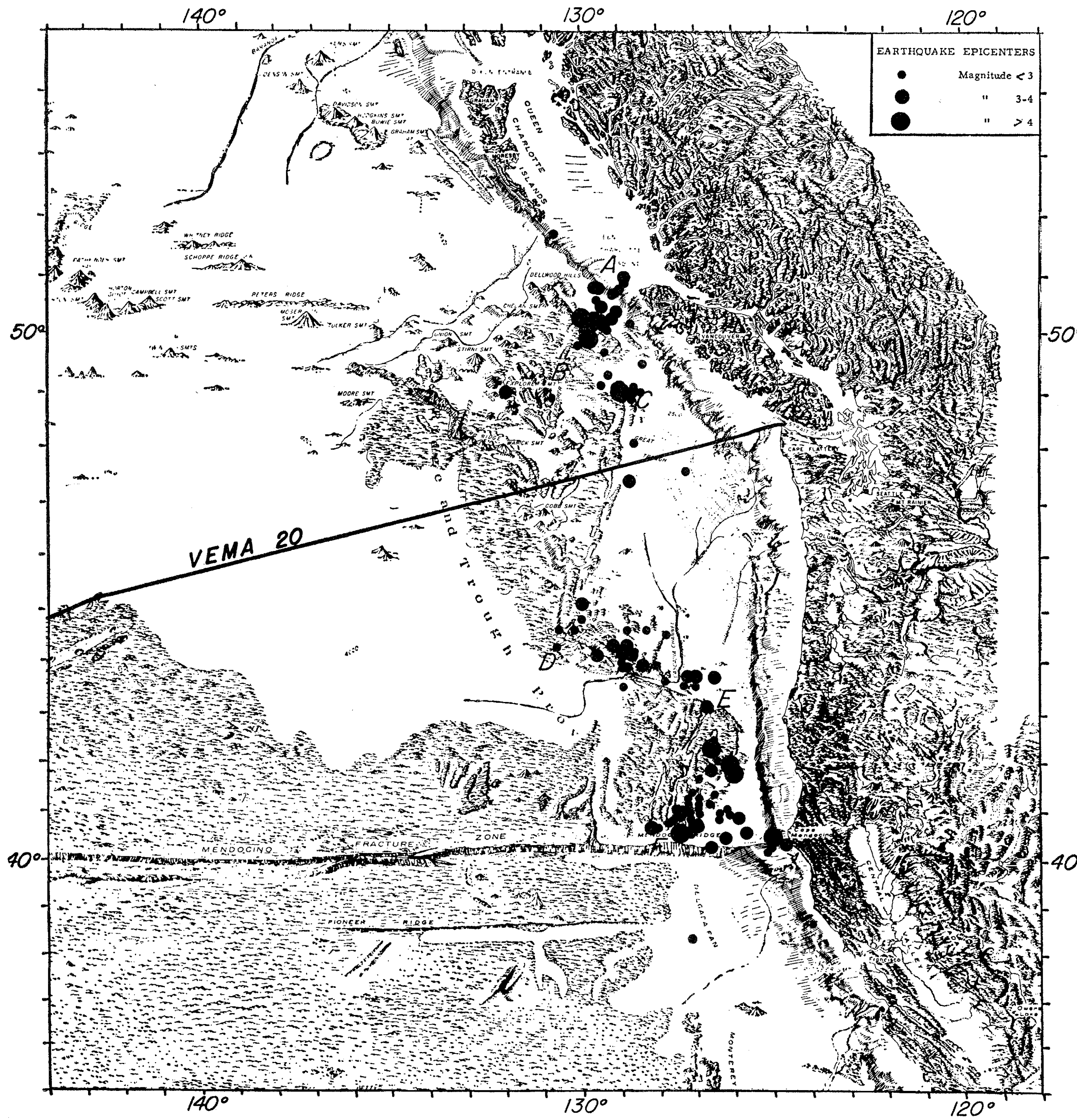

Fig. 3. Part of a physiographic diagram prepared by Menard. The *Vema* cruise-20 track, along which the magnetic profile at the top of Fig. 2 was taken, is also shown. The earthquake epicenters in the ocean for 1961, 1962, and 1963 are U.S. Coast and Geodetic Survey preliminary determinations. [From H. W. Menard, *Marine Geology of the Pacific* (McGraw-Hill, New York, 1964), copyright ©. Reproduced by permission]

