Analysis and Implications of the Sequence of Ridge Jumps That Eliminated the Surveyor Transform Fault

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By using magnetic anomaly data from a detailed geophysical survey west of the Juan de Fuca rise between longitudes 143°W-134°W and latitudes 42°N-48°N the history of spreading at the Pacific-Farallon spreading center in this region can be reconstructed for the period 35-20 m.y. ago (anomalies 12-5E). During this time period, relative migration of spreading axes separated by transform faults resulted in the elimination of the offset represented by the Surveyor fracture zone. Magnetic anomalies in the southern part of the region require eastward jumps of spreading centers of between 40 and 50 km, and those in the northern part imply westward jumps of up to 70 km. The locations of the spreading center jumps migrate along spreading axes with time, concurrently with northward or southward jumps of transform faults, and leave zones of extensively sheared crust with unidentifiable magnetic anomaly patterns in the crust between old and new spreading centers. Such a process may account for the disturbed zone of magnetic anomalies between the Murray and Molokai fracture zones and could be common to all ridge jumps. If so, it suggests that the new spreading centers do not begin simultaneously over long lengths but instead develop in a manner somewhat similar, but not identical, to a crack propagating through a solid.

INTRODUCTION

The magnetized portion of oceanic crust is continuously added (usually symmetrically) to crustal plates along a narrow axial zone of spreading centers [e.g., Atwater and Mudie, 1973]. The newly created crustal material becomes magnetized in the prevailing direction of the earth's field. Because of reversals of the earth's field with time, alternating bands of opposite polarity on the ocean floor are produced symmetrically about the ridge axis [Vine and Matthews, 1963]. At places where spreading centers are offset by transform faults, the magnetic anomalies are generated with similar offsets. In the northeast Pacific between 42°N and 48°N (Figure 1), however, distances measured between clearly identified anomalies on one side of a fracture zone are often different from those on the opposite side [Elvers et al., 1973]. As fracture zones are inactive extensions of transform faults, this requires changes of the lengths of transform faults between spreading centers with time.

Variation in the length of transform faults requires an asymmetry in the accretion of material to the two diverging plates and can be accomplished by two possible processes. Weisel and Hayes [1971] report continuous asymmetrical spreading between Australia and Antarctica. Discontinuous asymmetrical accretion, or jumping of ridge crests, appears to have changed the lengths of transform faults north of Iceland [Johnson and Heezen, 1967; Vogt et al., 1970], in the northeast Pacific [Harrison and Sclater, 1972; Menard and Atwater, 1969], in the east central Pacific [Anderson and Sclater, 1972; Herron, 1972; Sclater et al., 1971], and in the south Pacific [Molnar et al., 1975].

In the northeast Pacific west of the Juan de Fuca rise about 35 m.y. ago (the time of anomaly 12), there was an offset between two segments of the Pacific-Farallon spreading center of over 150 km along the Surveyor fracture zone. By about 19 m.y. ago (anomaly 5E), this offset was essentially eliminated. Elvers et al. [1973] inferred that this reduction in offset was due primarily to continuous asymmetrical spreading at the Pacific-Farallon spreading center. Using the same magnetic anomaly data [Elvers et al., 1972] to reconstruct the history of the spreading in this region between the times of anomaly 12 (~35 m.y.) and anomaly 5E (~19 m.y.), we conclude that the dominant process by which the Surveyor fracture zone was eliminated was a series of jumps of ridge crests. The detailed survey of magnetic anomalies in this region makes it particularly good for study of the detailed process by which asymmetries in the spreading history of a region occur.

