Structure and tectonic history of the eastern Panama Basin

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ABSTRACT

New marine geophysical data allow the preparation of revised bathymetric and magnetic anomaly charts of the Panama Basin and demonstrate that the eastern part of the basin, between the fracture zone at long 83°W and the Colombian continental margin, was formed by highly asymmetric sea-floor spreading along the boundary of the Nazca and Cocos plates 27 to 8 m.y. B.P. Lineated magnetic anomalies recording this history are oriented approximately east-west. The oldest set of north-flank anomalies overlaps in age with those adjacent to the Grijalva scarp, south of the western Panama Basin, where they are oriented 065°. Younger anomalies (5C to 5) in the eastern basin are approximately parallel to anomalies of this age identified on the Carnegie platform and the flanks of the Costa Rica rift. The eastern basin now contains a pattern of fossil spreading centers (including the Malpelo rift) and transform faults (including the Yaquina graben) that were abandoned 8 m.y. B.P. by a shift in plate boundaries that transferred a large section of the Cocos plate to the Nazca plate. Cessation of Nazca-Cocos spreading east of long 83°W was heralded by a 3-m.y. deceleration of spreading on the eastern segments, which created rough topography and axial rift valleys typical of slow-spreading ridges. Westward jumping of the Nazca-Cocos-Caribbean triple junction rejuvenated the northern segment of the fracture zone at long 83°W, causing uplift of the adjacent Coiba Ridge. Recently, active transform faulting has jumped farther west, from the foot of the Coiba Ridge to the Panama fracture zone.

Apart from changes in plate boundaries, the main event in the tectonic evolution of the region was initiation about 22 to 20 m.y. B.P. of the hot spot that created the Malpelo, Cocos, and Carnegie Ridges. Precursors of effusive ridge-building volcanism included major fracturing of the oceanic crust to the north of the present Malpelo Ridge. Both processes hamper identification of magnetic anomalies in the vicinity of the ridges. Our interpretation of the tectonic history is also incomplete in the easternmost parts of the basin, where data are insufficient; this impairs our interpretation of the adjacent continental geology in terms of changing interaction between oceanic and continental plates. The geologic history of the Isthmus of Panama is compatible with our application of the plate-tectonic model.

INTRODUCTION

The Panama Basin is that part of the eastern equatorial Pacific between the aseismic Cocos and Carnegie Ridges and the continental margins of Panama and Colombia. For the western half of the basin, the rigorous application of plate-tectonic principles to a high density of marine magnetic data has yielded a detailed and consistent evolutionary sceme that is corroborated by heat flow and reflection profiling data (Hey and others, 1977; Anderson and others, 1976). The Panama Basin west of long 83°W has been created in the past 12 m.y. by approximately north-south spreading from the Cocos-Nazca plate boundary, which is now actively spreading in three segments bounded by major transform faults. We call these segments, following Herron and Heirtzler (1967), Raff (1968), and Grim (1970a), the Galapagos rift, which extends from the transform fault at long 90°W (or Galapagos Island fracture zone) to long 85.5°W; the short Ecuador rift, between the transform faults at long 85.5° and 84.5°W (the Ecuador fracture zones); and the Costa Rica rift, whose eastern limit is the large transform fault near long 83°W that has been called both the Panama fracture zone (Molnar and Sykes, 1969) and the Coiba fracture zone (van Andel and others, 1971). Vogt and de Boer (1976) referred to the transform fault at long 85.5°W as the "Inca fracture zone." Part or all of the Cocos-Nazca spreading center has previously been called the Galapagos rise (Johnson and others, 1976) and the Galapagos spreading center (Sclater and Klitgord, 1973). Complications in its evolution include asymmetric spreading, performed in part by discrete jumps of the plate boundary, and the presence of a "hot spot," a locus of excessive volcanism at or near the plate boundary, which has created the Cocos and Carnegie Ridges and is now building the Galapagos Islands (Hey and others, 1977).

East of long 83°W, the structure, and presumably the tectonic evolution, is still more complex. Active Cocos-Nazca spreading does not extend into this older part of the basin. Seismicity there is restricted to the continental margins and at the fracture zone at long 83°W (Molnar and Sykes, 1969); most of the structural features of the eastern basin are evidently relict (van Andel and others, 1971). No patterns of lineated magnetic anomalies have heretofore been identified and correlated to the geomagnetic time scale, and the only age datum available is from (Deep Sea Drilling Project) site 155 on the Coiba Ridge, where 15-m.y.-old sediment overlies alkali basalt (van Andel, Heath, and others, 1973). However, extrapolation of plate and hot-spot motions determined from the detailed mapping of younger anomalies along the western part of the Cocos-Nazca boundary (Hey and others, 1977) has allowed Hey (1977) to predict some aspects of the tectonic evolution of the eastern basin. These include the formation of Malpelo Ridge and the eastern part of Carnegie Ridge by a hot spot about 20 to 18 m.y. B.P., their separation by continued north-south spreading along a segment of the Cocos-Nazca spreading center, and the increasing

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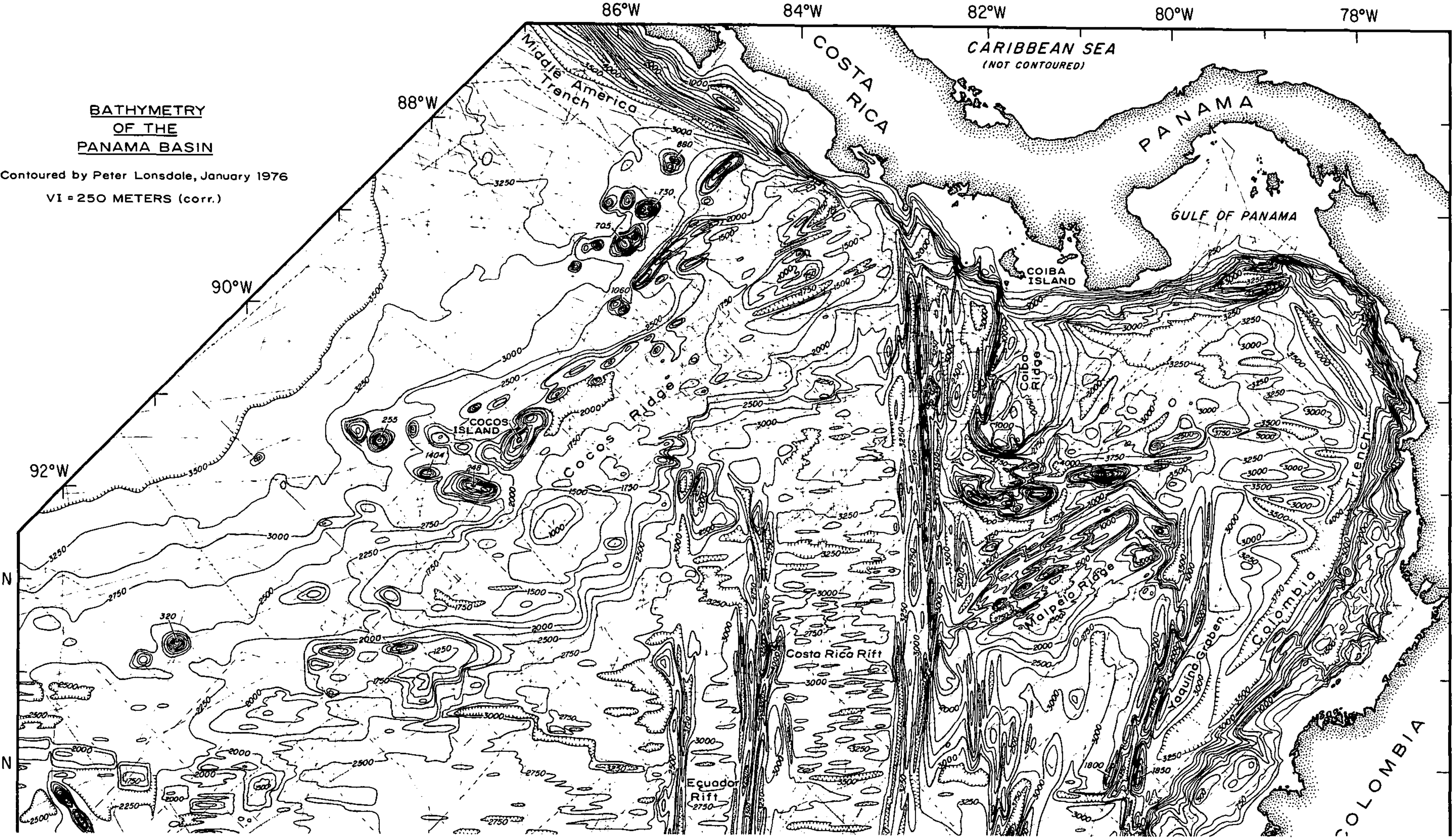


BATHYMETRY
OF THE
PANAMA BASIN

Contoured by Peter Lonsdale, January 1976

VI = 250 METERS (corr.)