pieces of evidence considered together. One of these is Raitt's finding (*24*) that, across the western part of the Mendocino escarpment, all values for crustal thickness are nearly equal and all values for mantle velocity are similar despite great differences in the depth of the ocean floor. The other comes from gravity data (*25*) which show that the differences in topography across the fracture zone are compensated at a shallow depth.

If we can say that an offset of the East Pacific Rise has been demonstrated, we must look for the crest of the rise under the continent, south of the Mendocino fracture zone. Since continental and oceanic structures are quite different one would not expect to find, on the continent, a crustal structure identical to that of the rise crest in the ocean, but one would look for similarities. It has been pointed out (*7, 15, 23*) that both the Basin and Range province and the Colorado Plateau are higher than the areas that surround them and have high heat flow, anomalous mantle velocities, and an unusually thin crust—properties characteristic of the axial zone of the mid-ocean ridge system. In addition, the Basin and Range province shows faulted topography similar to that of the Ridge and Trough province of the northeast Pacific. The inference is clear. Between 30° and 40°N, features of topography and of the upper mantle in the western United States are similar to corresponding features of the East Pacific Rise.

We postulated earlier in this article that the anomalous mantle present under western North America between 30° and 40°N continues westward under the oceanic crust. Alternatively, and especially in view of the fact that the observed heat flow in the oceanic area conflicts with this interpretation, one can take the view that, even though the uplift associated with the East Pacific Rise takes place under both the continent and the ocean and the basic cause of the uplift is the same in the two areas, the actual mechanisms may differ somewhat. The continuation of the mid-oceanic ridge system into the continents and the possibility that continental plateaus and mid-ocean ridges are of similar origin have been discussed extensively in the literature (*7, 26*). What we want to emphasize here is the fact that magnetic anomaly patterns of the Northeast Pacific appear to be genetically related to the East Pacific Rise.

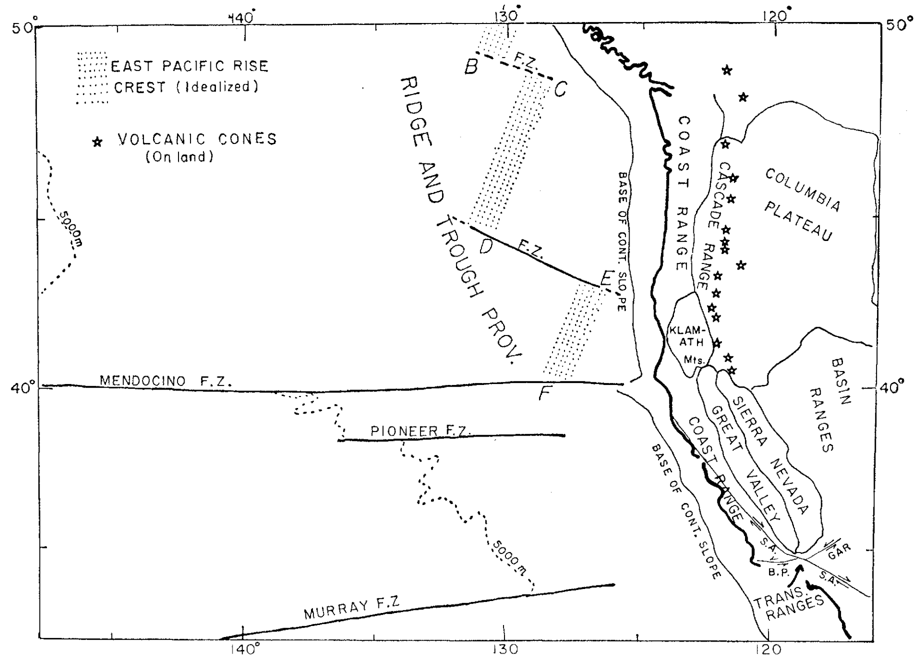

Fig. 4. Location of some of the principal geological features discussed. The eastern part of the Basin and Range province and the Colorado Plateau lie east of the area covered by this map. *GAR*, *B.P.*, and *S.A.* stand for Garlock, Big Pine, and San Andreas faults, respectively.