DATA INTERPRETATION

The magnetic anomaly profiles (Figure 1) are from the International Decade of Ocean Exploration (IDOE) 1971 Surveyor Seamap [Elvers et al., 1972], which also includes topographic and gravity anomaly profiles. In comparison with profiles of magnetic anomalies elsewhere in the Pacific and in other oceans [Heirtzler et al., 1968], many of the profiles from the NOAA survey contain either excess space between clearly identified anomalies or missing anomalies. Fortunately, several lines at the bottom of the survey area (lines 34-37) contain the continuous undisturbed sequences between anomalies 12 and 5E observed elsewhere. Therefore they can be used as a standard with which the other profiles can be compared. Since the profiles were plotted on a Mercator projection and the pole of rotation between the Pacific and Farallon plates was close to the north pole [Francheateau et al., 1970], the anomalies can be compared directly with one another from profile to profile irrespective of latitude and with little change from north to south. The trends of anomalies between 13 and 5D are all nearly north-south, and the trend of the Mendocino fracture zone is constant in this region. Thus no significant changes in
spreading direction took place between about 38 and 19 m.y., and only two major plates were involved.

By careful comparison of line 35 to other profiles, Figure 2 was constructed. The heavy lines indicate profiles for which we think anomalies can be correlated well with some segment of profile 35. The lines are light where we cannot recognize the anomalies on profile 35 or where the correlation is doubtful. In Figure 3 the anomalies are correlated and numbered according to the system of Pitman et al. [1968] and Chase et al. [1970].

Even though the eastern half of the spreading record for this portion of the sea floor has been destroyed by subduction, it is still possible to reconstruct most of the history with the available data from only the Pacific plate. We assume that the plates are rigid and therefore the total rate of crustal accretion was essentially constant within the survey area at any time. It then follows that any anomalous distance between identified magnetic anomalies within the survey area must be made up by compensating differences in the now destroyed Farallon plate. That is, the space between any two identified anomalies on the Pacific plate plus the space between those same two anomalies on the Farallon plate should always be twice the space between the same anomalies on the standard profile.

The configurations of the Pacific-Farallon spreading center at the times of nine chosen anomalies are schematically represented in Figures 4a-4i. The dotted lines on the Pacific plate separate areas where magnetic anomalies can be identified clearly and crustal accretion is interpreted to have progressed without disturbance from regions with disturbed or unintelligible anomalies. If symmetric spreading is assumed, the eastern counterparts of these areas must also necessarily have been accreted, at least initially, regularly and without disturbance to the Farallon plate. Where the spaces between identified anomalies are less than those of the standard profile, there is no record of the spreading history for the time periods that they represent. Missing segments on the Pacific plate correspond to excess accretion to the Farallon plate.

The true trends of anomaly patterns are not perfectly linear as in Figure 4. This figure was drawn to illustrate the way the spreading axes evolved through time. Thus Figure 4 is only a schematic representation with nonlinearity in the scale.

The configuration of the Farallon plate cannot be reconstructed uniquely. The configuration shown in Figure 4 is the simplest interpretation based upon the given data. We assumed that during the periods for which there is no record on the Pacific plate there was no migration of the spreading center which could have modified the configuration of the Farallon plate shown in Figure 4.

**Spreading History**

Between the times of anomalies 12 and 5E, two spreading axes offset from one another by about 150 km evolved into one single axis by migrations of the spreading axes relative to each other in both eastward and westward directions (Figure 4). Starting at some time before the formation of anomaly 13, a single transform fault connected the spreading axes north and south of the present Surveyor fracture zone and subsequently broke up into a number of short transform faults and spreading centers. This occurred by a relative eastward migration of segments of the spreading axis south of the Surveyor fracture zone and a relative westward migration of segments of the spreading axis north of it, thus distributing the offset over a larger portion of the spreading center.