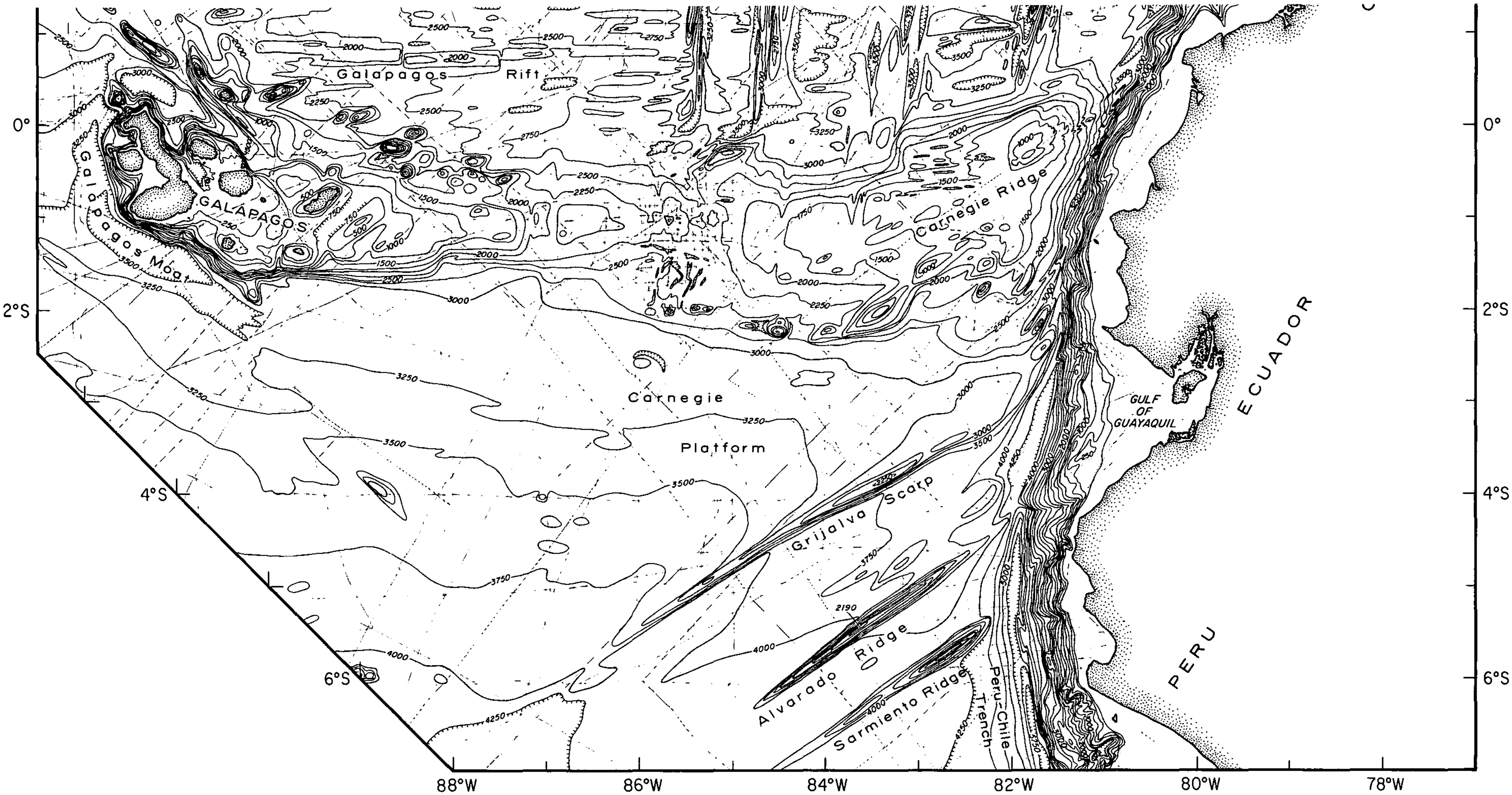
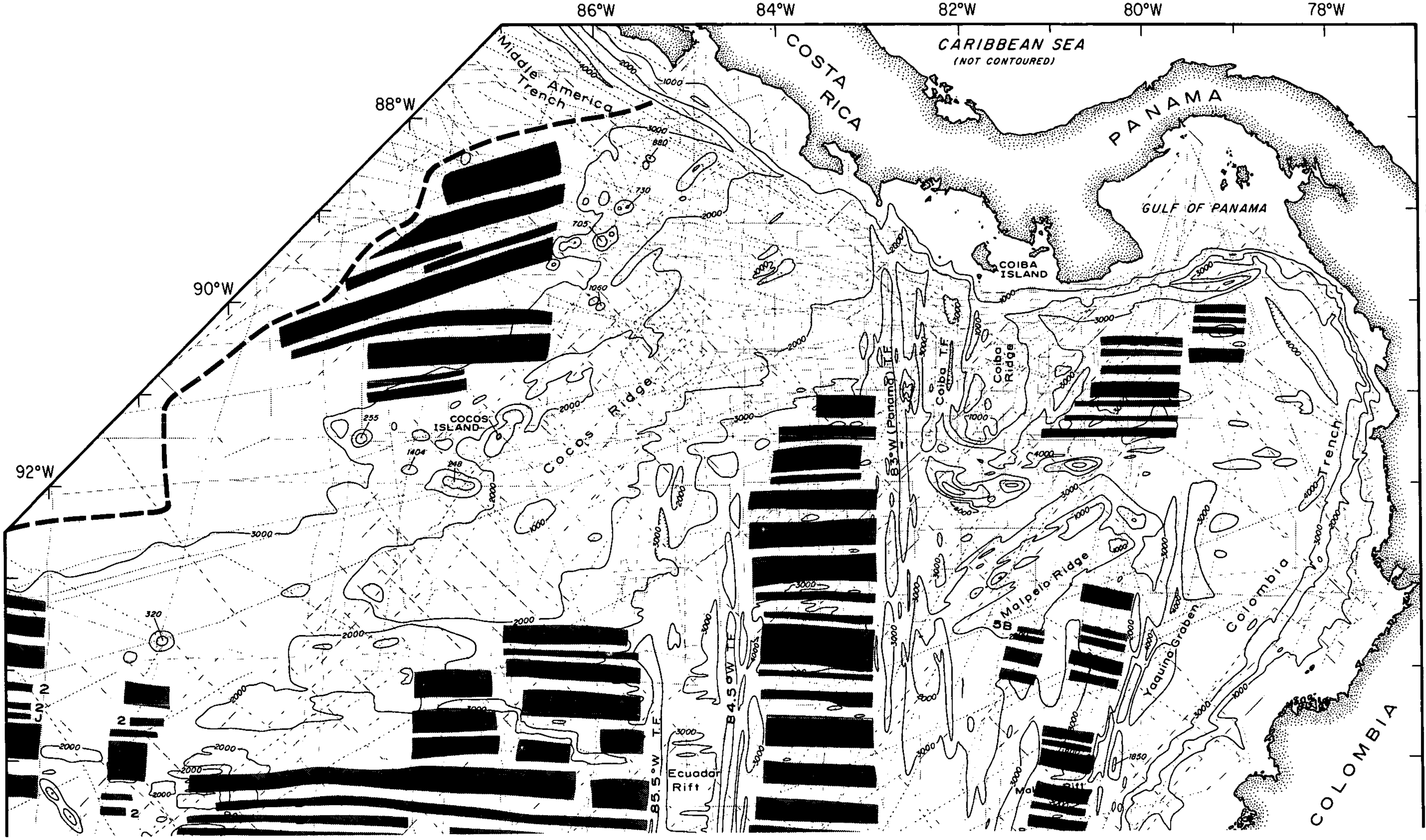


Figure 1. Bathymetry of Panama Basin, in corrected metres. In addition to data used by van Andel and others (1971; dashed lines), we have used soundings from Scripps Institution of Oceanography expeditions Scan, Piquero, Southtow, Risepac, Iguana, F. Drake, Cocotow, and Glomar Challenger 9 and 16; Lamont-Doherty Geological Observatory expeditions Vema 15, 17, 18, 19, 20, 21, 24, and 28 and Conrad 8, 11, 12, and 13; Oregon State University expeditions Yaloc 71 and 73; U.S. Coast and Geodetic Survey expeditions Oceanographer 1969 and 1970, and other U.S. Coast and Geodetic Survey traverses; U.S. Naval Oceanographic Office expeditions Bartlett and De Steiguer; University of Rhode Island expedition Trident 1975; Hawaii Institute of Geophysics expedition Kana Keoki 1973; and spot soundings from Hydrographic Office charts.


