

Tectonic Evolution of the Explorer-Northern Juan de Fuca Region From 8 Ma to the Present

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New magnetic anomaly data, in conjunction with Sea Beam and SeaMARC II data, has been used to schematically model the tectonic development of the Explorer-Northern Juan de Fuca Region with a series of five ridge-offset propagators during the last 8 m.y. The Sovanco Fracture Zone played a major role in the evolution of this area since its origin as a spreading center offset between the Explorer and Juan de Fuca Ridges approximately 7.4 Ma. Between this time and 2.5 Ma, the transform migrated southwards due to southward propagation of Explorer Ridge, and lengthened by the addition of three propagating ridge offsets as well as by asymmetric spreading to the east on Explorer Ridge. Since the independence of Explorer Plate at 4 Ma, there has been clockwise rotation of the Explorer Spreading Center relative to the Juan de Fuca Ridge. In response to forces acting at the convergent margin, the Sovanco Fracture Zone also underwent clockwise reorientation, and in the process developed into a broad zone of shear. The tectonic deformation associated with this rotation distorted the previously existing N-S magnetic anomaly pattern. Explorer Seamount, a major geological feature in the region, is modeled as a presently extinct southern spreading segment of the Explorer Ridge system which was isolated by the northward migration of the west end of the Sovanco Fracture Zone. The recent (<1 Ma) tectonic evolution of Explorer Ridge involved both northward and southward propagation of Southern Explorer Ridge, as well as an eastward ridge jump during the Brunhes. In the northern portion of the study area, the axis of spreading jumped 40 km to the NW around 0.3 Ma, from the eastern Explorer Deep to the western Explorer Rift.

INTRODUCTION

In comparison to the extensively studied Juan de Fuca Ridge, the Explorer Spreading Center, which lies to the north of the Sovanco Fracture Zone (Figure 1), has received relatively little attention. Elucidation of the role of rift propagation in the evolution of Explorer Ridge has been hindered in the past by the lack of detailed magnetic and bathymetric data. The objective of this study is to integrate a new magnetic anomaly compilation with recently acquired Sea Beam bathymetry and SeaMARC II side scan sonar data [Davis *et al.*, 1984a; Sawyer *et al.*, 1984], in a schematic model for the tectonic evolution of the Explorer-northern Juan de Fuca area from 8 Ma to the present (Ma here is used to denote age in million years before present). Further, the implications of this model for regional plate interactions are discussed.

The study of marine magnetic anomalies has proven to be one of the most useful techniques for deciphering the tectonic evolution of oceanic plates. In the northeast Pacific, the history of the Juan de Fuca plate system has been developed by a number of authors including Wilson [1965], Vine and Wilson [1965], Pavoni [1966], Vine [1968], Atwater [1970], Riddihough [1977], Menard [1978], and Carlson [1981]. Recent comprehensive analyses of both relative and absolute plate motions in the northeast Pacific were presented by Riddihough [1984] and Nishimura *et al.* [1984]. Following the development of the

propagating rift theory [Shih and Molnar, 1975; Hey, 1977], Hey and Wilson [1982] showed that the oblique magnetic anomaly offsets which had been recognized in the northeast Pacific anomaly pattern, and which appeared to be a contradiction to the theory of rigid plate tectonics [Raff and Mason, 1961; Vine, 1968], could result from the propagation of one ridge segment at the expense of another. Wilson *et al.* [1984] modeled the evolution of the Juan de Fuca Ridge during the past 17 m.y. with a series of 7 propagating rifts. A detailed study of the recent tectonic evolution of the youngest propagator on the Juan de Fuca Ridge was presented by Johnson *et al.* [1983].

Integration of magnetic anomaly data with other geophysical and geological studies [e.g., Srivastava *et al.*, 1971; Barr, 1972; McManus *et al.*, 1972; Barr and Chase, 1974; Hyndman *et al.*, 1978; Hyndman *et al.*, 1979; Riddihough *et al.*, 1980; Davis and Riddihough, 1982] has produced a general picture of the regional plate tectonic geometry which is summarized in Figure 1. The spreading segments of Explorer Ridge, together with the Sovanco Fracture Zone, comprise the boundary between the Pacific Plate and the much smaller Explorer Plate. To the east, the Explorer Plate converges with the North American Plate. The northeast-southwest trending Nootka Fault Zone is a transform boundary between the Explorer and Juan de Fuca plates [Hyndman *et al.*, 1979]. The northernmost segments of Explorer Ridge terminate against the Revere-Dellwood Fracture Zone, a transform fault that extends northwestward to the Dellwood and J. Tuzo Wilson spreading centers [Riddihough *et al.*, 1980; Currie *et al.*, 1984].

An early study of the northern Juan de Fuca Ridge by Barr [1972], suggested that the Sovanco Fracture Zone initiated between 8 and 9 Ma, and that the Explorer Plate has been moving largely independently since that time. In his analysis of the marine magnetic anomaly pattern, Riddihough [1977] argued that relative motion between the Juan de Fuca and Explorer plates is

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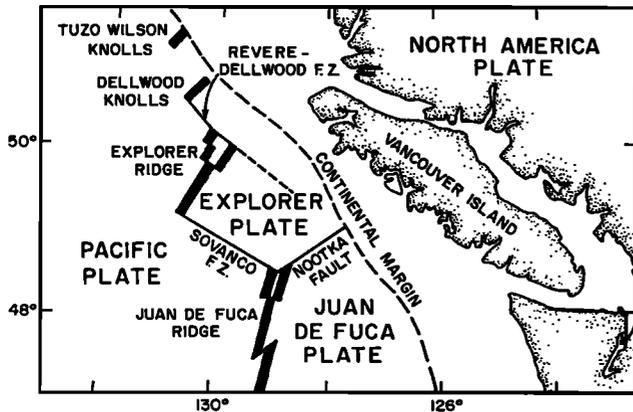


Fig. 1. Location diagram showing the spreading centers in the NE Pacific near Vancouver Island. The wide lines define the axis of current or recent spreading on the Northern Juan de Fuca and Explorer Ridges, and the much smaller Dellwood and Tuzo Wilson spreading segments. Explorer Ridge is bounded to the north and south by the Revere-Dellwood and Sovanco Fracture Zones, respectively. Explorer Plate is separated from the Juan de Fuca Plate to the southeast by the Nootka Fault.

required for at least the last 7 m.y. However, as a result of more recent analyses of the poles of rotation, Riddihough [1984] concluded that transform motion between these two plates was not initiated until 3 to 4 Ma. Around this time, the Explorer area was the youngest portion of the Juan de Fuca Plate entering the subduction zone. In his 1984 model, Riddihough proposed that the resistance to subduction provided by the buoyancy of this material resulted in its detachment at 4 Ma as the independent Explorer Plate. Since then, the plate has been rotating at a slower rate about a local pole such that its motion into the convergence zone has been sharply reduced.

Previous plate reconstructions in the Explorer area [Riddihough, 1977; Hyndman *et al.*, 1979; Riddihough *et al.*, 1980; Riddihough, 1984] have relied, for the most part, on the magnetics survey of Raff and Mason [1961]. New and more detailed sea surface magnetics data have become available over the last few years as a result of a series of multiparameter marine geophysical surveys off Canada's west coast conducted by the Pacific Geoscience Center in conjunction with other Canadian government agencies [Currie *et al.*, 1983]. In addition to this large data set, detailed magnetics information was obtained in the vicinity of the current axis of spreading on a number of recent cruises to Explorer Ridge. The newly compiled magnetic anomaly map for the Explorer Plate area constitutes the primary data base for this study.

TECHNIQUE

The plate tectonic reconstruction of the Explorer-Northern Juan de Fuca region was developed by correlating the linear magnetic polarity intervals. The anomalies were examined both in contour form and profile and, following two-dimensional inversion modeling, identified using the time scale of Ness *et al.* [1980]. As is the case in this study area, for magnetic anomalies formed by the magnetization of N-S trending bodies in a direction close to the present Earth's field at high latitudes, the geographical displacement of the anomalies from their source is insignificant.

Therefore the boundaries of the magnetic anomalies can be reasonably dated at the age of the corresponding reversal boundary.

Having identified the isochrons, the spreading rates and anomaly azimuths were then measured from the magnetic anomaly map using the method described by Riddihough [1977; 1984]. Spreading rates were measured perpendicular to the strike of the anomalies, and between reversal boundaries that represented an interval of approximately 1 m.y. The spreading rate was considered to be representative of the median time of the interval across which the measurement was made. No measurements were made across fracture zones or linear discontinuities in the magnetic anomaly pattern. An assumption inherent in this technique, and one that is critical in this area of frequent spreading readjustments, is that of orthogonal spreading. Although random deviations from this condition should be compensated by the closely spaced measurements along axis, the technique would not identify continuous oblique spreading along the whole ridge for periods of one million years or more. The trends of individual magnetic anomalies were determined by drawing a straight line through the peaks located at the centers of the anomalies. Azimuths were measured in degrees east of north and, using the orthogonal spreading assumption, a spreading direction was applied to the median age of the corresponding anomaly.

The high-resolution bathymetric Sea Beam data [Earth Physics Branch, Energy, Mines and Resources, 1984a,b, 1985a,b; Geological Survey of Canada, 1984a,b], in conjunction with the side-scan SeaMARC II data [Davis *et al.*, 1984b; Geological Survey of Canada Maps 12 and 14, 1987], allowed an accurate identification of the current plate boundaries in the region and also provided details of the structure of seafloor as old as 2.5 m.y. This information was integrated with the magnetic anomaly data in developing a tectonic history for the Explorer-Northern Juan de Fuca region.

DATA

The magnetics data compiled in this study incorporated the results from six different surveys whose tracklines, overlain on the magnetic anomaly map, are shown in Figure 2. The data in the northeast region was integrated from a map previously published by the Geological Survey of Canada [1979]. The majority of the coverage is represented by the ENE trending lines which were surveyed by CSS *Parizeau* in 1983 and 1985. The magnetics data along the NNE-oriented tracklines in the northwest area of the map was collected on CSS *Parizeau* in 1979. The spacing of these 1979, 1983, and 1985 lines is 10 km [Currie *et al.*, 1983]. The average water depth in the region is about 3 km. More detailed coverage over Explorer Ridge was obtained on surveys conducted aboard CFV *Endeavour* (1979 and 1985) and M.V. *Pandora II* (1984). A Barringer model OM 104 proton precession magnetometer was used to collect the data.