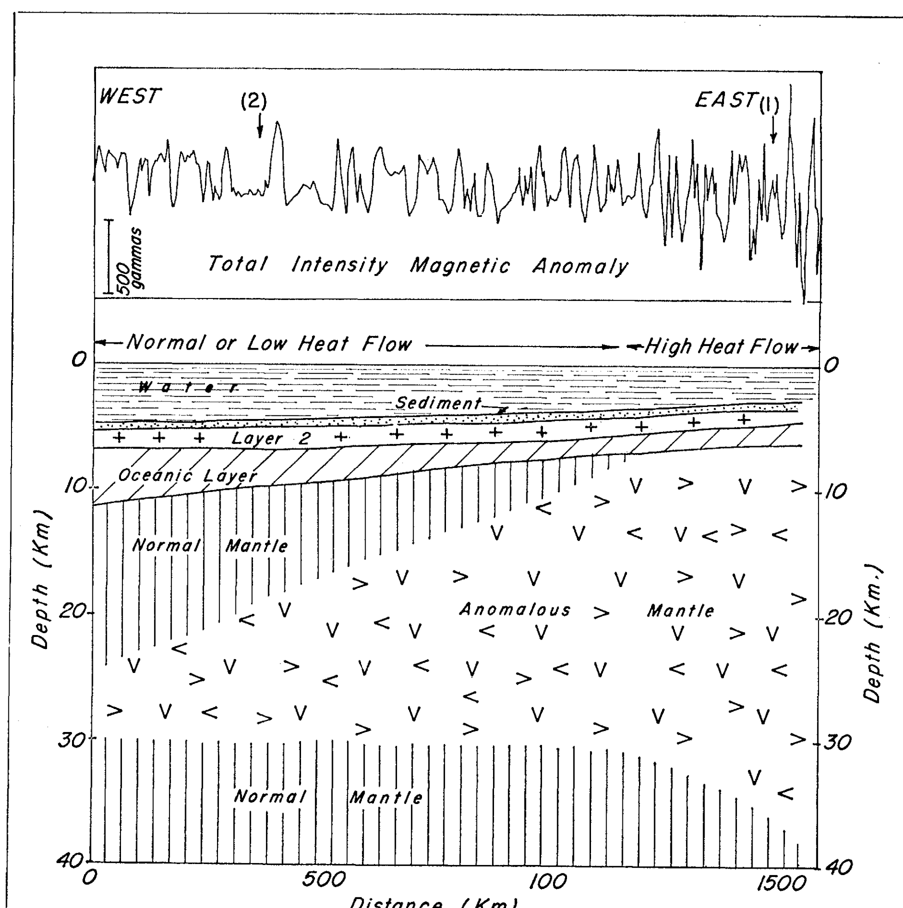

Fig. 5. Schematic crustal cross section of the oceanic part of the East Pacific Rise (crest and western flank) north of the Mendocino fracture zone. The magnetic anomaly profile obtained along the *Vema* cruise-20 track is projected in an east-west direction. North of the Mendocino fracture zone, the point labeled 1 is at 127°W. South of the fracture zone the crustal section still holds for the ocean area; the crestal zone is now under the continent, and point 2 is at 127°W.

Consequently the great offsets in the magnetic patterns are associated with offsets of the East Pacific Rise, even though this hypothesis does require the conclusion that, between the Murray and Mendocino fracture zones, the rise crest occurs under the continent.

Displacement Hypothesis

In recent years theories of continental drift and of evolution of the ocean floor have leaned heavily on interpretation of the offsets in the magnetic anomaly pattern in the northeast Pacific as arising out of tremendous strike-slip faults. However, this interpretation has raised several problems.