86°W
84°W
82°W
80°W
78°W
88°W
90°W
92°W
8°N
6°N
4°N
2°N
CARIBBEAN SEA
(NOT CONTOURED)
COSTA RICA
PANAMA
GULF OF PANAMA
COIBA ISLAND
Middle America Trench
COCOS ISLAND
Cocos Ridge
83°W (Panama) T.F.
Coiba T.F.
Coiba Ridge
Malpelo Ridge
Malpelo Rift
Yaquina Graben
Colombia Trench
COLOMBIA
85.5°W T.F.
84.5°W T.F.
Ecuador Rift
5B
2
1000
2000
3000
4000
880
730
705
1060
255
1404
248
320
1850

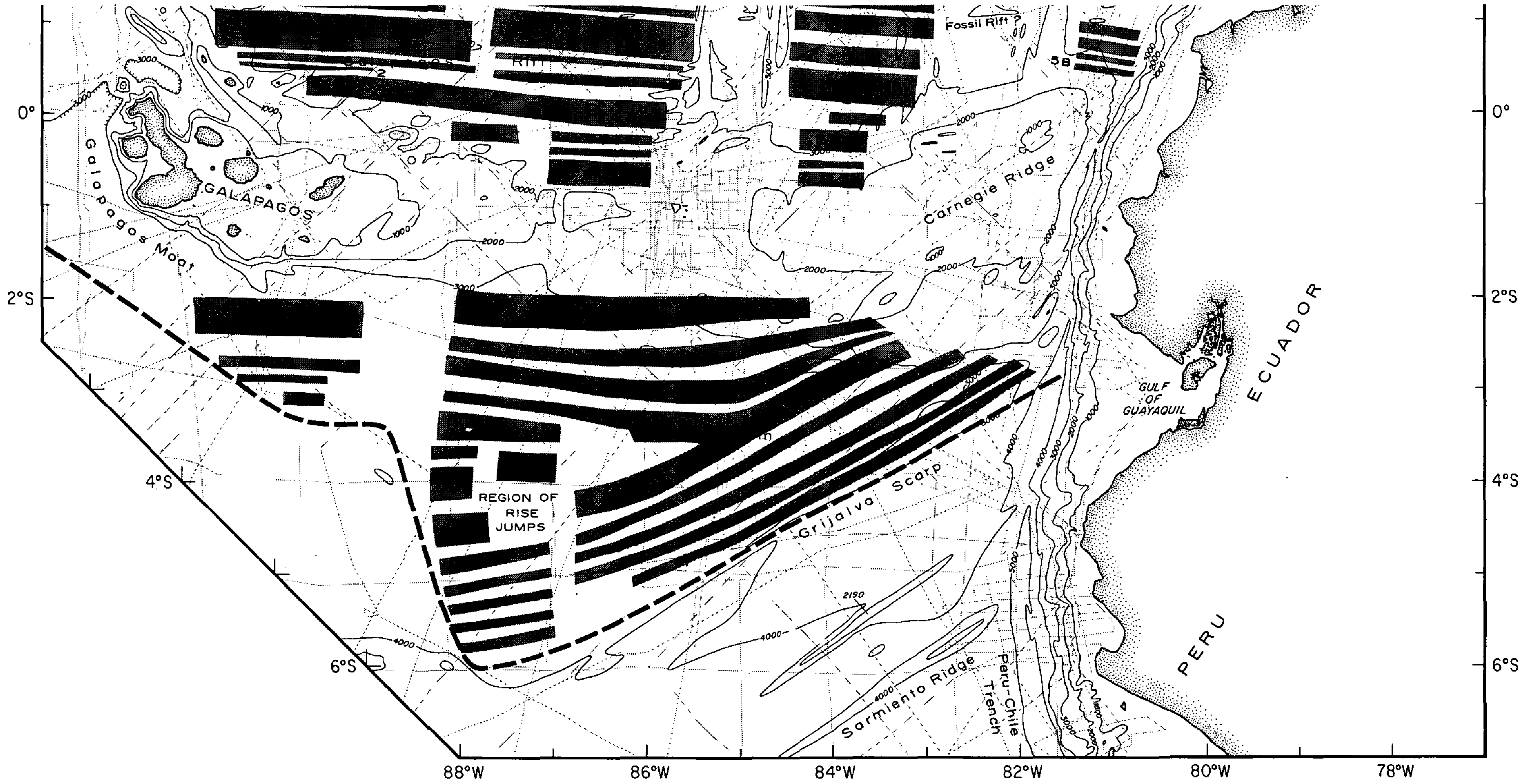


Figure 2. Identified magnetic anomalies and bathymetric track coverage. Identifications are based on those of Raff (1968), Grim (1970a), Sclater and Klitgord (1973), Hey and others (1977), Anderson and others (1976), Handschumacher (1976), and Hey (1977); those papers present most of the magnetic data as anomalies plotted along the tracks. Locations of correlatable magnetic anomalies are shown by shading, and anomalies are identified by numbering system of Heirtzler and others (1968).

Throughout this paper, we have used the Heirtzler and others (1968) geomagnetic time scale for anomalies older than 22 m.y. B.P., Blakely's (1975) time scale for 22 to 8 m.y. B.P., and the Talwani and others (1971) time scale for 8 m.y. B.P. to present. Bathymetry is indicated by contour interval of 1,000 m.

separation of the Malpelo and Cocos Ridges by cessation of Cocos-Nazca spreading east of long 83°W and continued spreading on the Costa Rica rift west of long 83°W.

In this paper we use new seismic reflection and magnetic data, mainly from Scripps Institution of Oceanography's 1974 expedition Cocotow, to define the pattern and duration of spreading between Carnegie and Malpelo Ridges, and to describe the extinct spreading center and transform faults abandoned there. We also describe and date patterns of older lineated magnetic anomalies north of Malpelo Ridge and south of eastern Carnegie Ridge. These new facts are explained with an elaboration of Hey's model for the early evolution of the Cocos-Nazca spreading center.

BATHYMETRY

A bathymetric map of the entire Panama Basin (Fig. 1) is offered as a replacement for that of van Andel and others (1971), which was based on pre-1964 Scripps expeditions and the reconnaissance survey of Yaloc 1969. Our new map is based on 1975 compilations prepared by the Defense Mapping Agency (including all available data from Scripps, Woods Hole, Lamont-Doherty, the Naval Oceanographic Office and the U.S. Coast and Geodetic Survey), with the addition of newer data from Scripps, Oregon State, the University of Rhode Island, and the Hawaii Institute of Geophysics. Almost all post- 1969 soundings have been positioned with satellite navigation, and their addition has reduced our dependence on much of the lower quality data (for example, U.S. Navy tracks in the eastern basin) that van Andel and others (1971) were obliged to use. Several detailed surveys of small patches have been incorporated into the chart: these include site surveys for deep-sea drilling on Cocos and Coiba Ridges (Truchan and Aitken, 1973), for deep towing on central and eastern Carnegie Ridge (Malfait, 1974; Lonsdale and Malfait, 1974; Lonsdale, 1975) and the Galapagos spreading center (Klitgord and Mudie, 1974), and for submersible dives on Malpelo Ridge (B. Heezen and P. Lonsdale, unpub. data) and Cocos Ridge (mapped by B. Heezen, M. Rawson, and D. Fornari). Structural trends mapped unequivocally in these detailed surveys, particularly transponder-navigated deep-tow surveys, have been extended in places into much larger adjacent regions where data are more ambiguous. Along the continental margin and around islands, oceanographic data have been supplemented by sounds from coastal charts; U.S. Hydrographic Office Charts 1787, 1817, and 1818 (covering parts of the Colombian coast) were particularly helpful.

Our new bathymetric interpretation is based on approximately three times as much data as van Andel and others' (1971) map. It also benefits from the greater understanding of the tectonic evolution of the western basin that has been provided by recent analyses of magnetic data (Sclater and Klitgord, 1973; Hey and others, 1977; Anderson and others, 1976); wherever the soundings permit, contours have been drawn to conform to the understood arrangement of active and fossil spreading centers and transform faults. A new compilation of identified magnetic anomalies is shown in Figure 2; it is based on the papers listed above, with the addition of new identification discussed below. That part of our chart south of the equator overlaps sheet 15 of the Bathymetry of the South Pacific (Mammerickx and others, 1974), which has a similar data base; it differs from the chart chiefly in the Ecuador Trench region, where we made use of recent surveys on Scripps expedition Cocotow and the University of Rhode Island Trident 1975 cruise. Its extreme southeast corner overlaps with the bathymetric map of Prince and Kulm (1975), and we have adopted their contours.