The magnetic anomalies were computed using the spherical harmonic coefficients of the IGRF for 1980. The values along tracklines were computer plotted on a transverse Mercator projection at a scale of 1:125,000, and then contoured by hand. Crossover errors for the 1983 and 1985 CSS *Parizeau* surveys

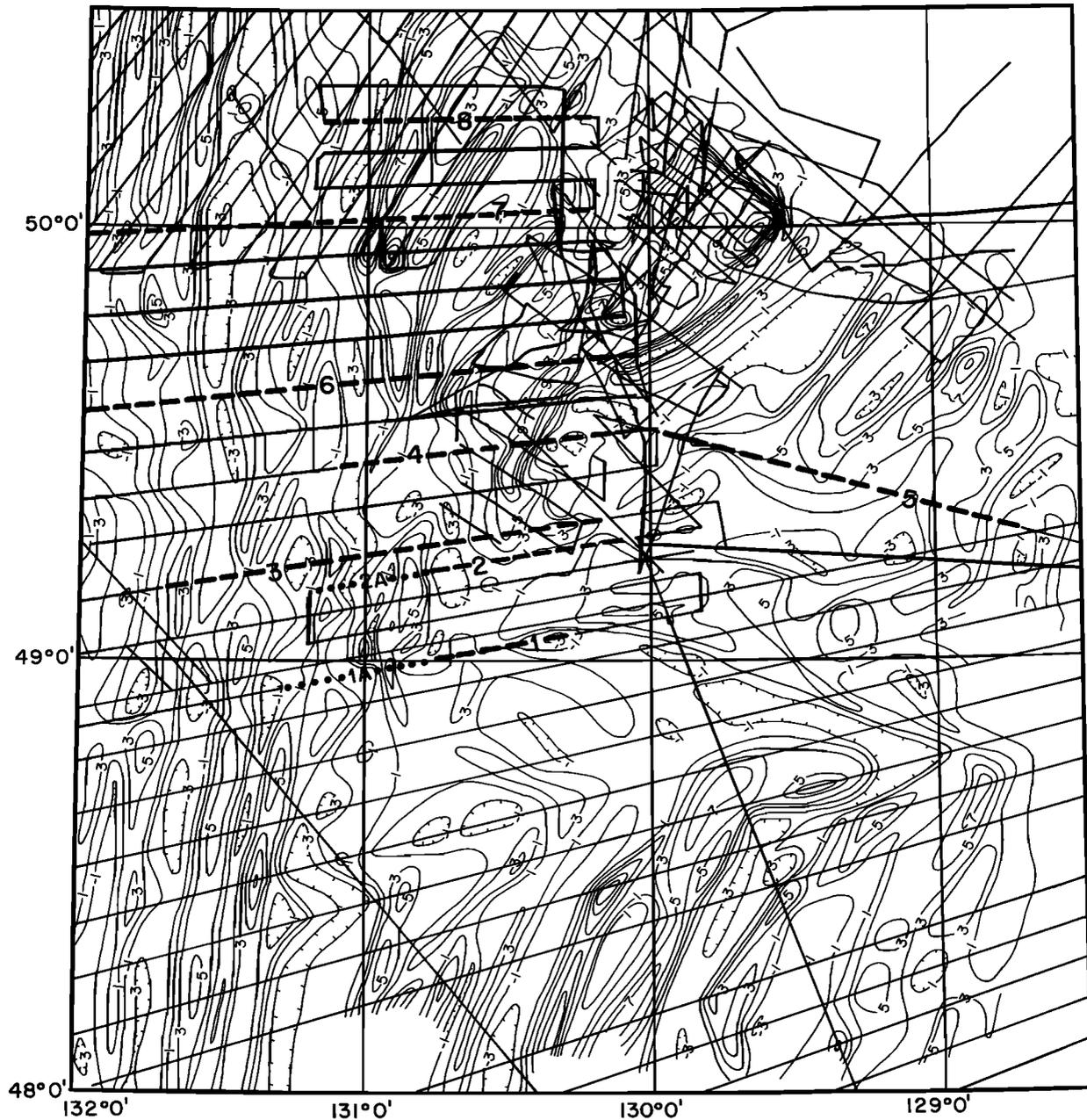


Fig. 2. Ship tracklines superimposed on the newly contoured magnetic anomaly data. Anomalies in the region bounded by latitudes 49°N and 50°N, and east of longitude 130°W, were incorporated from a previously compiled data set [Geological Survey of Canada, 1979]. Magnetic contour interval is 200 nT. Dashed tracklines are partial profiles that were subjected to inversion. The results of this modeling are shown in Figures 5a and 5b. Dotted tracklines 1a and 2a are segments over Explorer Seamount which were modeled at a larger scale.

were approximately ± 30 nT, and occasionally up to ± 60 nT. However, high crossover values (about ± 70 nT and rarely as high as ± 150 nT) exist in the northwest area of the map between the 1979 and 1985 data sets. Since the 1985 coverage in this region is more extensive, the values of this survey were used wherever possible for internal consistency, and the 1979 data was used only in the northwest corner of the map where no other information was available. The tectonic history proposed in this paper does not hinge on the anomalies in this NW area of the map and therefore inaccuracies resulting from the disagreement of these two data sets would not alter the interpretation significantly.

The IGRF does not appear to accurately represent the average field over this region because the net anomaly baseline in the area remains largely positive rather than zero. The +100 nT contour was chosen as the baseline for the map since the background zero level varied from about +30 nT to +150 nT. Similar results have been reported in other magnetic field studies in this area [Haines *et al.*, 1971; Srivastava *et al.*, 1971; Riddihough *et al.*, 1980; Johnson *et al.*, 1983], which may indicate that an entire region in the northeast Pacific is underlain with anomalously magnetic lower crust or upper mantle.

The Sea Beam echo-sounding system aboard the NOAA ship *Surveyor* was used to map the seafloor in the area of the northern

Juan de Fuca and Explorer Ridges in 1983 and 1984. Sea Beam is a multinarrow beam, bathymetric survey system which provides a three-dimensional view of the bottom [Renard and Allenou, 1979]. The high-resolution bathymetric charts interpreted in this study were produced at a 10-m contour interval by Energy, Mines and Resources, Canada, and the National Oceanic and Atmospheric Administration, United States [Earth Physics Branch, Energy, Mines and Resources, 1984a,b, 1985a,b; Geological Survey of Canada, 1984a,b].

Information regarding the sedimentary versus volcanic nature of the seafloor, which is lacking in Sea Beam data, can be obtained using side-scan sonar instruments such as SeaMARC II. This is a long-range side-scan imaging and bathymetric mapping tool that produces geometrically correct images of the seafloor [Blackinton et al., 1982]. The SeaMARC II data was collected by the Pacific Geoscience Center in cooperation with the University of Hawaii using the R/V *Kana Keoki*. The side scan sonar images discussed in this study were published by Davis et al. [1984b], and by the Geological Survey of Canada [1987].

REGIONAL GEOMORPHOLOGY

The Sea Beam acoustic imaging of the Northern Juan de Fuca and Explorer Ridges reveals a complex plate boundary configuration in this area (Figures 3a,3b). The Explorer Ridge system appears to consist of four separate segments (Figure 3a). The locus of spreading in the south is defined by a linear, 65-km-long bathymetric high named Southern Explorer Ridge. Between 49°32'N and 49°46'N, a well-defined axial valley trending N28°E is located at the crest of Southern Explorer Ridge. Beyond the northern and southern terminations of the valley, the ridge topography curves to the east. The axial valley shoals northwards to a broad plateau which rises to a depth of 1800 m at 49°47'N. This latitude coincides with the southern extent of Explorer Deep, the segment to the northeast of Southern Explorer Ridge. The shallowest, northern portion of the axial valley lies at the projected intersection of a seamount chain on the Pacific Plate with Southern Explorer Ridge, and is a known site of extensive hydrothermal activity [Tunnicliffe et al., 1986]. The occurrence of hydrothermal venting at the shoalest portion of a ridge segment in coincidence with the projected intersection of a seamount chain has also been observed elsewhere on the Juan de Fuca Ridge [Chase et al., 1985; Tivey and Delaney, 1985; Karsten et al., 1986]. To the north of the summit of Southern Explorer Ridge, the orientation changes to a trend of about N40°E, and the ridge appears to curve eastwards towards Explorer Deep. At its southern end, the ridge topography gradually diminishes to a broad low within which lies a line, trending approximately N15°E, of small volcanic cones about 1 km in diameter.

In contrast to the elevated ridge topography of Southern Explorer Ridge, the remaining three spreading segments of the Explorer system appear to be rifted valleys (Figure 3a). Explorer Deep consists of a 53-km-long rift which trends N36°E and has a maximum depth of 3300 m. The valley shoals and narrows to the south, and at the latitude of the northern termination of Southern Explorer Ridge, Explorer Deep begins to curve southwestward. This curvature of Explorer Deep and Southern Explorer Ridge toward one another is characteristic of an overlapping spreading

center configuration [Macdonald and Fox, 1983; Lonsdale, 1983; Johnson et al., 1983; Macdonald et al., 1984].

Explorer Rift is situated to the northwest of Southern Explorer Ridge and consists of two en echelon segments which, like Explorer Deep, are bathymetric lows (Figure 3a). The spreading centers are about 21 km in length and are oriented at N42°E (northern Explorer Rift) and N37°E (southern Explorer Rift). An unnamed linear pull-apart basin with approximate dimensions of 18 km by 5 km trends N159°E, and appears to connect Explorer Rift to Southern Explorer Ridge.

The four spreading segments of Explorer Ridge, as defined by Sea Beam, can also be identified in the SeaMARC II data. Strong reflections produced by the scarps bounding the axial valley of Southern Explorer Ridge can be resolved in the side-scan sonar images, which show the entire ridge segment to consist of hard acoustic reflectors indicative of unconsolidated seafloor and young volcanics. Explorer Deep, on the other hand, has substantial sediment cover suggesting a lack of very recent volcanic activity [Geological Survey of Canada, 1987]. Continuous seismic reflection profiles revealed sediment thicknesses of 100 to 200 m in Explorer Deep [Grill et al., 1981]. In contrast to Explorer Deep, the two rift segments comprising Explorer Rift, as well as the pull-apart basin, are floored by hard acoustic reflectors that presumably represent recently erupted basalts. This would support the previous hypothesis that Explorer Rift is very young, and that spreading has jumped from Explorer Deep to Explorer Rift within the last million years [Hyndman et al., 1978; Davis and Riddihough, 1982]. Based on the recovery of fresh basalts from both of the northern spreading centers, Cousens et al. [1984] estimate that the ridge jump occurred about 0.2 Ma.