1) It is difficult to see how crustal blocks could move through enormous distances along very nearly straight lines without appreciable distortion within the blocks.

2) Let us accept the postulate that the East Pacific Rise continues under the continent and that the formation of the Basin and Range topography and the uplifting of the Colorado Plateau are directly associated with the East Pacific Rise. Since the postulated displacement along the fracture zones must occur later than the formation of the rise, the displacement theory implies that the Basin and Range province and the Colorado Plateau have moved (after having been elevated and deformed) 1600 kilometers to the east since the early Tertiary. This implication can be rejected on geologic grounds. If one assumes, on the other hand, that only the mantle is involved in the motion under the continent, then one is called upon to imagine a shearing of the mantle under the crust and disappearance of the mantle movement, without a trace, in the middle of the continent. This would also imply the eastward migration of a topographic crest, starting in the early Tertiary.

3) If one takes the view that both the crustal displacements and the East Pacific Rise terminate at the continental boundary, one is hard put to explain the fact that, though the area between the Mendocino and Murray fracture zones and that between the Murray and Clarion fracture zones suggest the flank of a rise, the crest has disappeared. Also, the evidence presented by Menard (*27*) regarding the control of geological features in western North America by the continuation of the fracture zones (see Fig. 4) indicates that the activity of the zones does not terminate at the continental boundary. For instance, the Murray fracture zone appears to be continuous with the Transverse Ranges of Southern California. Geological provinces such as the Sierra Nevada and the Great Valley of California are bounded by the continuations of the Mendocino and Murray fracture zones.

4) The difference in displacement from 150 kilometers at the eastern end to 640 kilometers at the western end of the Murray fracture zone has not been adequately explained.

5) It is hard to explain the observation that earthquakes occur mainly where the crest of the East Pacific Rise intersects the fracture zones, or on the fracture zones between offset portions of the rise crest, and do not extend along the entire length of the fracture zones.

Alternative Hypothesis

In view of all the difficulties associated with the hypothesis of large fault displacements, one inquires whether it is possible that the various segments of the rise axis were never displaced at all but developed at their present positions. In that case one would have to ascribe the match in the magnetic anomaly pattern not to enormous strike-slip displacements but to the great similarity of magnetic patterns at constant distances from the rise axis, even for distant segments of the rise. Further, if the view that the water depth depends directly on the distance from the axis of the rise is accepted, discontinuity of the rise crest would demand differential uplift on the flanks, and the present topography of the fracture zones where they intersect the East Pacific Rise would be ascribable to this differential uplift. The important motion on the fracture zones, due to the formation of the rise, would then be vertical and not horizontal.

In this view it is tacitly implied that the long fracture zones of the northeast Pacific Ocean existed before the formation of the rise, even though major faulting took place during the formation of the rise. We feel it is necessary to assume that at least the major fracture zones existed prior to the formation of the rise. They were perhaps nothing more than zones of weakness (*28*) in the crust and upper mantle that determined the locations of the offsets and the changes in orientation of the crest of the rise as well as the corresponding pattern of fracturing of the crust. Otherwise it is difficult to explain the remarkable linearity and regularity of spacing of the large fracture zones in the northeast Pacific Ocean (*7*). As to why the rise crest is discontinuous and did not form along a continuous line in the first place, a possible answer perhaps lies in the overall nature and shape of the globe-encircling mid-ocean ridge system (*6*). When viewed on an ocean-wide scale, the mid-ocean ridge system appears to be curved; when studied in detail, sections of the crest generally are found to lie along straight lines often trending north-south. Offsets and changes in direction are thus necessary to accommodate the straight line segments in a curved overall pattern. It is also possible that the large offset at the Mendocino fracture zone is associated with the continuation of the rise from the ocean to the continent at an oblique angle to the west coast of North America.

Basic to our thinking is the view that the major phenomenon we are dealing with is the mid-ocean ridge system, which comes into existence because of changes in the underlying mantle. Preexisting local variations in the properties of the crust and upper mantle decide the exact location of the ridge crest, and thus the vertical displacements on the fracture zones are nothing more than important details in the topographic expression of the mid-ocean ridge system.