The most significant new features of our chart include the clearer demarcation of structural trends on aseismic ridges (especially on Malpelo and Carnegie Ridges), on young crust (where active spreading axes are generally marked by a ridge, and the flanks have small-scale ridges and troughs orthogonal to the spreading direction) and, particularly, along fracture zones. Recent data allow the major fracture zones of the western basin to be portrayed as impressive north-south scars with narrow ridges and deep troughs that in places are continuous for hundreds of kilometres and have a relief greater than 2 km. In the eastern basin are two similar and approximately parallel structures (one of them mapped as "Yaquina graben" by van Andel and others, 1971) that we will show were also formed by transform faulting. Our contours differ least from previous interpretations for Cocos Ridge, which was adequately surveyed on early Scripps expeditions. An important exception is near its northeast end, where we have mapped troughs that trend 060° and are the surface expression of deep, partly sediment-filled grabens (Bentley, 1974).

SEPARATION OF MALPELO AND CARNEGIE RIDGES

Magnetic Anomalies

The Cocotow 3 meridional traverse between the northeastern corners of Malpelo and Carnegie Ridges is shown in Figure 3. It is

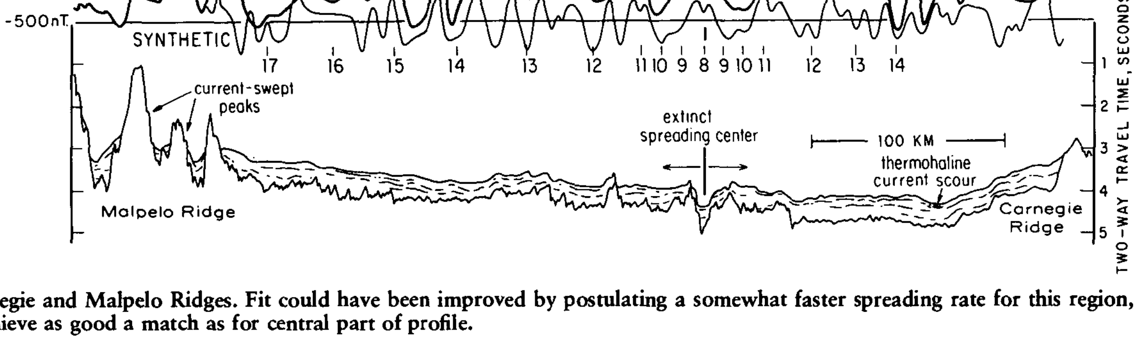


Figure 3. Profile of Cocotow 3 traverse between Malpelo and Carnegie Ridges (see Fig. 4 for location). Synthetic magnetic profile was generated using reversal time scale discussed in Figure 2 caption, spreading rates indicated at top of this figure, magnetization of 4 A/m, and magnetized layer that is 500 m thick and has an upper surface that coincides with basement relief. Note that anomaly match is poor within 50 to 100 km of Carnegie and Malpelo Ridges. Fit could have been improved by postulating a somewhat faster spreading rate for this region, but even so, we could not achieve as good a match as for central part of profile.

unlike most profiles in the eastern basin in having rather simple basement relief and magnetic anomalies that are readily correlated to the geomagnetic reversal time scale. The anomalies on this profile are mirrored about a basement trough at lat 1°40′N, which we identify as a fossil spreading center. Correlation with anomalies on the subparallel Conrad 11-11 and F. Drake 3 tracks, and, south of the spreading center, with those on a grid of Oceanographer 1970 tracks, establishes their orientation as 100° (Fig. 4), almost orthogonal to the Cocotow 3 traverse. Spreading half-rates for the period 14.5 to 11 m.y. B.P. were 35 mm/yr to the north and 20 mm/yr to the south (a full rate of 55 mm/yr, with 27% asymmetric accretion). For the older crust that flanks Malpelo and Carnegie Ridges, the fit of observed and synthetic magnetics is not as good (Fig. 3); spreading rates may have been somewhat faster on both flanks, while the same sense of asymmetry was preserved.

Asymmetric spreading is characteristic of the Cocos-Nazca spreading center (Hey and others, 1977). On the Costa Rica rift segment (along the long 83.5°W meridian) the observed magnetics from 8 m.y. B.P. to the present are best modeled with rates of 30 mm/yr to the north and 36 mm/yr to the south (Hey and others, 1977). Note that the sense of asymmetry is different from that which we have just described, although in both cases it was apparently performed by "continuous asymmetric spreading," which preserved complete sequences of magnetic anomalies. This contrasts with discontinuous jumps of the spreading centers west of long 86°W, which has caused asymmetric crustal accretion there (Hey and others, 1977; Anderson and others, 1976). However Hey and others (1977, their Fig. 9) suggested that the sense of asymmetry on the Costa Rica rift was reversed before 9 m.y. B.P., with faster accretion to the north, as on the contemporary Malpelo rift. Their matches of observed and synthetic anomalies for this period are rather poor, however.

The youngest anomalies on this spreading segment, which we name the Malpelo rift, indicate that at about 11 m.y. B.P., 3 m.y. before spreading stopped, the spreading rate was more than halved, to a full rate of 25 mm/yr, and became approximately symmetric (Fig. 3). However, the length of the reversal sequence involved (essentially encompassing the whole of anomaly 5) is so short that any slight degree of asymmetry or continuous deceleration in spreading rate cannot be adquately resolved.

Hey and others (1977) suggested that asymmetric spreading on this plate boundary expresses attempts by the spreading center to remain near the hot spot, and that the relative volume of the Cocos and Carnegie Ridges along any meridian indicates whether the hot spot was centered under the Cocos plate or, as now at the Galapagos Islands, under the Nazca plate. Our new observations are consistent with these speculations. During the earlier period of faster accretion to the Cocos plate, the hot spot was presumably beneath the Nazca plate, building the massive eastern part of Carnegie Ridge. The subsequent change in sense of asymmetry found

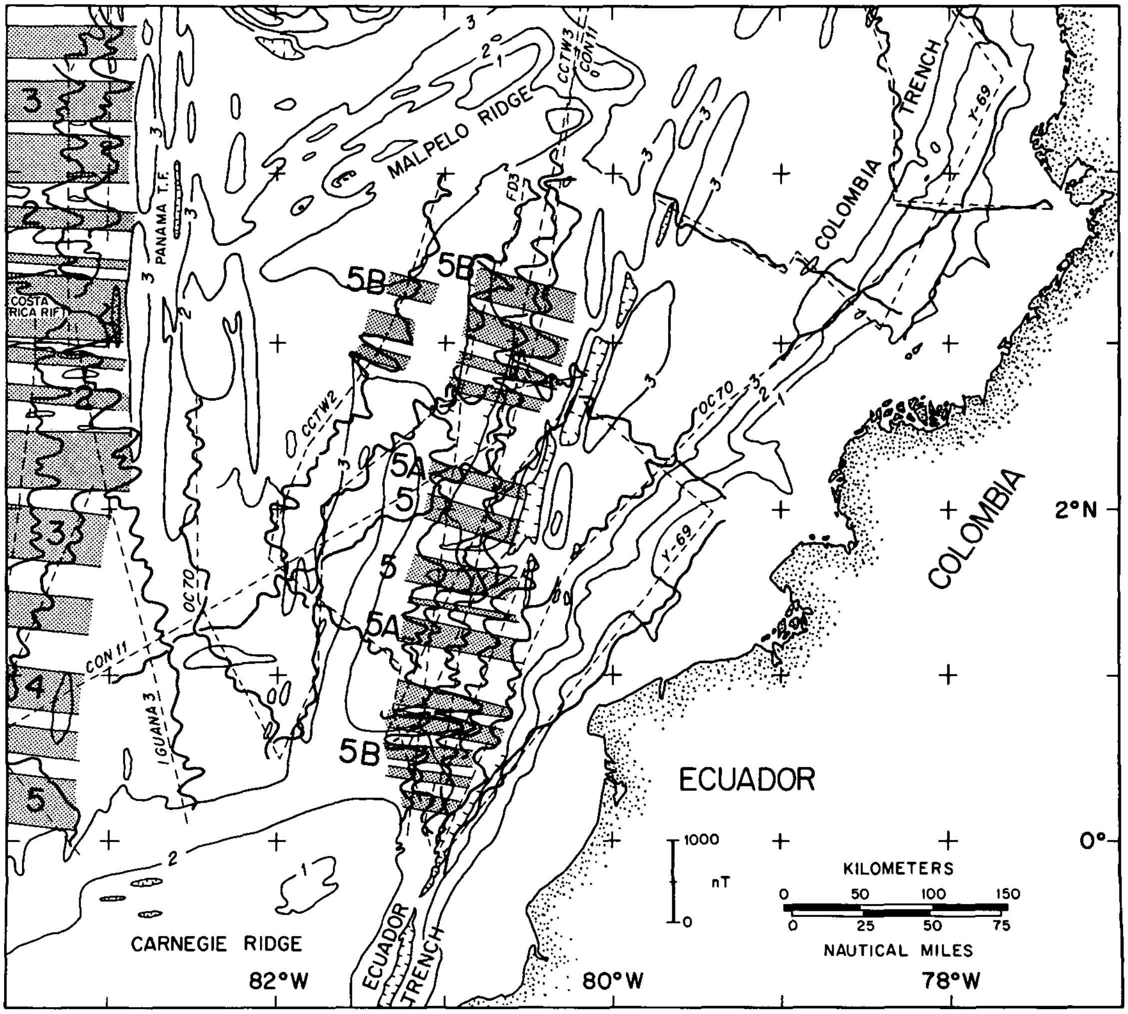


Figure 4. Magnetic anomalies between Malpelo and Carnegie Ridges, numbered according to time scales listed in caption of Figure 2. Note anomaly 5 to 5B sequence along long 81°W, mirrored around extinct Malpelo rift spreading center at lat 1°40′N. Magnetic anomalies on western (Costa Rica rift) segment are from Hey and others (1977). Tracks are labeled for Conrad 11.11 (CON 11) Yaloc 69 (Y 69), Iguana 3, Cocotow 2 (CCTW 2), Cocotow 3 (CCTW 3), F. Drake 3 (FD 3), and some lines of Oceanographer 70 (OC 70). Unlabeled profiles on Costa Rica rift are from Oceanographer 69; those on Malpelo rift are from Oceanographer 70.