It is not clear when the Surveyor fracture zone no longer was a single transform fault between 42°N and 44°N. Between latitudes 43°N and 44°N, Elvers et al. [1973] interpreted anomalies 13 and 12 as trending northeast south of the Surveyor fracture zone. If this is correct, at the time that these anomalies were formed, the transform fault represented by the
Surveyor fracture zone was already fragmented, and the reorganization of the spreading center had already begun. In the northern portion of the survey area, anomalies 13 and 12 and 8 and 7 are clear (Figures 2, 3, and 4e). Between anomalies 12 and 8, however, the magnetic anomalies cannot be identified confidently and the precise position of the spreading center in the interval of time between their formation cannot be determined (Figures 4c and 4d). The distance between anomalies 12 and 8 is about 60 km less than that for the standard profile. Thus approximately 60 km of material was added preferentially to the Farallon plate, and the offset of the spreading centers decreased from 150 to 90 km. At the time of anomaly 8 the spreading axes were realigned into three straight segments with the offsets between them concentrated into two regions, inferred as transform faults in Figure 4e. Each offset was on the order of 45–50 km. This general configuration of three linear spreading centers was maintained from anomaly 8 to at least the time of anomaly 7. During this interval, however, at least two eastward migrations of segments of these spreading axes took place, resulting in a lengthening of the northern spreading axis and a shortening of the southern one. Thus the transform faults that offset these spreading centers jumped or migrated south (Figures 4e and 4f).

By a series of eastward jumps, segments of the central axis joined the northern axis and reduced the number of axes from three to two shortly after the formation of anomaly 7 (Figures 4f and 4g). From the time of anomaly 6C to that of 6A the southerly migration of transform faults reversed. The southern axis lengthened and the northern axis shortened by a westward migration of the northern axis in the south central portion of the survey area (Figures 4g and 4h). Once again the lengthening of one spreading center and the shortening of its neighbor was accompanied by a jumping or migration of transform faults perpendicular to the direction of spreading. It is not clear if these ‘jumps’ of the faults occurred continuously or at a few discrete times.

Until the time of anomaly 6A, the total offset had been reduced only to about 85 km. Between the time of anomalies 6A and 5E the spreading axis north of about 44.5°N jumped or migrated west and essentially eliminated any lateral offsets between the previously segmented spreading centers to produce a continuous ridge axis within the entire survey area (Figures 4h and 4l).

The elimination of the lateral offset between spreading centers at the Surveyor fracture zone occurred in two major episodes. The first, during the time interval between the formation of anomalies 11 and 8, took place first by a northward migration of the zone of offset (or transform fault) caused by successive westward jumps or migration of the spreading center in the northern portion of the survey area. The second episode took place after the time of anomaly 6A and before the
start of 5E by a similar migration of the zone of offset. In the
intervening time there was a reorganization of the spreading
axes and a southward migration of the offsets (transform
faults) so that by the time of anomaly 6A, most of the offset of
the spreading center was in the southern portion of the region.
During this interval the total offset between spreading centers
changed very little. At the time of anomaly 5E, the spreading
center was quite linear (Figure 3) but perhaps with a small dis-
continuity in the axis near 45°N. By the time of anomaly 5D
this axis was offset by 15 km and suggested the creation of a
new fracture zone.

RIDGE JUMPS

Ideally, it would be possible to interpret all the anomalies on
the magnetic profiles, particularly those occupying excess
space between well-identified anomalies. Continuous asym-
metrical spreading should give stretched out sequences, and
jumps of spreading axes should produce anomaly sequences
symmetrical about abandoned spreading ridges. Two exam-
amples are shown in Figure 5. The top two segments are from
profile 35, where spreading was continuous and symmetrical.
Immediately below are two segments from profiles 19 and 24
where excess spaces between identified anomalies are present
(see also Figure 3). In profile 19, excess space occurs between
anomalies 7 and 7a, and in profile 24 between anomalies 7a
and 8. If continuous asymmetrical spreading were responsible
for the excess space, east-west stretching of the anomaly
shapes would be expected. Stretched segments of profile 35 to
match the allowable spacing between identified anomalies
present in profiles 19 and 24 are shown in Figure 5c. A clean
eastward jump should have introduced additional anomalies
symmetrical about the location of an abandoned ridge crest. If
profile 35 segments had jumps of magnitudes to match the ex-
cess distances in profiles 19 and 24, they would appear as in
Figure 5d. The symmetry would be evident on either side of the
location of the jumps for a distance equal to the magnitude of
the jumps. However, neither model generates the observed
anomaly patterns, and evidently the process of asymmetrical
accretion is more complex than either of the two simple
processes considered.