In connection with this hypothesis of ridge formation, a few further points should be made.

It is reasonable to assume extensional forces away from the crest of the ridge. Where the crest is offset, maximum shear stresses would be set up in the portion of the fracture zone between the two crest segments. This would be the only part where the otherwise normal faulting would have a strike-slip component, and these stresses might explain the unusual earthquake activity in this area. On the other hand, there appears to be no reason, under the displacement hypothesis, why earthquakes should not occur along the entire length of the fracture zone.

We recognize that the matches of the magnetic anomalies on the two sides of the fracture zones are surprisingly good. Further work will be necessary to establish whether these close matches are possible only through actual displacements or whether the magnetic pattern is sufficiently similar on different segments of the rise and sufficiently dependent on the distance from the rise crest to support the views presented here. If the magnetic pattern does not repeat itself accurately in two adjacent segments, we will have a situation such as exists across the Murray fracture zone, where matching of the anomaly pattern indicates different offsets at different sections of the fracture zone. In fact, if the hypothesis given here is valid, one would expect to find that the magnetic pattern varies somewhat from segment to segment, and, as new surveys are made, to find other instances of different offsets along the same fracture zone. In addition there would be instances where anomalies found on one segment are absent in an adjacent segment. The explanation, in terms of a "disturbed zone," given by Raff (*29*) for the difference in offset at the two ends of the Murray fracture zone appears less tenable to us, primarily because it is difficult to see why this disturbed zone should be created on the flanks rather than on the axis and why the magnetic anomalies should not show a coherent pattern over the "disturbed zone."

Long straight fractures are usually associated with strike-slip motions, whereas we are assuming that the major faulting on the fracture zones is normal faulting. Some support for our thesis comes from the fact that the Murray fracture zone appears to be continuous with the Transverse Ranges of Southern California, which are remarkably straight although not primarily strike-slip in origin (strike-slip motion on the closely associated Garlock fault is opposite in sense to that postulated for the Murray fracture zone). Most recent studies of the bottom relief in the various oceans have revealed remarkably linear structures. It is possible that the normal mode of deformation of the oceanic crust is along straight lines. If this is the case, it would not be surprising to find that uplift of the East Pacific Rise in discontinuous segments causes the formation of linear fracture zones (for example, along *BC* and *DE* of Fig. 3) or that it causes vertical motion along previously existing linear zones of weakness in the crust (and perhaps the upper mantle), such as the great fracture zones of the northeast Pacific.

Essential to our hypothesis is evidence of repetition of the general structure, and of its dependence on the distance from the rise axis, from one rise segment to another. We feel that only further geophysical surveys will establish whether or not this repetition and dependence exist. A critical area for study would be the southeast Pacific, where observation from a vessel crossing the East Pacific Rise at high magnetic latitudes should reveal that the ridge has a well-developed magnetic anomaly pattern. We are, of course, not stating that no strike-slip faulting can occur in oceanic areas. Here we consider only the problem of prominent fracture zones that intersect the East Pacific Rise. On the other hand, while we have discussed only the fracture zones in the northeast Pacific, there is no reason why our suggestion should not be equally valid for the fracture zones which intersect other parts of the mid-ocean ridge system.

A corollary of the views presented here is the conclusion that movement across the San Andreas fault subsequent to the formation of the East Pacific Rise was either small or, as recent seismic evidence suggests, confined to the superficial layers of the crust (*30*).

The structure of the crust and the mantle, as well as the magnetic pattern over the northern extension of the East Pacific Rise (off British Columbia, Washington, and Oregon) appears to depend largely on the distance from the axis of the rise. It is suggested that (i) the different segments of the crest of the East Pacific Rise developed at their present locations; (ii) the matches in magnetic pattern are due to similarities in the pattern at equal distances from the rise crest; (iii) it is not necessary to invoke large-scale strike-slip movements along the fracture zones of the northeast Pacific; and (iv) differential uplift due to the formation of the rise is responsible for depth differences across fracture zones.

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