on the Costa Rica rift could record the movement of the hot spot to the Cocos plate that create the Cocos Ridge bulge between long 86° and 87°W. However, even though the hot spot is no longer centered beneath the Cocos plate, and may now be so far away from the Costa Rica rift that it has no influence there, slower accretion to the north persists on this segment.

Magnetic anomalies on the youngest part of the Malpelo rift are of normal amplitude (that is, they are well matched with a magnetization of 4 A/m; Fig. 3). However, adjacent to the eastern part of Carnegie Ridge, on which the hot spot was probably centered 18 to 21 m.y. B.P., sea-floor spreading anomalies (especially those just younger than anomaly 5B) have much higher amplitudes on most tracks. For example, on the Cocotow 2 track (Fig. 4), amplitudes are as high as 750 nT, comparable to those in the recent long 95° to 85.5°W "Magnetic Geochemical Anomaly" (Vogt and Johnson, 1973). The latter is a region of anomalies with unusually high amplitudes that are thought to be caused by an iron and titanium enrichment in basalts erupted at the spreading center (Vogt and Johnson, 1973; Anderson and others, 1975; Vogt and de Boer, 1976). This enrichment has been releated to the influence of the nearby Galapagos hot spot, perhaps because nearness to the hot spot affects the size and depth of differentiating magma chambers. The transition from high- to normal-amplitude magnetic anomalies on the Malpelo rift about 13 m.y. B.P. may mark the waning influence of the increasingly remote hot spot.

Sediment Thickness

Interpretation of the seismic reflection profile (Fig. 3) supports our age assignment based on magnetics. On the current-swept ridges in and around the Panama Basin, sedimentation rates are highly variable in both space and time (see for example, Heath and van Andel, 1973), but on the flanks of the Cocos-Nazca spreading center all published rates (from DSDP site 84 and from interpretation of seismic profiles over well-dated crust) are between 35 and 50 m/10^6 yr (Hays and others, 1972; Klitgord and Mudie, 1974; Anderson and others, 1976). An airgun transect (figured in Anderson and Hobart, 1976) of the well-dated Costa Rica rift segment of the spreading center indicates a relatively constant accumulation rate there of 0.055 s of two-way travel time (44 m at the sonic velocity of 1.6 km/s indicated by results from nearby DSDP holes) in 10^6 yr. The sediment thickness around the extinct spreading center at long 81°W (Fig. 3) is, at 0.55 s, about the same as that on 10-m.y.-old crust at long 83.4°W, and it thickens gradually to 0.65 s on both flanks. The "thickness" of sediment on airgun profiles becomes a less precise measure of basement age on older crust, because lithification decreases both true thickness and, by increasing sonic velocity, apparent thickness. Differential deposition and erosion by fast bottom currents, which prevents interpretation of crustal age from sediment thickness over much of the Panama Basin, is little in evidence in Figure 3: the steep, shallow slopes of Malpelo Ridge have been scoured (as is typical of the aseismic ridges; see for example, van Andel and others, 1971; Truchan and Aitken, 1973), and impeded deposition of the younger parts of the section at the foot of Carnegie Ridge shows the effect of the fast thermohaline current that debouches from the Ecuador Trench (Lonsdale, 1977).

Fossil Spreading Centers and Transform Faults

There is a basement trough, 600 m deep and 7 km wide, at the site where the magnetic anomalies of Figure 3 indicate that sea-floor spreading stopped about 8 m.y. B.P. Although it contains about 500 m of sediment, it still causes a 500-m depression in the sea floor, because of the even accumulation of sediment on its flanks (Fig. 3). Bathymetric tracks adjacent to the Cocotow 3 profile show that the trough is oriented approximately east-west, parallel to the local magnetic anomalies (Fig. 4); it is a "fossil" spreading center that became extinct 8 x 10^6 yr ago and is preserved snug beneath a blanket of pelagic sediment. The feature is very similar to a set of east-west grabens between long 86° and 88°W on the north flank of the Galapagos spreading center (Fig. 1). Anderson and others (1976) demonstrated that those grabens mark fossil rise crests that spread at full rates of 60 to 70 mm/yr until abandoned by southward jumps of spreading-center segments between 5 and 2 m.y. B.P.

About 50 km west of the Cocotow 3 crossing, the graben marking the fossil Malpelo rift spreading center is offset 80 km to the south by a broad zone of ridges and troughs that strike 010° (a fossil transform fault at long 82°W). Near long 82°30'W there seems

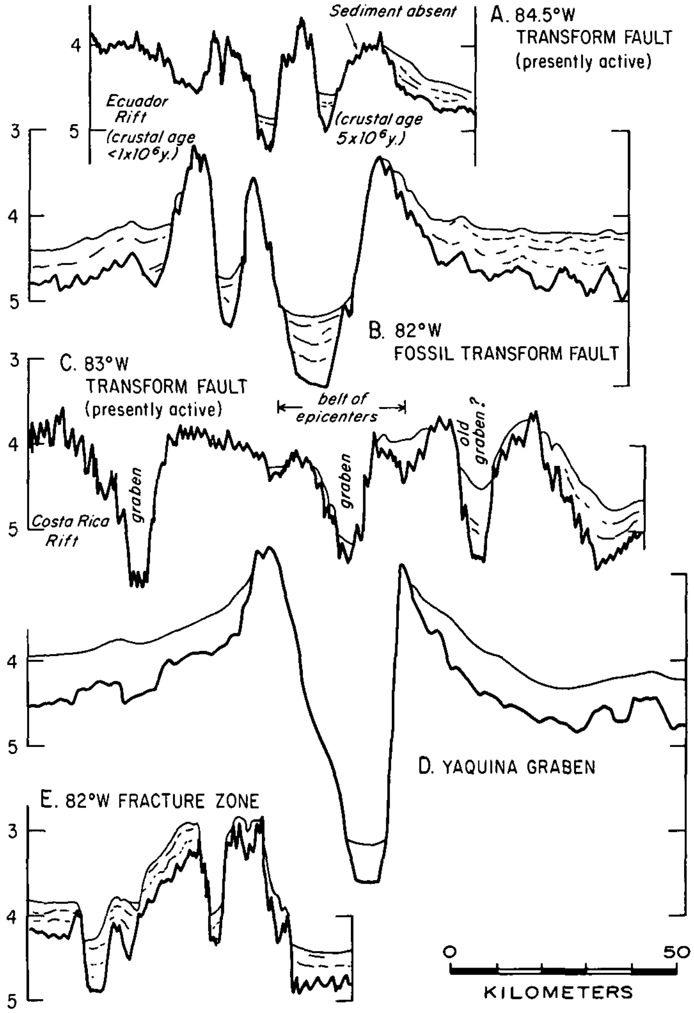


Figure 5. Line drawings of active and extinct Panama Basin transform faults and fracture zones, all to same scale and with same vertical exaggeration (×20). Profiles are from (A) Cocotow 4: long 84.5°W, lat 1.5°N; (B) Cocotow 2: long 82°W, lat 1.5°N; (C) Cocotow 3: long 83°W, lat 3.5°N; (D) Yaloc 69: long 80.3°W, lat 2.6°N (from van Andel and others, 1971); (E) Cocotow 2: long 81.6°W, lat 2.6°N. All profiles are projected normal to strike of transform fault or fracture zone shown and are approximately west-east, west to left. Depths are two-way travel times in seconds.

to be another, much shorter, offset before it intersects the ridges and troughs of the Panama fracture zone near lat 0°45′N, long 83°W (Fig. 4). At these western segments the magnetic evidence for a fossil rise-crest origin is less convincing. However, the basic structure of an east-west graben, largely filled with sediment, is maintained and is well displayed in the Iguana 3 seismic reflection profile at lat 0°45′N, long 82°40′W.