Although distinction between jumping of spreading centers
and continuous asymmetric spreading cannot always be unam-
biguously distinguished from identification of anomalies, un-
der certain conditions geometric constraints can define
Fig. 4. Schematic sequence showing configuration of the Pacific-Farallon spreading center at the times of anomalies 12, 11, 10, 9, 8, 7, 6C, 6A, and 5E. Dotted lines enclose regions where crustal accretion has been interpreted to be symmetric (i.e., areas occupied by heavy lines in Figure 2).
whether jumps must necessarily have happened. If excess space between two identified anomalies is more than twice the distance between the same two anomalies on the standard profile, then jumping must have taken place. With totally asymmetric spreading (the addition of new crustal material to only one plate at a spreading center) the maximum separation between two anomalies must be twice that of a symmetrically spreading axis. In Figure 4b the excess space in profiles 19 and 24 is significantly greater than twice the allowable space between identified adjacent anomalies of profile 35 (Figure 5c). Thus jumps must have occurred between the times of anomalies 7, 7a, and 8. Areas where jumps unambiguously took place are shaded in Figure 3 by upper right to lower left diagonal lines. The lack of identifiable anomalies described above within these areas suggests the jumping process somehow destroys or distorts the oceanic crust’s original magnetic signature (compare Figures 5b and 5d).

In contrast, it is more difficult to distinguish jumps from continuous asymmetric spreading when there are gaps in the magnetic anomaly sequence or unusually short distances between identifiable anomalies. In such cases the important information was carried away on the Farallon plate. Nevertheless, many of these asymmetries are best explained by jumps of the spreading center. On profiles 2-19 there should be approximately 85 km more space between anomalies 6B and 5E than is present. Nevertheless on most of the profiles, all of the positive and negative anomalies can be identified and correlated with anomalies on the standard profile. Some portion of the standard profiles is simply missing from each of the profiles 2-19. The sharp juxtaposition of complete anomalies which should be widely spaced is expected from westward jumps of the spreading axis or totally asymmetric spreading. The locations of such behavior are shaded in Figure 3 by upper left to lower right diagonal lines.

CONCLUSION

From the gross features of the magnetic anomaly pattern a first approximation of the history of spreading between the Pacific and Farallon plates between 42°N and 47°N can be derived. The positions of well-identified magnetic anomalies require discontinuous migrations of segments of spreading centers with respect to each other. The pattern of migration shows that the reduction of a large offset between spreading centers can be quite complex, involving many jumps of the spreading center in either direction.

West of the Juan de Fuca rise, jumps of the old Pacific-Farallon spreading center of 40-50 km can be recognized; in other places we infer jumps of the order of 70 km. These distances correspond to jumps of the ridge axes into oceanic crust of about 1.5- and 2.3-m.y. age, respectively. Sometimes segments of spreading ridges up to about 160 km long appear to jump simultaneously. In other cases, much shorter segments seem to jump successively and give the appearance of a zone propagating up through the plate. For instance, the inferred westward migration between anomalies 6B and 5E started at 44.6°N and at 48°N. With time, the loci of jumps migrated toward each other, ending around 46.5°N. This process took place over approximately a 2 m.y. period. In such places where ridge jumps propagated along a spreading axis, a transform fault must also propagate with the jumps, in a direction perpendicular to the direction of spreading (Figure 6). In a continuous process the propagation of transform faults would leave a zone of extensively sheared crust between the old and new spreading centers the width of the jump. This phenomenon may account for some of the zones with extra space and in which the anomalies are unidentifiable.