The SeaMARC II data indicates that Explorer Rift and Explorer Deep are oriented approximately orthogonal to the Revere-Dellwood Fracture Zone, which forms the northern boundary of the Explorer spreading center system. At the intersections of these two segments with the fracture zone, features characteristic of other ridge-transform intersections [Fox and Gallo, 1984], such as the curving of rift-parallel faults into the transform, are observed [Geological Survey of Canada, 1987]. In contrast, the southern intersection of Southern Explorer Ridge with the Sovanco Fracture Zone is much more ambiguous. The difficulty in identifying the exact location of the ridge-transform intersection lies primarily in the poor definition of the Sovanco Fracture Zone. Neither bathymetry, seismicity, or magnetics data reveal a narrow, linear principal displacement zone for the transform motion [e.g., Milne et al., 1978; Cowan et al., 1986]. The limited Sea Beam coverage in the Sovanco area displays a number of left-laterally offset, elevated blocks which are bounded by northwest and northeast trending lineations (Figures 3a,3b). A series of NW-SE oriented faults are located to the south of the blocks in the eastern part of the Sovanco (Figure 3b). Based mainly on this data, Cowan et al. [1986] interpret the transform to consist of a broad (12-18 km wide) zone of deformation within which crustal blocks have rotated clockwise in response to right-lateral transcurrent motion.

Spreading at the northern end of the Juan de Fuca Ridge is concentrated in a N20°E trending graben named West Valley (Figure 3b). As is the case for Northern Explorer, spreading has

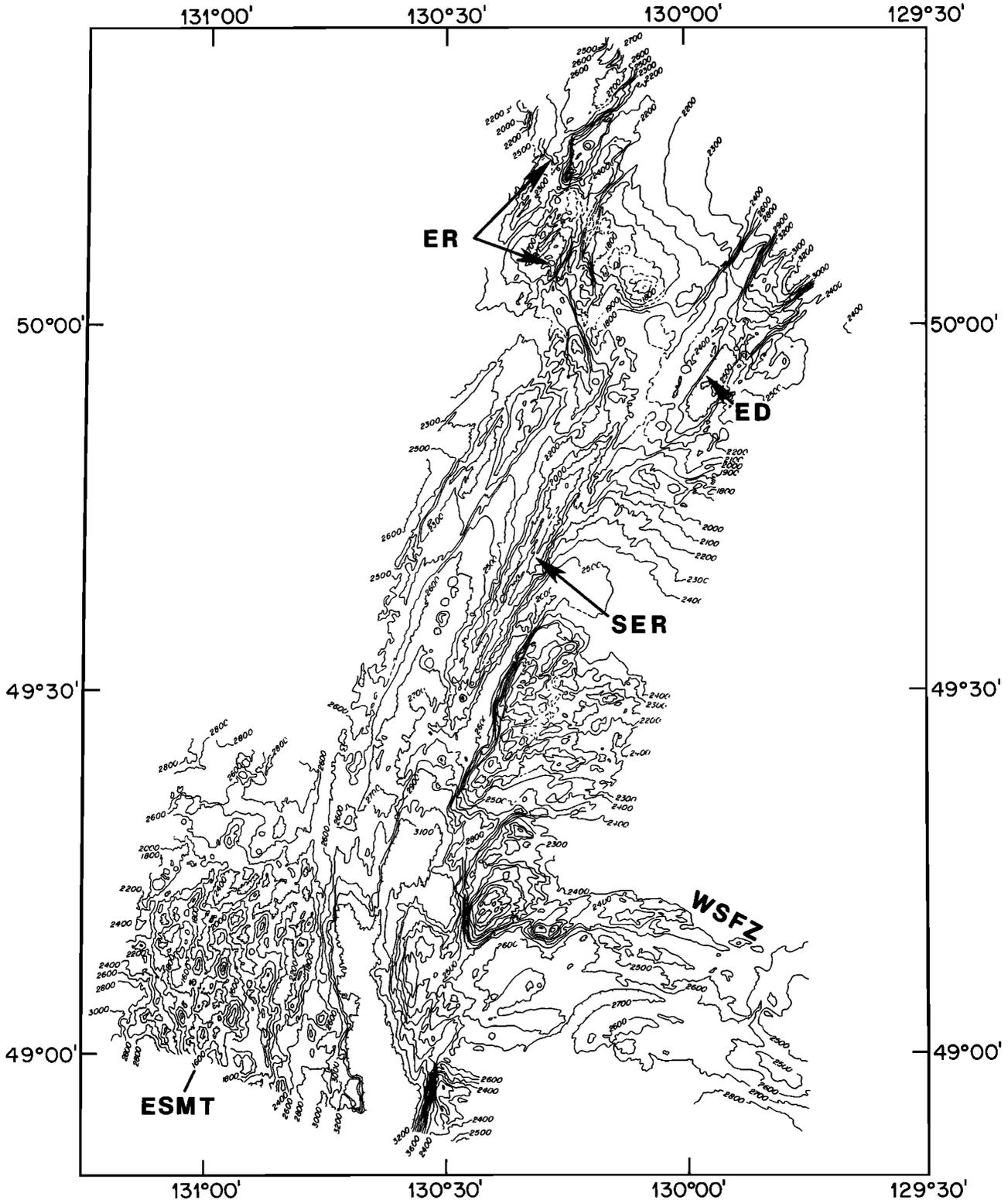


Fig. 3a. Sea Beam bathymetry over Explorer Ridge and the western portion of the Sovanco Fracture Zone adapted from Geological Survey of Canada [1987] map 4. Contour interval is 100 m, except over Explorer Seamount where the interval is 200 m. Terminology used: ER, Explorer Rift; ED, Explorer Deep; SER, Southern Explorer Ridge; ESMT, Explorer Seamount; WSFZ, Western Sovanco Fracture Zone.

recently jumped westward from Middle Valley to West Valley [Davis and Lister, 1977], and Karsten *et al.* [1986] constrain the timing of this jump to less than 0.2 Ma. At its northern end, West Valley terminates at a triple junction intersection with the

Sovanco Fracture Zone and the Nootka fault [Hyndman *et al.*, 1979]; the exact position of this triple junction, however, is not clear.

In addition to allowing a more accurate identification of the

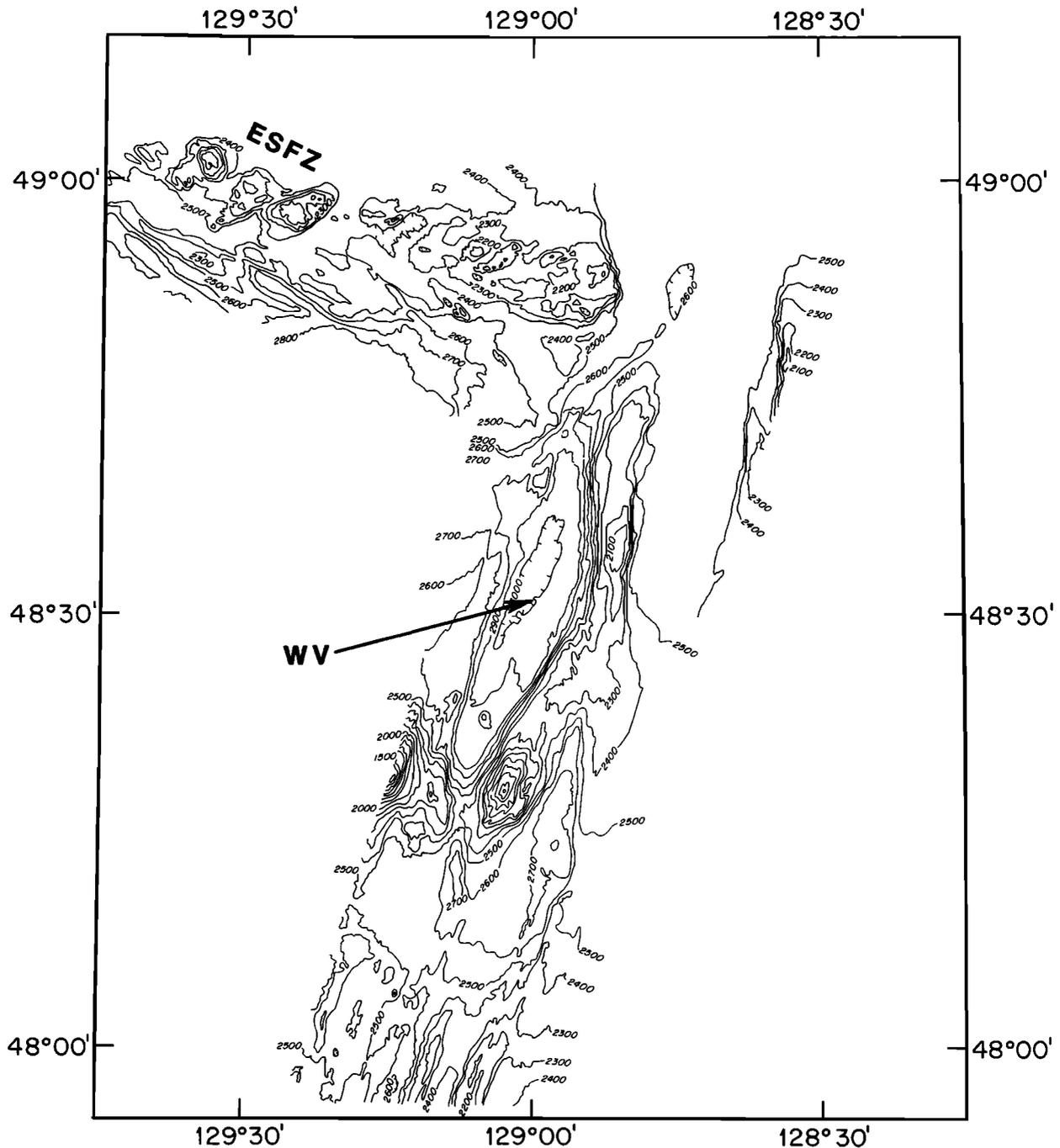


Fig. 3b. Sea Beam bathymetry over the eastern portion of the Sovanco Fracture Zone and Northern Juan de Fuca Ridge adapted from *Geological Survey of Canada* [1987]. Contour interval is 100 m. Terminology used: ESFZ, Eastern Sovanco Fracture Zone; WV, West Valley.

current plate boundaries, the Sea Beam and SeaMARC II data provide information on off-axis geomorphology. In the area of Southern Explorer Ridge, the bathymetry is extremely asymmetric about the ridge axis. Immediately to the west of Southern Explorer Ridge is a broad valley within which lies a line of small volcanic cones trending approximately N24°E (Figure 3a). The valley floor is white to light grey in the SeaMARC II images, suggesting that it is sedimented. To the west of the valley is a broad topographic high that is almost identical to the western half of Southern Explorer Ridge (Figure 3a). This "half-ridge," which is bounded to the east by a N28°E

trending lineation, and to the west by a constructional flank similar to that of Southern Explorer Ridge, is similar to the "ridge bows" described by *Kappel and Ryan* [1986]. Two more distinct NE-SW trending lineations are visible in the Sea Beam coverage to the west. The orientation of the eastern one is N31°E, while the lineament furthest to the west strikes N43°E and comprises the eastern boundary of another broad topographic high. If these lineations represent previous trends of Southern Explorer Ridge, then it appears that the axis of spreading has shifted progressively counterclockwise in the recent past (<1 Ma).