A seismic profile across the fossil transform fault near long 82°W (Fig. 5, B) shows a 50-km-wide structure with several kilometres of relief, comparable to large active transform faults in the western Panama Basin (for example, Fig. 5, A). The relief along Panama Basin transform faults seems to be composed of a combination of deep grabens and constructional volcanic ridges, both parallel to the direction of transform faulting. Commonly, there is a pair of grabens, separated by a horst 10 km or more wide (Fig. 5, A). A crossing of the transform fault at long 83°W (Fig. 5, C) shows three rift valleys, whose sediment fill (perhaps an indication of age) increases from west to east. At this latitude the seismicity is now narrowly concentrated along the central trough, perhaps suggesting that only one graben contains an active transform fault at any one time and that the location of the strike-slip faulting may jump from one graben to another. The fundamental role of grabens in producing the topography along transform faults has been emphasized by recent geophysical studies elsewhere, particularly by high-resolution surveys with a deep-tow instrument (Detrick, 1974) and a submersible (Francheteau and others, 1975) in the FAMOUS area of the Mid-Atlantic Ridge.

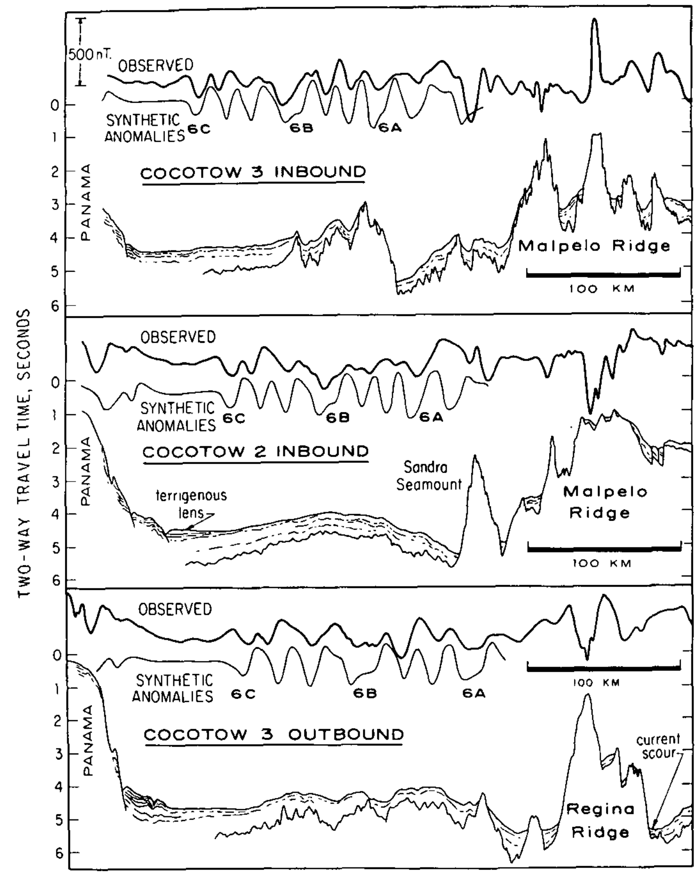


Figure 6. Profiles between Panama slope and Malpelo Ridge. See Figure 7 for location; profiles selected are tracks 2, 4, and 6 of that figure. Profiles have not been projected normal to magnetic lineations; all synthetic anomalies have been generated at a spreading half-rate of 40 mm/yr. Other parameters as listed in caption for Figure 3.

We agree with van Andel and others (1971) that the Yaquina graben (Fig. 5, D) is a deep fault-bounded trough whose overall trend is about 025°, but which is divided into en echelon segments that strike about 010°. We disagree with their interpretation of it as a dilation crack opened in old crust by interaction of this corner of the Nazca plate with the South American continent. From its general morphology, absence of seismicity and, particularly, its right-angle intersection with the set of 16 to 8 m.y. B.P. magnetic anomalies shown in Figures 3 and 4, we identify it as the trace of a major set of en echelon transform faults abandoned 8 m.y. B.P. Existing data are insufficient to define the former length of offset along this transform fault, but a trough deeper than 4 km extends from the extinct spreading center at lat 1°40′N to about lat 4°N, a distance of more than 250 km. We cannot identify an orthogonal fossil spreading segment to the east of its northern termination, but the data here are sparse. It is possible that instead of being a left-lateral offset of the Nazca-Cocos spreading center, the northern termination of the Yaquina transform fault was the Nazca-Cocos-Caribbean triple junction, so that the crust east of it was part of the old Farallon plate; we will return to this point later.

Beyond the fossil spreading centers, the ridges and troughs of the transform fault at long 82°N are continued in a "fossil fracture zone," with narrow ridges and troughs (Fig. 5, E) that extend to the margins of Malpelo and Carnegie Ridges. A fracture-zone trough extends south from the intersection of the fossil spreading center and the Yaquina graben and is truncated by subduction at the trench near lat 1°N, long 80°30′W. The poorly-mapped complex of troughs around lat 5°N, long 79°W probably represents the northern fracture-zone traces of the Yaquina transform fault. It should be noted, however, that seismicity associated with the Colombia Trench plate boundary extends to about long 78°30′W in this region, so the rough topography there may be partly of recent origin.

CRUST NORTH OF MALPELO RIDGE

Structure

The three Cocotow profiles shown in Figure 6 give a representative view of the shallow structure between Malpelo Ridge and the slope of the Isthmus of Panama. Seismicity indicates that the isthmian slope lies along the Caribbean-Nazca plate boundary, which here probably has strike-slip motion (Jordan, 1975). The oceanic crust slopes down toward this margin; this dip is probably inherited from the period before 9 m.y. B.P. when the Nazca-Cocos spreading center was active at this longitude, and the sea floor south of Panama was part of the Cocos plate, being subducted beneath the Caribbean plate. Independent evidence of this period of subduction is the late Oligocene to mid-Miocene andesitic volcanism in adjacent parts of Panama (Terry, 1956). The relatively smooth oceanic basement between the Panamanian margin and lat 5.5°N is bowed down on the south also, perhaps in part by isostatic depression under the load of the adjacent shallow ridges to form a moat similar to that which partly encircles the Galapagos Islands (Fig. 1). These shallow ridges include Malpelo Ridge, of which a small fragment rises above sea level at lat 3°59′N, long 81°36′W; Sandra Seamount, with a peak at 440 m; and Regina Ridge, a complex elongate feature that has a shoal sounding of 162 m (Fig. 7).

Sediment cover over low-relief basement (for example, on the

Cocotow 2 profile, Fig. 6) is a fairly even blanket with a thickness of 0.7 to 0.8 s (550 to 650 m), onlapped in the north by a lens of terrigenous sediments. We interpret the seismic profiles as showing a "mini–continental rise" with a proximal slump facies (shaken off the slope by local earthquakes) and a distal, flat-lying, turbidite facies. Although on reflection profiles the terrigenous unit seems clearly demarcated from the pelagic blanket, the latter undoubtedly has a significant component of fine-grained terrigenous debris and ash, and its observed thickening to the north may be partly a function of proximity to land. However, we think that near this active continental margin varying crustal age is the more important factor. We therefore infer that this section of crust is older than that south of Malpelo Ridge, and becomes older to the north. Sediment cover is much more uneven around the steeply sloping ridges in the southern part of the region, and the reflection profiles indicate that some of the topographic moat around Regina Ridge (Fig. 6, bottom) is caused by impeded deposition, attributable to the thermohaline current that passes through this gap between Malpelo and Coiba Ridges (Laird, 1971).

Malpelo Ridge is a complex of constructional volcanic ridges and fault blocks aligned at 060°. Malpelo Island is defined and crossed by faults with a similar trend: it is composed of icelandites