The model of spreading that we present in Figure 4 ignores a number of finer details evident from the anomaly pattern of Figure 2. Undulations in the trend of anomaly patterns were ignored. These have been suggested to be the result of local asymmetrical spreading [Blakely, 1975]. Significant variations in the trend of anomaly patterns away from north-south direction around anomaly 6 were also ignored. The cause of these deviations may be from a number of factors, including (1) the mismatch of the map’s projection with the pole of rotation for the Pacific plate versus the Farallon plate, (2) continuous asymmetrical spreading, and (3) possible failure of rigid plate assumption. There is clear evidence for minor continuous asymmetrical spreading in Figure 3. Variations in the distances between some anomalies cannot be accounted for simply by
the change in distance of the different anomaly profiles to the pole of rotation (e.g., the width of anomaly 8 is greater in the central portion of the survey area than in the southern portion).

On the gravity and topographic profiles of the survey area, there are no features which can correspond with locations of the ridge jumps. The only exception is the ridge with an associated gravity anomaly near the location of anomaly 6 (called the anomaly 6 ridge by Elvers et al. [1972]). This feature matches well with the location of the inferred westward jumps between anomalies 6B and 5E, but its more specific course is less certain.

Although ridge jumps have occurred at various times at various segments of several spreading centers, little is known about how any of these jumps actually took place. For those near the equator the magnetic anomalies are sufficiently poorly defined that even the times of the jumps are not well known. Elsewhere the number of profiles is too few to permit a detailed understanding. Moreover, the process itself seems to destroy the magnetic anomalies within the portion of the one plate that is suddenly added to the other by the jump. The disturbed zone of magnetic anomalies between the Murray and Molokai fracture zones is a good example of this. Anomalies older than anomaly 20 and younger than anomaly 13 are clear, and extra space between them requires some form of asymmetric accretion to the Pacific plate. Although Malahoff and Handschumacher [1971] interpret the anomalies in the excess space as anomalies 13–8 formed by a secondary spreading center, we think an explanation in terms of a ridge jump is more plausible [Harrison and Sclater, 1972; Menard and Atwater, 1969]. Correlation of the anomalies in the disturbed zone is much worse than in the region east and west of it, and identifications of individual anomalies cannot be made with certainty. The topography, though rough, supports the ridge jump model [Harrison and Sclater, 1972]. The pattern of propagating jumps found in the region west of the Juan de Fuca rise may be applicable to the disturbed zone, and the disturbed magnetic anomalies may be a consequence of the same postulated shearing of the position of the Farallon plate added to the Pacific plate by the jump. Thus the jump would not have occurred at the same time along the whole segment of the rise. The coverage of profiles of magnetic anomalies in the disturbed zone may be inadequate to map the series of jumps that created the final configuration of the Pacific–Farallon plate boundary between the Murray and Molokai fracture zones. Nevertheless, a clear anomaly (probably 13) can be seen just south of the Murray fracture zone near 129°W but cannot be seen further south (see Figure 1 of Malahoff and Handschumacher [1971]).

Propagation of the loci of ridge jumps appears to have occurred also for the small jump in the South Pacific [Molnar et al., 1975] and may be characteristic of all jumps. It may not be possible to form new, long spreading centers suddenly. Instead, a new spreading center may develop in a localized area and propagate through the plate. The propagation of the new spreading center would be somewhat similar to that of a crack propagating through a solid or to the tearing of paper. Nevertheless, to maintain rigid plate motion at all times, the new spreading center cannot simply end, as a propagating crack or tear can, but must connect with the rest of the plate boundary through transform faults. As the new spreading center propagates, new transform faults must form and old ones become inactive. This process must shear the lithosphere between the new and the old spreading center, a phenomenon that would seem to require a lot of work. Nevertheless, if new, long spreading centers cannot form ‘instantaneously’ but develop by a propagation of a spreading center, then this fact supports the contention that continental breakup occurs by rift zones propagating through the continents [e.g., Burke and Dewey, 1973; Maasha and Molnar, 1972; Scholz et al., 1975]. The stresses needed to propagate a rift zone may be much less than those needed to break the continent apart all at once.

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