There are no equivalent NE-SW trending ridges to the east of

Southern Explorer Ridge and instead, a broad plateau which rises to a depth of 1800 m is situated east of the southern end of Southern Explorer Ridge (Figure 3a). This feature is bounded to the north and west by steep tectonic scarps which meet at the northwest corner in an orthogonal configuration. The eastern boundary of the plateau is located beyond the Sea Beam coverage but available data suggests that it is constructional.

Explorer Seamount, situated to the southwest of Southern Explorer Ridge and with approximate horizontal dimensions of 80 km by 40 km, is a major geological feature of the region (Figure 3a). Although the general trend of the seamount is NW-SE, the high-resolution Sea Beam data reveals Explorer Seamount to consist of a series of narrow curvilinear ridges oriented at between N150°E and N170°E, which are superimposed on the broader elevated topography. The steep eastern edge of Explorer Seamount is also the western boundary of a NW-SE trending rifted valley. The valley has a sedimented appearance in the SeaMARC II images [Geological Survey of Canada, 1987], similar to that of Explorer Deep. The limited side-scan data over the eastern part of Explorer Seamount, on the other hand, suggests that it consists of rough acoustic reflectors with local patches of smooth reflectors. Explorer Seamount, which rises to a depth of 900 m, is the shallowest feature in the study area. There is no bathymetric edifice equivalent in scale to Explorer Seamount on the eastern side of the rifted valley, although the broad plateau situated to the east of Southern Explorer Ridge may represent an eastern portion of Explorer Seamount that was moved northwards during past events involving major plate boundary readjustments. The similarity of the eastern scarp of Explorer Seamount and the steep western boundary of the plateau, as well as their equivalence in topographic scale, would support this idea.

From the Figure 4 overlay of the structural features interpreted from the Sea Beam and SeaMARC II data on the new magnetic anomaly pattern, it is apparent that all four current and recent Explorer spreading segments lie within a lobster-shaped Brunhes boundary. This magnetic boundary is strongly asymmetric about the axis of current spreading of Southern Explorer Ridge, being approximately three times wider to the west than to the east. Asymmetry of the Brunhes is also observed about Explorer Deep, but in this case the axis of recent spreading is situated near the western edge of the anomaly. The northern and southern topographic boundaries of Explorer Seamount appear to correspond to NW-SE trending discontinuities in the magnetic anomaly pattern. The left-laterally offset and elevated blocks of the Sovanco Fracture Zone, with the exception of the very eastern and western blocks, are overlain by a broad, positive, generally E-W trending magnetic anomaly.

MAGNETIC ANOMALY INVERSIONS AND ANOMALY IDENTIFICATION

Eight coincident magnetic field and bathymetry profiles, represented by the dashed lines in Figure 2, were chosen for two-dimensional inversion modeling. Using the observed field and topography, a Fourier method for calculating potential anomalies [Parker, 1973] was applied iteratively to solve for the source magnetization [Parker and Huestis, 1974]. The assumptions

inherent in this technique are as follows: there is no vertical variation in magnetization, the topography is two-dimensional, the magnetization is parallel to a geocentric axial dipole field direction, and the upper boundary of a constant thickness source layer is the observed bathymetry. The high- and low-pass filter used in the modeling of each profile was the approximate profile length and the average water depth, respectively. The crustal magnetization derived from the Fourier inversion is nonunique. Parker and Huestis [1974] showed that for any given topography there exists a magnetization distribution known as the annihilator that will produce no external magnetic field on the level of the observations. Therefore any multiple of it may be added to the magnetization solution and the sum will also be a solution which reproduces the observed field.

The results of the inversion modeling, together with the anomaly identifications, are shown in Figures 5a and 5b. For each profile, the upper solid curve is the observed magnetic field. The dotted line, being the field produced by the forward modeling of the observed bathymetry and the calculated crustal magnetization, represents a control on the validity of the crustal magnetization generated by the inversion technique. The middle profile displays the calculated magnetization as a solid line, the annihilator as a dotted line, and the anomaly identifications as the numbers associated with the peaks. The lower curve is the bathymetric profile, and the assumed thickness of the source layer in kilometers is indicated by the letter *t* at the top.

Figure 5a shows five inversion profiles over Explorer Seamount with lines 1A and 2A representing expanded portions of lines 1 and 2, respectively. The results indicate that a coherent reversal sequence overlies Explorer Seamount independent of the bathymetry. Comparison of this sequence with the geomagnetic time scale suggests that the largest positive peak, also interpreted as the youngest part of the seamount, is best tentatively identified as anomaly 2.1'. If this interpretation is correct, Explorer Seamount is not younger than 2.5 m.y. The fact that anomaly reversals can be seen to continue within the seamount to the east of the 2.1' anomaly peak may imply that the youngest material lies within the seamount and not at the eastern edge. NRM measurements of five basalt samples from Explorer Seamount averaged 3.8 A/m, consistent with an older age for the seamount since NRM values of basalts from the current Explorer spreading axis range from 30 A/m to 50 A/m. A single Curie temperature from one of the seamount basalt samples was 425°C, and exhibited the irreversible heating and cooling curves associated with the unmixing of oxidized titanomagnetite, properties that are also consistent with the older age for the seamount.

Lines 4 through 8, shown in Figure 5b, are profiles across Southern Explorer Ridge and Explorer Rift. In line 4, which overlies the southern end of Southern Explorer Ridge, the asymmetry of the Brunhes boundary about the ridge is evident, with Southern Explorer Ridge situated towards the eastern edge. The tectonic scarp bounding the high plateau to the east of Southern Explorer Ridge appears to be a magnetic reversal boundary as well as a tectonic boundary, indicating that this pronounced structural feature is at least 0.7 m.y. The older age would be consistent with the hypothesis that the plateau may be an eastern portion of Explorer Seamount which was displaced from the area now occupied by the valley to the east of Explorer