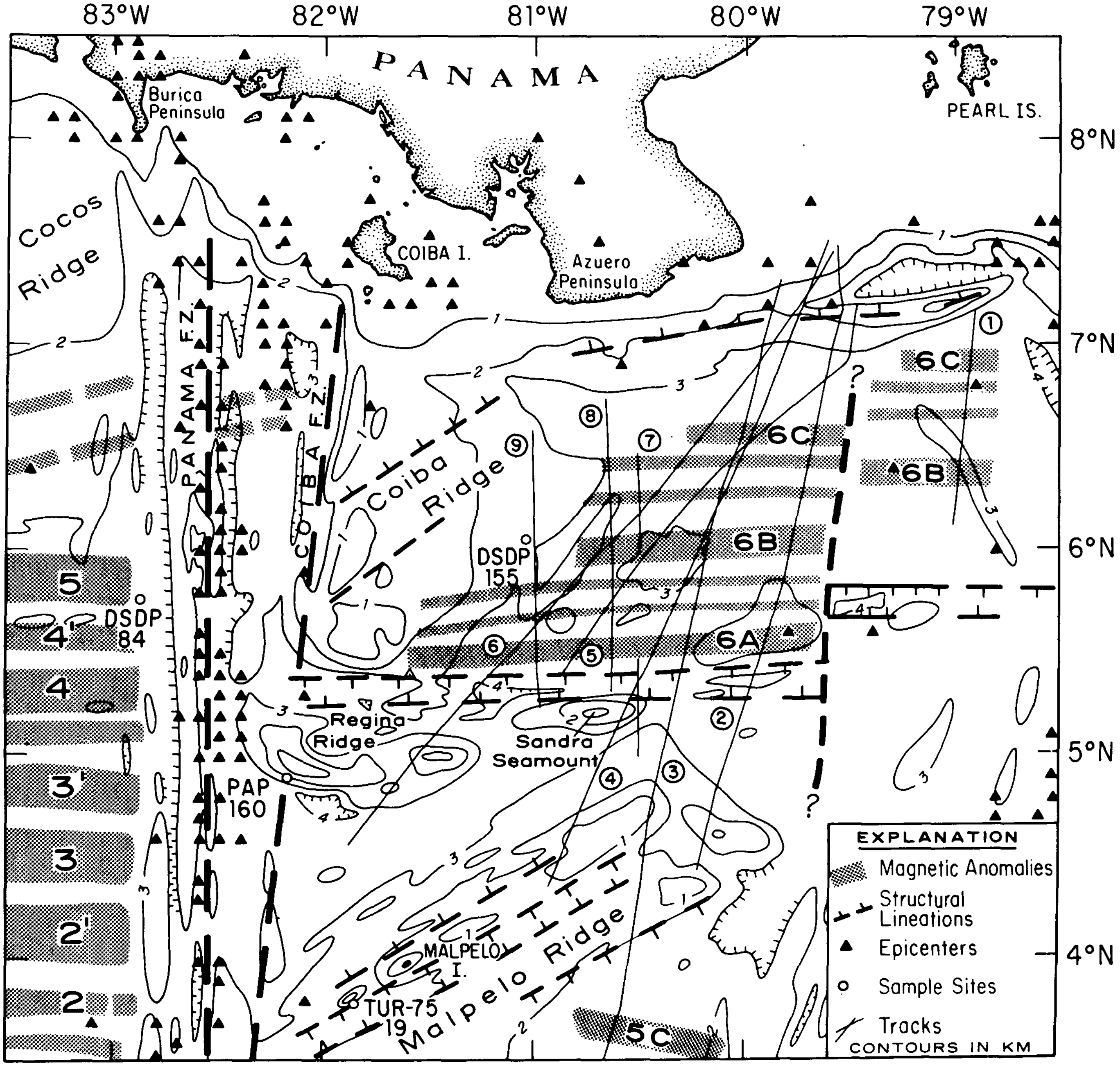


Figure 7. Crustal structure between Malpelo and Panama, showing 1965 to 1975 epicenters (defining present plate boundaries), magnetic anomalies, tracks of profiles shown in Figures 6 and 8, and locations of sampling sites.

(intermediate-composition rocks of tholeiitic lineage; M. N. Bass, 1976, personal commun.). Southeast of the island is a 4-km-deep graben, with as much as 1 km of sediment fill. One of us (Lonsdale) has ascended the northwest boundary of this graben in the U.S. Navy submersible DSV Turtle; direct observation confirms that it is a fault scarp, with vertical steps hundreds of metres high, and rocks collected during the dive are altered tholeiitic diabases (Tur 1975-19, Fig. 7; analyzed by R. Batiza, 1976, personal commun.). What is known of the geology of Malpelo Ridge is consistent with Hey's (1977) suggestion that it represents excessively thick oceanic crust produced 18 to 20 m.y. ago as an early manifestation of the hot spot that subsequently built Carnegie Ridge, Cocos Ridge, and the Galapagos Islands. The steep normal faults were probably produced by differential contraction during crustal cooling (as postulated by Heath and van Andel, 1973, for similar faults that bounded the Carnegie Ridge). However, Malpelo Island has evidently suffered subsequent tectonism, which elevated it and may have caused a recent renewal of volcanism (McConnell, 1943).

Sandra Seamount and Regina Ridge have extremely steep slopes (an average of >45° for depth differences of 3,000 m), implying that they are also defined by steep normal faults, oriented approximately east-west. Their crests are jagged and rocky: from their slight depth and lack of wave planation (which has cut a 3-km-wide insular shelf around Malpelo Island) we infer that they too have been recently elevated. A dredge haul from the steep southwestern slope of Regina Ridge (station Papagayo 16D) contained tholeiitic diabases and basalts similar in composition to those collected on Malpelo Ridge (M. N. Bass, 1976, personal commun). At DSDP site 155, near the gradual eastern margin of Coiba Ridge, bedrock cored beneath sediment dated paleontologically as 15 m.y. B.P. was alkali basalt, although its anomalous composition may be partly attributed to halmyrolysis (van Andel, Heath, and others, 1973). We believe that the DSDP site 155 sample of rocks atypical of rise-crest volcanism marks an episode of off-axis eruption and that its age (the only directly dated submarine basement anywhere in the eastern Panama Basin) may be largely irrelevant to the big tectonic picture: in this instance, we prefer to trust the evidence of lineated magnetic anomalies, and we base our chronology on them. Alkali basalts have been dredged at the northwestern margin of Cocos Ridge (Engel and Chase, 1965) from seamounts that are much younger than the crust on which they are built (Heezen and Rawson, 1977).

Magnetic Anomalies

The old crust south of the Azuero Peninsula has lineated east-west anomalies that can be matched to the geomagnetic time scale by postulating north-south spreading at a rate of 40 mm/yr for the interval 26 to 22 m.y. B.P. (Figs. 7, 8). This set of anomalies and those described above south of Malpelo Ridge are part of a continuous sequence formed on the north flank of the Malpelo rift, and disrupted between lat 5.5° and 4°N by the complex topography of the ridge and its outliers. The limits of this northern anomaly sequence are not well defined. To the east, an Oceanographer 70 track (line 1 of Fig. 7) recorded anomalies that can be correlated with those west of long 79.5°W, if a fracture zone with 30-km offset exists along the meridian. The southern boundary of reasonably well-matched anomalies is the axis of the deep east-west trough between Malpelo and Coiba Ridges. This trough is also offset about 30 km at long 79.5°W (Fig. 7). The anomaly sequence cannot be followed up the east flank of Coiba Ridge; this could be accounted for by an intervening fracture zone (for examples along the basement "hinge" of Coiba Ridge mapped by Truchan and Aitken, 1973), or by overprinting by subsequent tectonism and volcanism (for example, around DSDP site 155). The northern limit of the east-west anomaly sequence seems to be the extinct Panama Trench. An alternative interpretation is that the transition near lat 6°35′N from high-amplitude to low-amplitude anomalies marks the boundary between crust formed by north-south Nazca-Cocos spreading and by east-west Pacific-Farallon spreading (rather than merely the change from the long interval of normal polarity between anomalies 7 and 6C to the period of frequent reversals between anomalies 6C and 6). We do not favor this alternative, because we see no indication in the basement topography of a major step caused by the age difference across the boundary that this interpretation implies.

The mirror of this anomaly sequence, on crust that accreted to the Nazca plate, should be found south of Carnegie Ridge, where the boundary between Nazca-Cocos and Pacific-Farallon crust is preserved at the Grijalva scarp (Rea and Malfait, 1974; Hey, 1977). Unfortunately, the southern anomaly sequence has suffered lateral tectonic erosion at the Ecuador Trench, and the section that has been subducted includes the counterpart of the best defined northern section, that southeast of the Azuero Peninsula. Farther southwest a sequence of lineated anomalies just north of the Grijalva scarp is oriented at 065° (Figs. 2, 9; see also Fig. 3 of Hey, 1977), and has an age of 24 to 21 m.y. During anomaly 6 time (21 to 20 m.y. B.P.) and spreading center west of long 82°W changed to a more east-west orientation and subsequently formed crust with east-west anomalies 5C, 5D, and 5E south of Carnegie Ridge (Fig. 2). This change in strike was probably accomplished by a series of spreading-center jumps, which resulted in the repetition of anomaly 6 on the southern flank west of long 86°, and in its absence on this flank near long 82°W. Only the area between long 86° and 83°W remained relatively undisturbed during this reorientation, and the anomalies there can be convincingly matched to synthetics for the sequence from anomalies 6B to 5C, with a spreading half-rate on this flank of 40 mm/yr (Fig. 9). Thus, the spreading rate on the south flank near long 85°W 24 to 17 m.y. B.P. was approximately

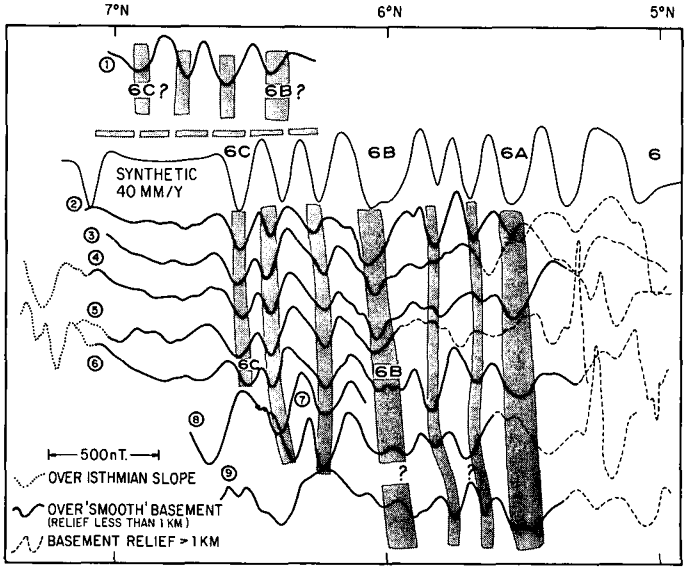


Figure 8. Magnetic anomalies south of Panama, all profiles projected north-south. See Figure 7 for track locations. Synthetic magnetic profile was generated in same manner as synthetic profiles in Figure 6.

equal to that on the north flank near long 80°W 26 to 22 m.y. B.P. (Fig. 7).