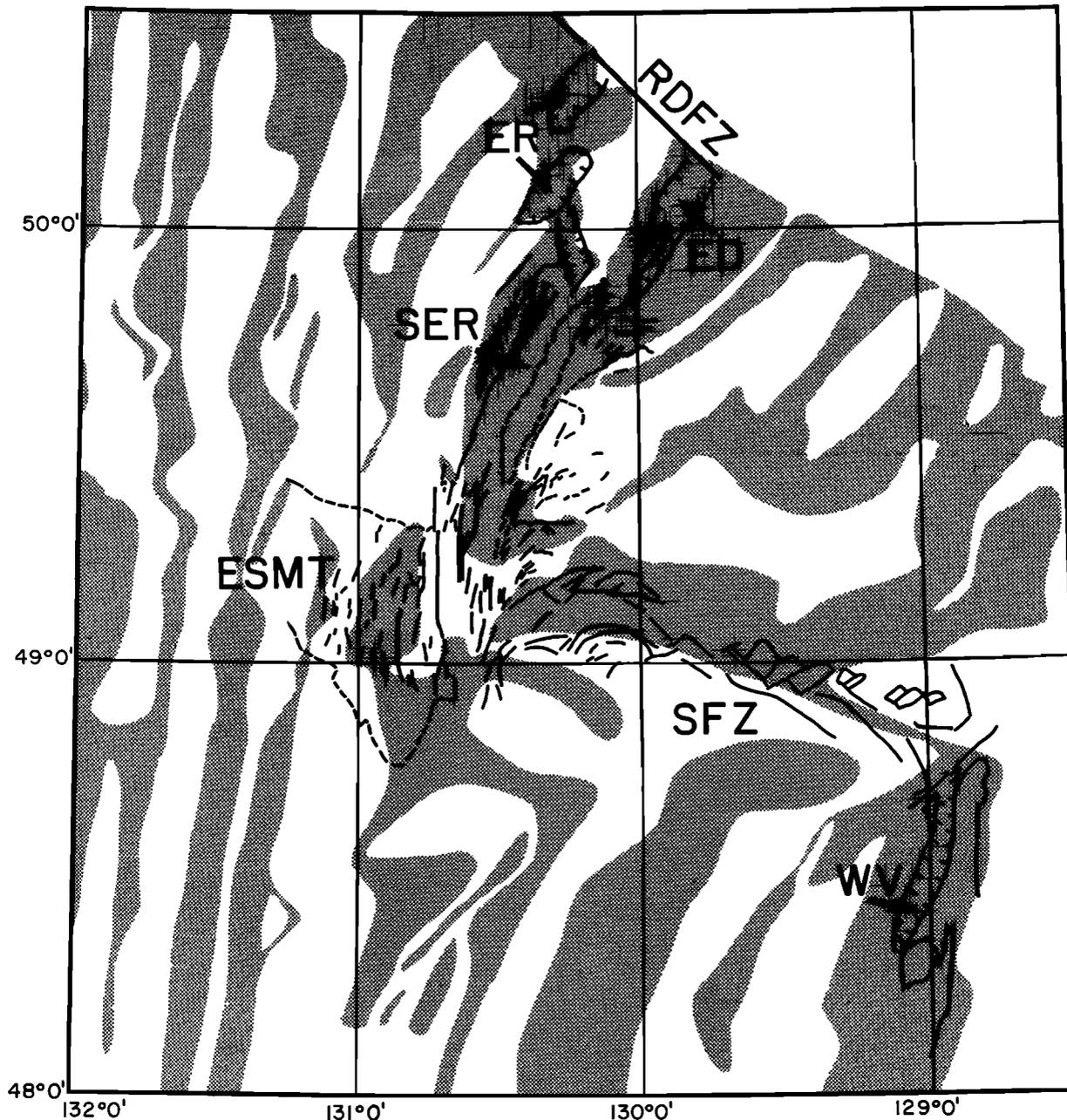
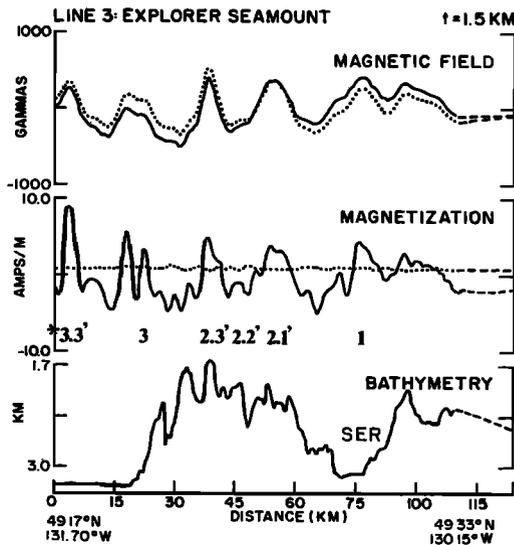
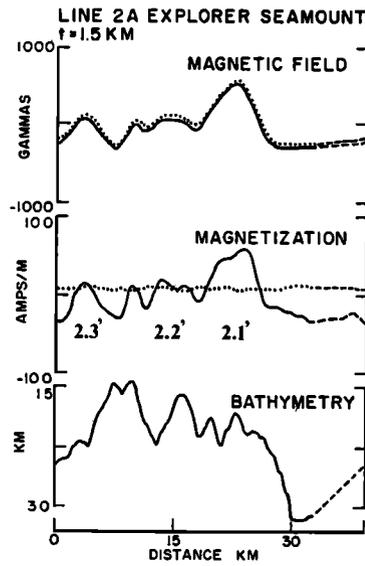
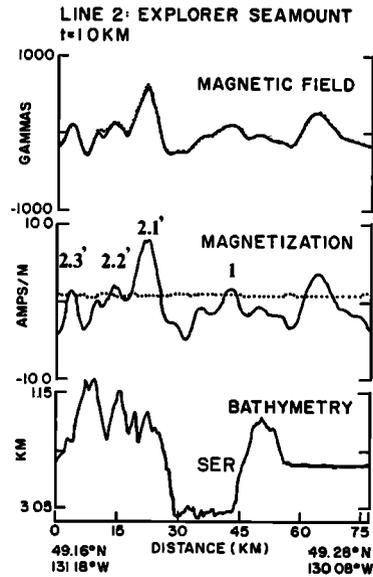
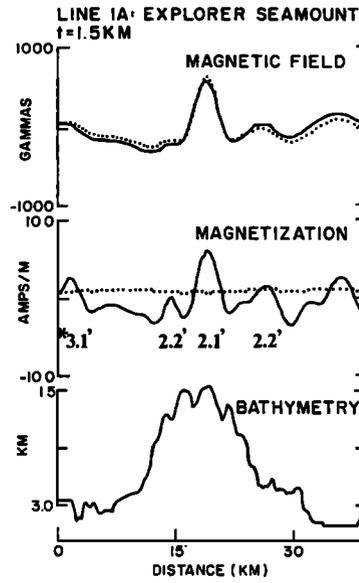
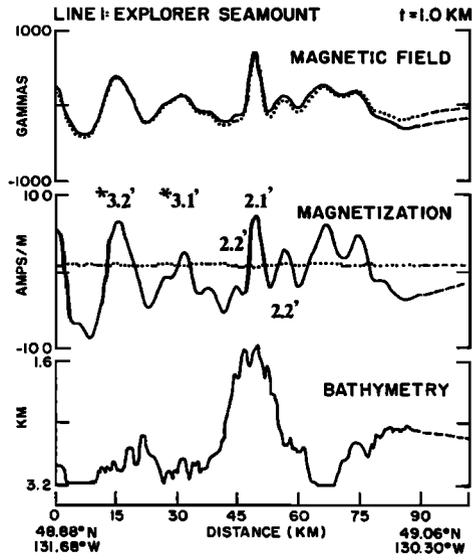


Fig. 4. Line drawing interpretation of the major tectonic features in the area superimposed on the schematic magnetic anomaly compilation. Stippled areas are positively magnetized, while white areas are negatively magnetized. Dashed lines represent the approximate boundaries of topographic highs. The left-laterally offset and rotated blocks of the Sovanco Fracture Zone are shown at approximately 49°N. Terminology used: RDFZ, Revere-Dellwood Fracture Zone; ER, Explorer Rift; ED, Explorer Deep; SER, Southern Explorer Ridge; ESMT, Explorer Seamount; SFZ, Sovanco Fracture Zone; WV, West Valley.

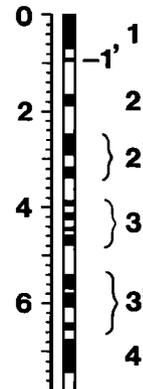
Seamount (Figure 5a, line 2). Line 5 in Figure 5b overlies a positive magnetic anomaly on the Explorer Plate which is continuous for approximately 50 km in an E-W direction (Figure 2). The bathymetric profile for line 5 reveals no positive topographic feature associated with this anomaly although the depth is 500 m to 700 m shallower than depths at equivalent distances from the ridge on the Pacific Plate (see lines 6 through 8, Figure 5b). It is unlikely that the increased sediment influx from the adjacent continental margin can entirely account for this depth difference between the Pacific and Explorer Plates. A seismic study by *Malacek and Clowes* [1978] indicated the

presence of a thin veneer (<250 m) of sediments and anomalously thick crust over a considerable area which extends 60 km east of Explorer Ridge. The anomalous thickness of the crust was attributed to crustal compression within Explorer Plate as had been predicted by the tectonic model of *Riddihough* [1977]. Inversion of the magnetic field and bathymetry data in this profile resulted in a positive magnetization for the crust.

Line 6 crosses the peak of Southern Explorer Ridge as well as the two "half ridges" lying to the west (see Figure 3a). Anomalies 1', 2', 3, and 3' can be identified on the Pacific Plate; however, anomaly 2 is missing west of Southern Explorer Ridge.



AGE (MY) ANOMALY NO.



The relative magnetic low immediately to the west of Southern Explorer Ridge overlies the sedimented valley discussed in the previous section and could represent hydrothermally leached Brunhes-age crust [Levi and Riddihough, 1986], rather than a magnetic reversal boundary. The valley overlain by a positive magnetic anomaly to the east of Southern Explorer Ridge in this profile is the southern end of Explorer Deep. Line 7 overlies Southern Explorer Rift and a seamount chain lying to the west on the Pacific Plate. The narrow peak associated with Explorer Rift is identified as the Brunhes. The bathymetric effects of the seamounts have been removed in the magnetization profile, allowing a more confident identification of the anomaly sequence although the general shape of the magnetization profile indicates inadequate low-frequency filtering. Line 8 crosses Northern Explorer Rift and shows the valley to be overlain by a positive anomaly peak which was identified as the Brunhes.

Having used the crustal magnetizations calculated by the inversion technique to constrain the isochron identifications in profile, this information could then be transferred to the magnetic anomaly map (Figure 6). The most complete reversal sequence north of the Sovanco Fracture Zone is found to the east and west of Northern Explorer, where the anomaly identifications shown in Figure 6 are similar to those of Riddihough *et al.* [1980]. Figure 6 shows a distorted anomaly pattern in a large, wedge-shaped region which extends from south and east of Explorer Seamount, northward to the area east of Southern Explorer Ridge. A coherent reversal sequence lies to the west of this zone and appears to originate within Explorer Seamount. The new data over Explorer Seamount is the most significant difference from the older Raff and Mason [1961] map, in which the Explorer Seamount area was overlain by a broad, poorly defined negative anomaly. The new compilation reveals a number of linear discontinuities in the magnetic anomalies which run oblique to the general N-S trend. These are interpreted as the traces of five propagating offsets with A, B, C, and D being right-lateral, and E the only left-lateral offset (Figure 6). Propagator C has been previously identified as a magnetic anomaly discontinuity by Riddihough *et al.* [1980, Figure 9].

As has been previously observed [Riddihough, 1977, 1984; Carlson, 1981], clockwise rotation of the anomalies with time occurred on both the Explorer and Juan de Fuca segments. In addition, the new data confirms earlier observations of

asymmetric spreading, with faster spreading to the east than to the west, on Northern Explorer [Riddihough, 1977; Riddihough *et al.*, 1980; Davis and Riddihough, 1982]. It is apparent from Figure 6 that the Sovanco Fracture Zone has lengthened with time, and currently offsets the northern Juan de Fuca Ridge from Southern Explorer Ridge by approximately 120 km.

Spreading rates and anomaly azimuths measured from the magnetic anomaly compilation are shown in Figure 7. The map was divided into five separate regions for this purpose: anomalies east and west of Northern Explorer, anomalies east and west of Southern Explorer, and the anomalies west of the Juan de Fuca Ridge. Data older than 6.5 m.y. were obtained from the Raff and Mason [1961] compilation. Spreading has been asymmetric in Northern Explorer, about 1 cm/yr faster to the east than to the west, since at least 3 Ma resulting in the northwestward migration of Explorer Ridge. On the other hand, spreading since the Jaramillo appears to have been 3 times faster to the west than to the east on Southern Explorer Ridge. Spreading rates measured west of Explorer Ridge are consistently slower than those measured west of the Juan de Fuca Ridge for the last 7.5 m.y., and the rates have generally declined for both ridge systems during this time interval.

The graphs on the right side of Figure 7 show that clockwise reorientation of the anomalies from a N-S trend began about 8 Ma. Rotation continued at approximately the same rate on both the Juan de Fuca and Explorer Ridges until 4 Ma. Since this time, the Juan de Fuca Ridge has remained at an orientation of about N20°E, while Explorer Ridge has continued to rotate at a rate significantly faster than that prior to 4 Ma. For example, a change in azimuth of about 12° is observed in the Explorer anomalies between the start and end of anomaly 2', which is equivalent to a rotation rate of 13°/m.y. during the time interval of 3.4 Ma to 2.5 Ma. This clockwise motion allowed the ridge to be oriented more perpendicular to the convergence zone (see Figure 1). The current spreading segments of Northern Explorer are oriented between N36°E and N42°E, while Southern Explorer Ridge has an orientation of N28°E. Total spreading rates on Explorer Ridge are plotted at the bottom of Figure 7 and show considerably faster spreading in the north than in the south: 4.4 cm/yr and 3.0 cm/yr, respectively, during the Brunhes. This difference is consistent with a current pole of rotation for Pacific/Explorer motion calculated by Riddihough [1984] as lying to the southwest. Similar results for spreading rate and anomaly azimuths were obtained by Riddihough [1977, Figure 3; 1984, Figure 6] for the Explorer and Juan de Fuca Ridges, and a similar rotation history was determined by Carlson [1981, Figure 5] for the Juan de Fuca Ridge.

EVOLUTION OF THE EXPLORER-NORTHERN JUAN DE FUCA REGION

A plate tectonic history for this area must account for the following features: (1) the observed linear offsets in the magnetic anomaly pattern; (2) clockwise anomaly rotation; (3) asymmetric spreading with faster spreading to the east on Explorer Ridge; (4) a magnetic reversal sequence originating within Explorer Seamount; (5) lengthening of the Sovanco

Fig. 5a. (opposite) Results of inversion of the magnetic data from lines shown in Figure 2. The upper solid line is the actual magnetic field data, while the upper dotted line is the magnetic field generated by the calculated magnetization and bathymetry and used as a consistency check. The middle graph shows the inverted crustal magnetization in units of amps per meter as a solid line and the annihilator as a dotted line. The numbers associated with the magnetization peaks are anomaly identifications. An asterisk in front of an anomaly number indicates crust formed at the Juan de Fuca Ridge. The bottom curve is the bathymetric profile with a depth scale in kilometers. The assumed thickness of the magnetic layer in kilometers is indicated by the letter *t* at the top. SER defines the location of the current axis of spreading on Southern Explorer Ridge. Filters used in the inversion program were average water depths for short wavelengths and approximate trackline lengths for long wavelengths. The time scale used in the magnetic anomaly identifications, based on Ness *et al.* [1980], is shown in the lower right corner.

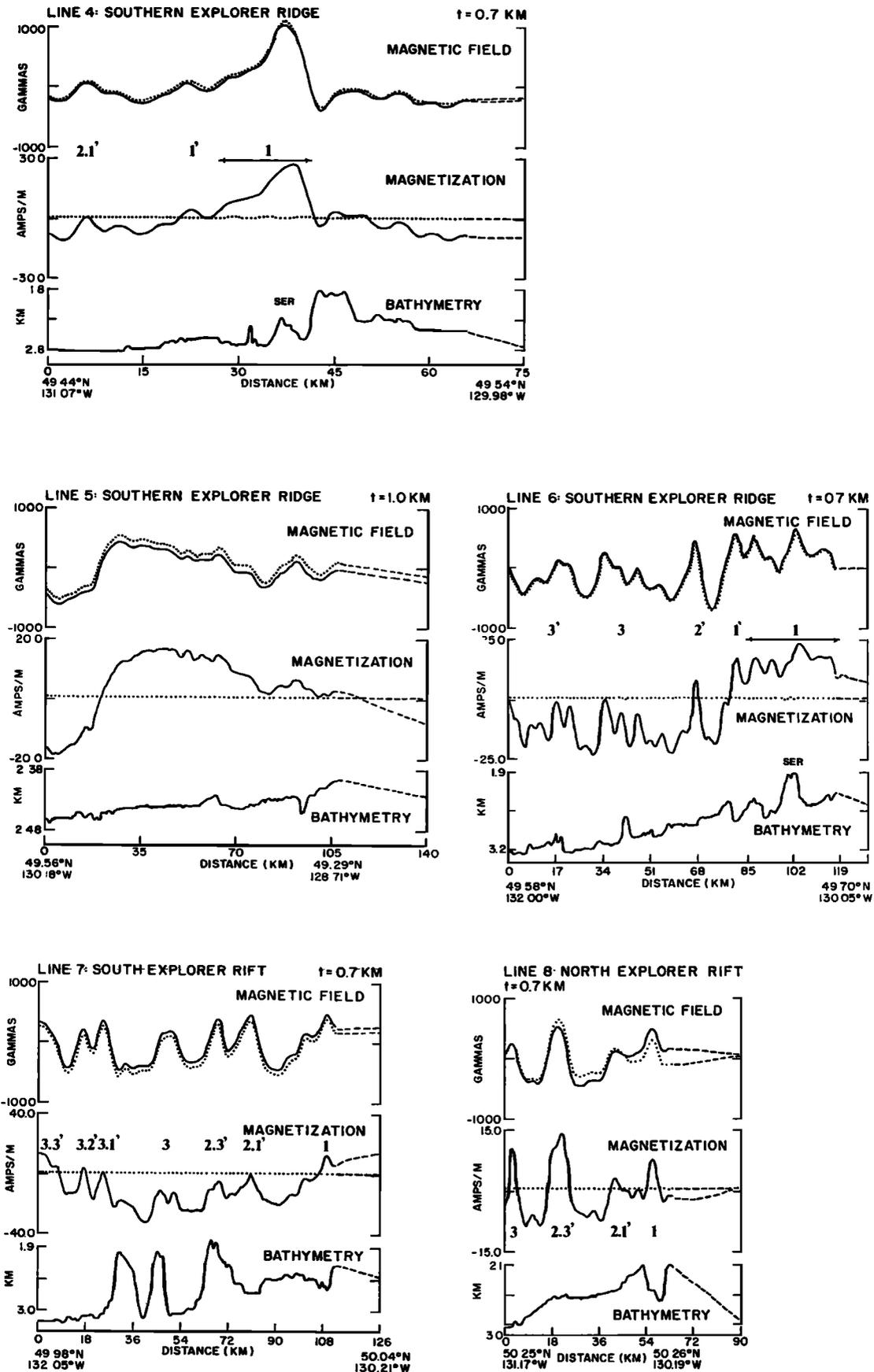


Fig. 5b. Inversion of additional profiles from the tracklines of Figure 2. The same format as Figure 5a is used.

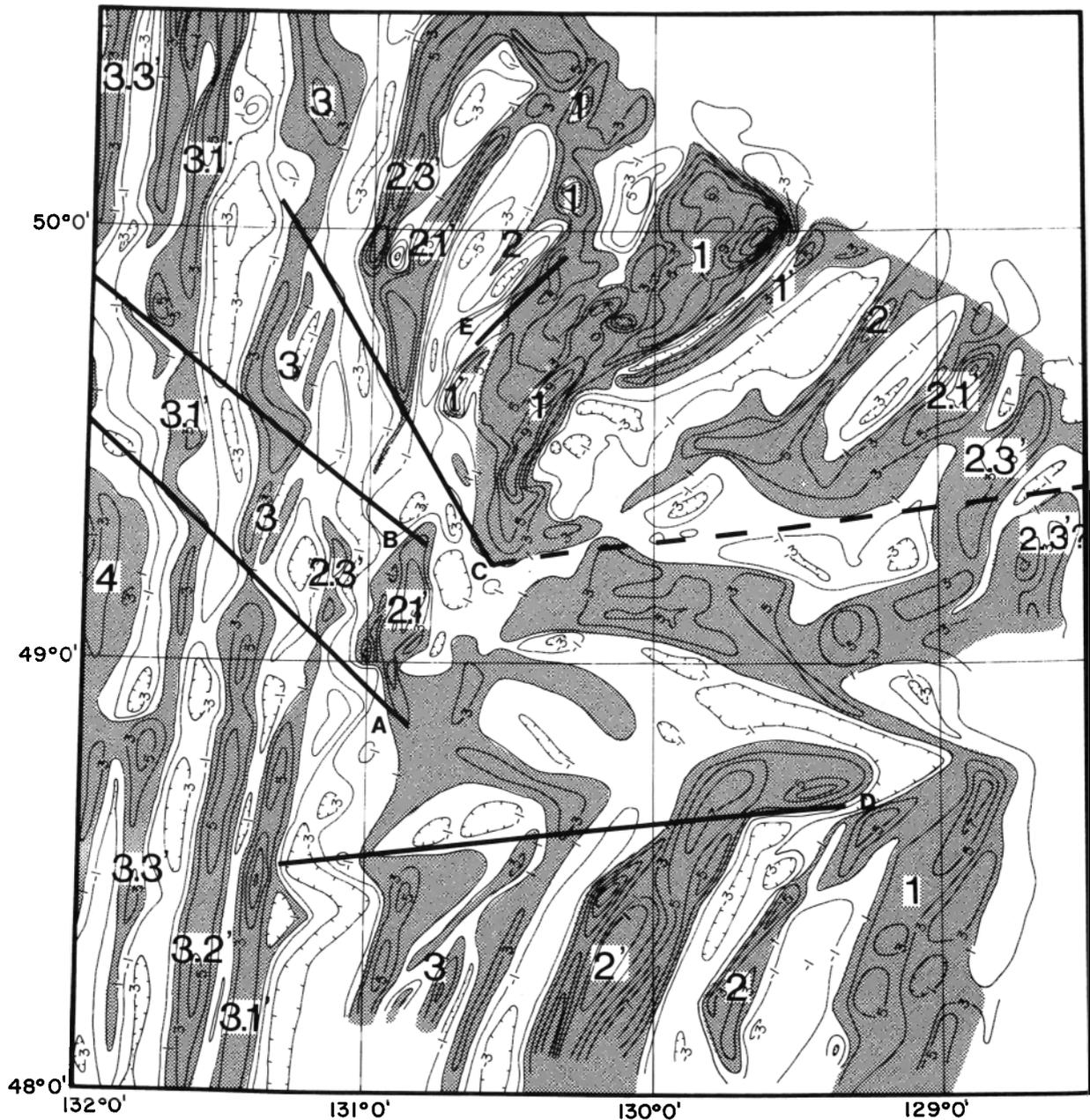


Fig. 6. Contour map of magnetic anomalies for the new data compilation overlain with anomaly identifications. Solid lines represent proposed propagator wakes and dashed lines represent hypothetical propagator wakes which are needed in a comprehensive model but are not clearly supported by the data. As in Figure 4, grey stippled areas are regions of positively magnetized crust and white areas are negatively magnetized. Labels A, B, C, D, and E are used to identify propagators discussed in the text.

Transform with time; (6) a predominance of E-W trending anomalies in the Sovanco Transform region.

The time of the earliest discontinuous N-S anomaly on the Pacific Plate west of the Juan de Fuca Plate is 7.4 Ma (Figure 8); until the end of anomaly 4' (7.8 Ma), the Explorer and Juan de Fuca Ridges were essentially one continuous spreading center. We suggest that two offsets (A and B in Figure 6) developed around the beginning of anomaly 4 time (7.4 Ma), as can be seen in the original *Raff and Mason* (1961) data. Offset A represents the first appearance of the Sovanco Fracture zone, which then began to propagate southward at 1.9 cm/yr. The northern offset,

B, propagated in the same direction as A at a slower rate of about 1 cm/yr. The origin of the Sovanco by a southward propagating offset has been previously proposed by *Wilson et al.* [1984], although the time and place of initiation, as well as the rate of propagation, differs from this interpretation of the combined *Raff and Mason* [1961] and the new magnetics data. Propagator 5 of *Wilson et al.* [1984] first appeared at 8.56 Ma at a latitude of about 51°N and propagated southward at approximately 3.9 cm/yr, whereas offset A originated at 7.4 Ma at a latitude of 49.6°N and propagated at a rate of 1.9 cm/yr.

Half-spreading rates measured from Pacific Plate anomalies

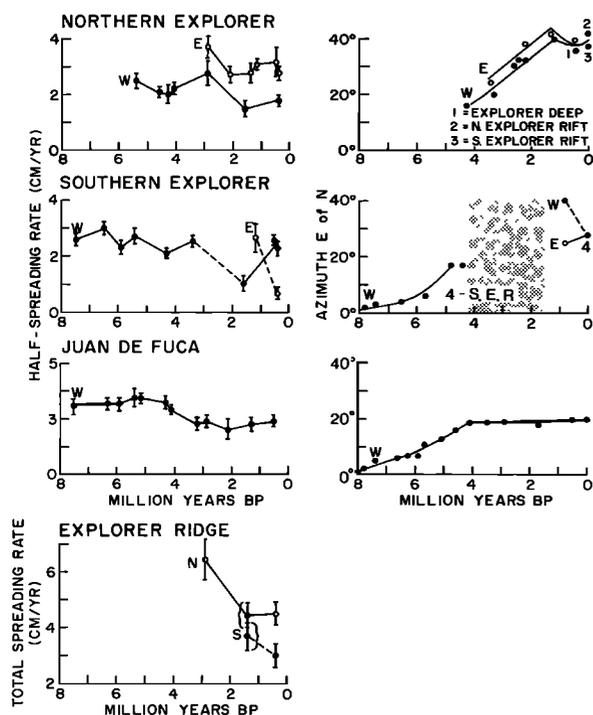


Fig. 7. Spreading rates and azimuths of the axis of spreading for the Explorer and Northern Juan de Fuca Ridges shown as a function of time. Spreading rates are shown on the left side of the figure and azimuths on the right. Spreading rates have generally decreased on all segments over the last 6 m.y. while the axes of spreading have rotated in a clockwise direction. The latter movement allowed the ridge to become more orthogonal to the zone of active subduction (see Figure 1). In the lower left curve, N, Northern Explorer and S, Southern Explorer. Error bars on spreading rates are standard deviations obtained from at least four separate measurements. Azimuths have an average error of $\pm 2^\circ$.

were slightly slower on the Explorer Ridge than on the Juan de Fuca Ridge at the beginning of anomaly 4 time. The portion of ridge that would eventually produce Explorer Seamount can be modeled as the southernmost spreading segment of the Explorer Ridge system (ESS or Explorer Seamount Segment in Figure 8), bounded by offset A to the south and offset B to the north. If one extrapolates through time and assumes that spreading on Explorer has been asymmetric with faster spreading to the east since the time of the initiation of the Sovanco Fracture Zone, then the independence of the Explorer Plate is not required until 4 Ma as proposed by *Riddihough* [1984]. At this time the anomaly azimuths on the Explorer and Juan de Fuca ridges begin to differ significantly, and corresponding plate motion can no longer be described by the same pole of rotation relative to the Pacific Plate.

Having made the assumption of asymmetric spreading to the east since 7.4 Ma, total spreading rates on Explorer Ridge are only slightly slower than those on the Juan de Fuca Ridge at 4.8 Ma, consistent with a previously identified pole of rotation for Pacific/Juan de Fuca motion to the north [*Riddihough*, 1984]. However, asymmetric spreading with approximately 30% faster accretion to the east than to the west may have resulted in the northwestward migration of Explorer Ridge, and lengthening of the Sovanco Transform Fault. We suggest that two new magnetic anomaly offsets developed at the end of anomaly 3'

time, or 4.8 Ma. The one to the north on Explorer Ridge, offset C in Figure 6, began to propagate to the south at a rate of 2.9 cm/yr. Offset D developed on the Juan de Fuca Ridge and began to propagate northward at about 1 cm/yr. The trace or "pseudofault" of propagator D in the magnetic anomaly pattern lies to the north of that of propagator 7 in *Wilson et al.* [1984].

By 3.4 Ma or the beginning of anomaly 2' (Figure 8), Explorer Plate has clearly separated from the Juan de Fuca Plate as a result of its resistance to subduction at the convergent margin [*Riddihough*, 1984]. Continued clockwise rotation, with a faster total spreading rate in the north than in the south, indicates that Explorer/Pacific motion was centered on a nearby pole of rotation to the southwest. Relative motion between the Juan de Fuca and Explorer plates is taken up by the Nootka fault [*Hyndman et al.*, 1979]. At this time, the three northern propagators continued to move south while offset D propagated to the north. There is evidence for the eastern branch of the northward propagator on the Juan de Fuca in the magnetic anomaly compilation of *Connard et al.* [1984]. As is the case on the Pacific Plate, the discontinuity in the Juan de Fuca Plate magnetic anomaly pattern first appears at the end of anomaly 3', or 4.8 Ma.

By 2.5 Ma (Figure 8), propagator D will have intersected the Sovanco Transform Fault, thereby increasing its length. Assuming that spreading was roughly perpendicular to the N170E trending ridges of Explorer Seamount, then the direction of spreading on the Explorer Seamount Segment was approximately parallel to that on the Juan de Fuca Ridge at 2.5 Ma. Northern Explorer Ridge was by this time, however, oriented 120° more clockwise than the Juan de Fuca Ridge. A major plate boundary reorganization, in which the Sovanco Fracture Zone plays a significant role, began to take place at this time. We propose that the transform, in response to forces acting at the convergence zone, began to reorient in a clockwise direction. This led to a situation of greater tectonic equilibrium [*Menard and Atwater*, 1968], since the clockwise movement allowed the Sovanco Fracture Zone to approach an orthogonal configuration with the more clockwise strike of Northern Explorer Ridge. The northward movement of the transform boundary would then have isolated the Explorer Seamount segment from the remainder of Explorer Ridge. It is possible that during this period of plate boundary readjustment, the plateau now situated to the east of Southern Explorer Ridge may have been moved northward from its position as the eastern portion of Explorer Seamount. However, an exact mechanism for such a translocation, such as a major, throughgoing, NE-SW-oriented strike-slip fault, is not evident in the data.

During the migration of the Sovanco Fracture Zone through the crust, the transform will have produced a broad shear zone. Tectonic deformation within this shifting zone will have distorted the previously existing N-S magnetic anomaly pattern, possibly replacing it with an E-W magnetic fabric. In this regard, the most likely process to have produced the present E-W magnetic anomaly trend involves coherent alteration associated with serpentinization of ultramafics along E-W oriented fractures within the shear zone. The secondary magnetite formed during this alteration process would have been magnetized in the

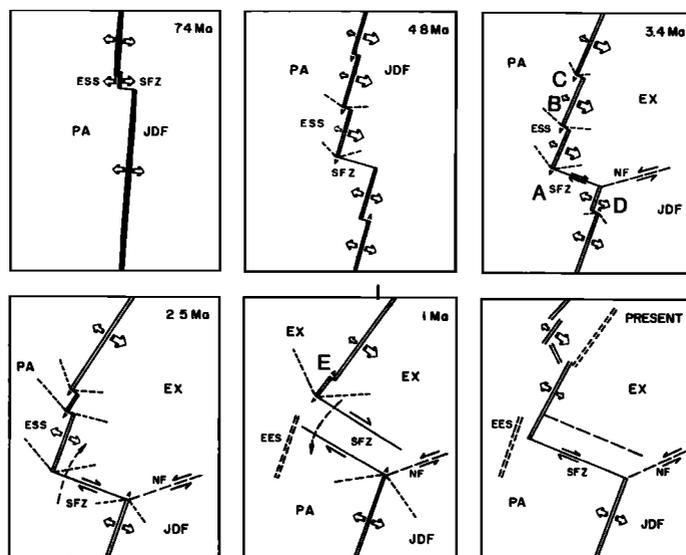


Fig. 8. A concept for the tectonic evolution of the Explorer and Northern Juan de Fuca Ridges during the last 8 m.y. Size of the arrows is roughly proportional to the half-rate of spreading. Thin dashed lines are propagator wakes, the broad dashed line represents the Nootka Fault. Terminology used: PA, Pacific Plate; JDF, Juan de Fuca Plate; EX, Explorer Plate; ESS, Explorer Seamount Segment; EES, Extinct Explorer Seamount; SFZ, Sovanco Fracture Zone; NF, Nootka fault. Letters A, B, C, D, and E in bold identify propagators interpreted from equivalently labelled linear discontinuities in the magnetic anomaly pattern shown in Figure 6. Dashed arrow at 2.5 Ma indicates direction of SFZ reorientation between 2.5 Ma and 1 Ma. Similarly, the dashed arrow at 1 Ma shows counterclockwise direction of motion for the SFZ between 1 Ma and the present.

direction of the contemporaneous field. *Fox and Opdyke* [1973] showed that serpentinized intrusive rocks can be strongly magnetic and are commonly associated with, or are products of, the tectonics of fracture zones. The presence of a roughly E-W oriented gravity low in this area [*Earth Physics Branch, Energy, Mines, and Resources, Canada, 1985a*] supports this hypothesis, since it indicates the presence of lower density material.

By 1 Ma (Figure 8), the Sovanco Fracture Zone will have reached its northernmost position as indicated by the southern limit of the Jaramillo to the west of Southern Explorer Ridge (Figure 6). Also by this time, offsets B and C have been absorbed by the transform fault, thereby increasing its length. The Explorer Seamount segment now exists as an abandoned spreading center on the Pacific Plate to the southwest of Explorer Ridge. At 1 Ma, a new left-lateral offset (E in Figure 6) developed in Northern Explorer. The segment to the north of this offset would be the proto-Explorer Deep which, on the basis of the Jaramillo anomaly on the Explorer Plate (Figure 6), extended about 22 km southward of its present limit [Botros et al., 1986]. The segment south of offset E is the proto-Southern Explorer Ridge. Between 1 Ma and the present, this southern segment appears to have propagated to the north as spreading declined in Explorer Deep. During the same time interval, the southern tip of Southern Explorer Ridge may have propagated to the south as indicated by the present southern extent of the Brunhes anomaly over this segment. The southward propagation of Explorer Ridge would have caused the western end of the Sovanco Fracture Zone to reverse its northward motion through the crust. The more northward extent of the Jaramillo on the Juan de Fuca Plate, in comparison to the present northern limit of West Valley [Connard et al., 1984; Karsten et al., 1986], supports a progressively more southward position for the transform fault between 1 Ma and the present.

The magnetic anomaly "pseudofaults" at the northern end of Southern Explorer Ridge (Figure 6) do not show the classic form of a V pointing towards the propagator tip as described by *Hey and Wilson* [1982]. Assuming the half-ridges lying to the west of Southern Explorer Ridge (Figure 3a) were produced by this segment, northward propagation of Southern Explorer Ridge must have occurred very rapidly between the Jaramillo and the beginning of the Brunhes (offset E in Figure 6). Since the trace of the pseudofault does not intersect the current northern tip of Southern Explorer Ridge which lies further to the east, it appears that the locus of spreading on Southern Explorer Ridge has jumped to the east during the Brunhes. This mechanism would account for the extreme asymmetry of the Brunhes boundary about Southern Explorer Ridge (Figure 4). Constraints placed by the bathymetry and the magnetic anomaly pattern, however, suggest that southward propagation of Southern Explorer Ridge probably occurred after the eastward ridge jump.

Support for continued northward propagation on Southern Explorer Ridge comes from geochemical analyses by *Michael et al.* [1986], who reported the occurrence of iron-enriched Fe-Ti basalts at the highest portion of the ridge. This latitude corresponds to a distance of 18 km, or about 600,000 years, behind the northern propagator tip and is consistent with the model of *Christie and Sinton* [1981] for northward propagation of this ridge segment. In addition to the FeTi enrichment, the axial rocks of Explorer Ridge are substantially more magnetic (30-50 A/m) than those found on a normal MORB spreading center [Johnson and Atwater, 1977]. Coupled with the high amplitude magnetic anomalies shown in Figure 6, this medium spreading rate ridge fulfills all of the requirements for the magnetotelechemistry hypothesis, i.e., FeTi basalts, highly magnetic extrusives, and high amplitude magnetic anomalies [Vogt and Johnson, 1973]. In addition to the rock data in support

of recent rift propagation, submersible observations of rifting in the absence of recent volcanic activity, together with a northward age progression of hydrothermal deposits from oldest to youngest at the shoalest portion of the ridge, led *Tunncliffe et al.* [1986] to propose that the central axial rift of Southern Explorer Ridge is propagating northward into previously unbroken crust.

With the timing constrained by the width of the Brunhes anomaly over Explorer Rift, spreading may have jumped westward from Explorer Deep to the two en echelon segments comprising Explorer Rift around 0.3 Ma, thereby producing the present Explorer spreading center configuration (Figure 8). The now extinct Explorer Seamount segment is located on the Pacific Plate to the southwest of Southern Explorer Ridge.

IMPLICATIONS FOR REGIONAL PLATE INTERACTIONS

One of the major drawbacks inherent in any attempt to decipher the tectonic evolution of this complex region is the fact that half of the story is missing. In the case of the Explorer Plate, no marine magnetic anomalies older than about 3.4 Ma remain. Therefore an interpretation of the plate tectonics of the region prior to this time hinges on the Pacific Plate anomaly data. In an area where rift propagation, ridge rotation, asymmetric spreading, and ridge jumping are not uncommon, the usual simplifying assumptions of symmetric and perpendicular spreading become questionable, and the solutions nonunique.

The timing of the independence of the Explorer Plate from the Juan de Fuca Plate is not clear and can only be constrained to one of two epochs; if one assumes that spreading was symmetric about Explorer Ridge between 8 Ma and 3 Ma, then the total spreading rate on Explorer Ridge was slower by approximately 2 cm/yr than the contemporaneous spreading rate on the Juan de Fuca. In this case, Pacific/Explorer motion and Pacific/Juan de Fuca motion would have been centered on different poles of rotation since approximately 7.5 Ma. On the other hand, if one assumes that spreading has been asymmetric to the east on Explorer Ridge since 8 Ma, such that the total spreading rate on Explorer is not significantly slower than the total spreading rate on the Juan de Fuca, then the independence of the Explorer Plate is not required until the azimuths of the anomalies formed at the Explorer and Juan de Fuca Ridges, and the assumed directions of spreading, begin to differ significantly at 4 Ma. The question arises whether it is valid to assume that spreading can be asymmetric for a period of 7 m.y.? In other words, can asymmetric spreading occur on a steady-state basis? Such an assumption may not be unreasonable in this complex region, and was therefore invoked in the tectonic history suggested in Figure 8.

The proposed history for the Sovanco Fracture Zone is one of an offset that lengthens and propagates southward from the time of its initiation at around 7.5 Ma to approximately 2.5 Ma. The idea that the Sovanco offset has moved southward rather than remained stationary is supported by the presence of a NW-SE trending, as opposed to an E-W trending, linear discontinuity in the Pacific Plate magnetic anomalies.

Clockwise rotation of the Sovanco Fracture Zone began at the end of anomaly 2' time (2.5 Ma), following considerable rotation

of Northern Explorer Ridge in the same direction during anomaly 2'. This reorientation, like the earlier clockwise rotation of Explorer Plate and Northern Explorer Ridge, is a direct response to forces acting at the convergent margin. The readjustment of the Sovanco Fracture Zone is probably delayed with respect to that of Explorer Ridge since the resistance to motion on transforms, which must break through old crust in order to reorient themselves, is much greater than the resistance to motion at spreading centers. In our hypothesis, large-scale deformation associated with the movement of this shear zone through the crust is used to account for the lack of coherent, N-S oriented anomalies in the large, wedge-shaped region which extends from east of Explorer Seamount, northwards to the area east of Southern Explorer Ridge (Figure 6). In invoking serpentinization of ultramafics along E-W trending fractures as a mechanism for producing the observed E-W magnetic fabric, this model predicts the occurrence of high magnetic intensity and high susceptibility rocks in the region of the Sovanco Fracture Zone.

Anomaly distortion within a migrating Sovanco Fracture Zone cannot explain all of the E-W oriented anomalies, however, since some are found to the north of the northernmost extent of the transform (for example, line 5, Figure 5b). The ambiguous anomaly pattern in this area may be the result of crustal deformation within Explorer Plate as suggested by the occurrence of several intraplate earthquakes (G. C. Rogers, personal communications, 1986). The observed recent counterclockwise rotation of Southern Explorer Ridge, which may represent an attempt by this ridge segment to achieve an orthogonal configuration with the Sovanco Fracture Zone, has resulted in a considerable difference between its orientation and that of the northern Explorer spreading segments comprising Explorer Rift. If spreading is occurring perpendicular to the current trends of each of these rift segments, then the approximately 12° more clockwise orientation of Explorer Rift compared with Southern Explorer Ridge implies that some degree of compression, and hence intraplate deformation, must be taking place to the east.

CONCLUSIONS

1. Over the last 8 Ma, the Explorer-Northern Juan de Fuca region has had a complex tectonic history of northward and southward propagating rift offsets, and this history is further complicated by both asymmetric spreading and rapid spreading center jumps.

2. The Sovanco Fracture Zone originated as an offset between Explorer Ridge and the Juan de Fuca Ridge approximately 7.4 Ma. Since the time of its formation to the end of anomaly 2', the transform has migrated southward due to southward propagation of Explorer Ridge, and has been lengthened by asymmetric spreading to the east on Explorer Ridge, as well as by the addition of three propagating offsets. Two of the offsets were southward moving propagators from Explorer Ridge and one was a northward moving propagator from the Northern Juan de Fuca Ridge.

3. At the end of anomaly 2', the Sovanco Transform developed into a broad zone of shear that underwent first clockwise, and then counterclockwise rotation. The current expression of the Sovanco Fracture Zone, as well as the area to the north and south,

is overlain by an E-W magnetic fabric which may have been produced by remagnetization of ultramafics during shearing and serpentinization.

4. Southwest of Explorer Ridge, Explorer Seamount is composed of a series of curvilinear ridges that are overlain with lineated magnetic anomalies. These anomalies are interpreted as having formed at an abandoned spreading center segment originally a part of the Explorer Ridge system. The Explorer Seamount segment may have been isolated from the remainder of Explorer Ridge by the northward movement of the Sovanco Fracture Zone between 2.5 Ma and 1 Ma. Although there is no bathymetric feature equivalent in scale to Explorer Seamount immediately to the east, the broad plateau situated east of the southern end of Southern Explorer Ridge may represent an eastern portion of Explorer Seamount that was moved northwards during this period of major plate boundary reorganization. The reason for the mass excess that forms the general elevation of the seamount is not clear.

5. Analysis of the anomaly patterns argues for a separation of the Explorer Plate from the Juan de Fuca Plate, but the timing of this separation is not uniquely determined due to a lack of magnetic anomaly data older than 3.4 Ma on Explorer Plate. The Pacific Plate magnetic anomaly pattern will allow the formation of a separate Explorer Plate at the Nootka Fault either at 4 Ma or 7 Ma. The 4 Ma date is preferred on the basis of the available data, but this interpretation requires an assumption of asymmetric spreading to the east on Explorer Ridge between 4 Ma and 7 Ma.

6. The recent (<1 Ma) tectonic evolution of the Explorer Spreading Center system involves rapid northward propagation of Southern Explorer Ridge between 0.9 Ma and 0.7 Ma as Explorer Deep "retreated" northwards. During the Brunhes, an eastward jump of Southern Explorer Ridge took place followed by southward and continued northward propagation. In the northern Explorer region, Sea Beam and SeaMARC II data suggest that the locus of spreading has recently shifted about 40 km to the northwest, from the eastern Explorer Deep to the western Explorer Rift. Magnetic anomaly data over Northern Explorer indicates that the ridge jump occurred approximately 0.3 Ma.

7. Analyses of rock samples from Explorer Ridge reveal that, like spreading centers with similar tectonic environments where multiple events of rift offset propagation have taken place (Galapagos and Juan de Fuca Ridges), Explorer extrusive rocks are both FeTi enriched and very strongly magnetized. The along-strike pattern of FeTi enrichment shows the maximum enrichment to be 18 km (0.6 m.y.) behind the most recent passage of a propagating offset. This further example adds to the growing body of evidence that the tectonic history of a spreading center can strongly influence both the geochemical and geophysical properties of the upper extrusive crust.

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