Our interpretation is that eastern segments of the young Nazca-Cocos plate boundary were already aligned east-west with north-south transform faults in the period 26 to 22 m.y. B.P. (and leave an extant record of this activity on the north flank), while segments farther west were still spreading obliquely, orthogonal to the old Farallon plate fracture zone at the Grijalva scarp (Hey, 1977). We suspect that the northern boundary between Nazca-Cocos and Pacific-Farallon crust is not far north of the anomaly 6B-6C sequence (inasmuch as the southern boundary is not far south of its counterpart near the intersection of Grijalva Scarp and the trench) and probably lies near the foot of the isthmian slope.

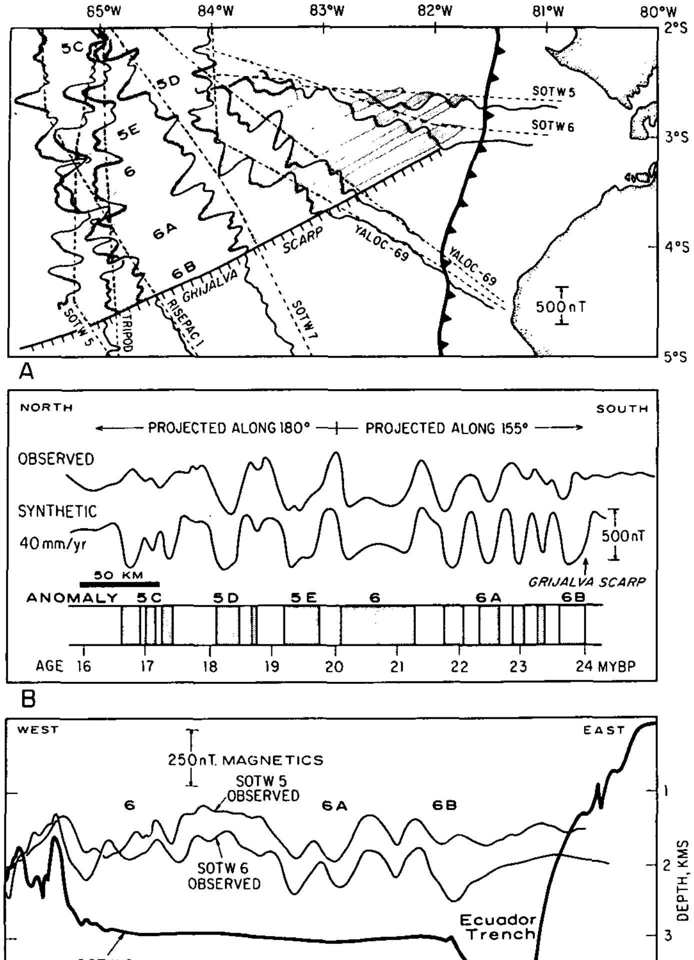


Figure 9. Structure south of eastern Carnegie Ridge. A. Magnetic anomalies correlative with geomagnetic time scale are shaded and labeled according to the Heirtzler and others (1968) numbering system. B. Synthetic modeling along one of the tracks (Risepac 1), justifying identifications; magnetization of 10 A/m, spreading half-rate of 40 mm/yr, and flat 500-m-thick layer (no seismic record was available) were used in modeling. Note change in strike of projection, reflecting trend of older anomalies parallel to Grijalva scarp and more east-west trend of younger anomalies. C. Magnetic anomalies near intersection of Grijalva scarp and Ecuador Trench. Bathymetric profile is from Southtow 6.

Coiba Ridge

Coiba Ridge, at the northwestern corner of the eastern part of the Panama Basin, is quite different in structure and in origin from the other ridges of the Panama Basin. The simple, and, we believe, essentially correct, interpretation of east-west reflection traverses is that it is "a large eastward-sloping slab with its high western edge uplifted along one of the faults of the Coiba Fracture Zone" (van Andel and others, 1971, p. 1497). The tilted slab does have inherited or superimposed structures that trend about 060° (Truchan and Aitken, 1973); these include a large basement ridge with a trough on its northwest side (A in Fig. 10). Coiba Ridge bears a striking resemblance in structure and tectonic setting to Mendocino Ridge (Fig. 10), which is formed by minor underthrusting along a strike-slip transform fault adjacent to a trench-transform-transform triple junction (Silver, 1971). At present, the Nazca-Cocos transform-fault boundary between the Costa Rica rift and Middle America Trench is about 50 km west of the Coiba Ridge scarp, although the north-south band of strike-slip earthquakes is more diffuse than farther south (Fig. 8; Molnar and Sykes, 1969). We will demonstrate that at about 8 m.y. B.P., this plate boundary lay directly adjacent to the Coiba Ridge and that the tectonic environment was then similar to that prevailing today near the Mendocino triple junction.

ORIGIN AND FATE OF OCEANIC CRUST EAST OF YAQUINA GRABEN

Panama Basin

The available magnetic data east of long 80°W are inadequate to define the pattern and orientation of isochrons in the easternmost part of the Panama Basin. However, anomalies of several hundred nanoteslas occur throughout the region (for example, Figs. 4 and 8). They are sufficient to establish that the crust was formed by approximately meridional spreading at a segment of the Nazca-Cocos boundary, rather than being a remnant of the Farallon plate created by east-west spreading. Crust of that origin south of the Grijalva scarp has vanishingly small anomalies, because of the location near the magnetic equator.

Northwestern South America and the Caribbean

The basement of southeastern Panama and western Colombia is oceanic crust, complete with pillow basalts and radiolarian cherts (Bandy, 1970; Case, 1974; Case and others, 1971). Most of these rocks are of Late Cretaceous age, and they probably represent slabs of Farallon plate obducted in early Cenozoic time. The Caribbean may contain a large extant fragment of Farallon plate that was isolated by fracturing of that plate in early Cenozoic time (Edgar and others, 1971; Malfait and Dinkleman, 1972) and subsequently became stagnant relative to the mantle (Jordan, 1975). Deep Sea Drilling Project sites in the Caribbean Sea have dated the basaltic basement there as Upper Cretaceous, which would be appropriate for a wedge of Farallon plate that avoided subduction, but the significance of these ages is disputed (Saunders and others, 1973). Christofferson (1973) has tentatively assigned lineated magnetic anomalies north of Panama to a Late Cretaceous reversal sequence, although their quality is too poor for a reliable identification.

At present the Nazca plate is being thrust beneath western Colombia. The outcrop of the subduction zone is marked by a band of shallow earthquakes in the Colombia Trench, and the downgoing slab is defined by a Benioff zone that dips to the southeast (Molnar and Sykes, 1969) and extends to a depth of more than 200 km. For example, an earthquake with a focal depth of 213 km at lat 3.7°N, long 75.5°W, 400 km from the trench, occurred on March 2, 1969. The subduction zone also feeds active andesitic volcanoes, which extend in a line 150 km above the Benioff zone from Ecuador to lat 5°N in Colombia (Hantke and Parodi, 1966). The relatively low seismicity and slight depth of the Colombia Trench, compared to the Peru-Chile Trench, suggest that subduction there is relatively slow; also, the topography of marginal plateaus and offshore banks (between lat 5° and 1°N in Fig. 1) is reminiscent of the Oregon margin, where slow subduction is occurring (Kulm and Fowler, 1974). Hence, the minimum 400 km of penetration by oceanic lithosphere implies that subduction has continued here for much of late Cenozoic time. The current episode of andesitic volcanism in Colombia, which we consider a delayed-reaction manifestation of this process, began in middle Miocene time (Campbell, 1974a).

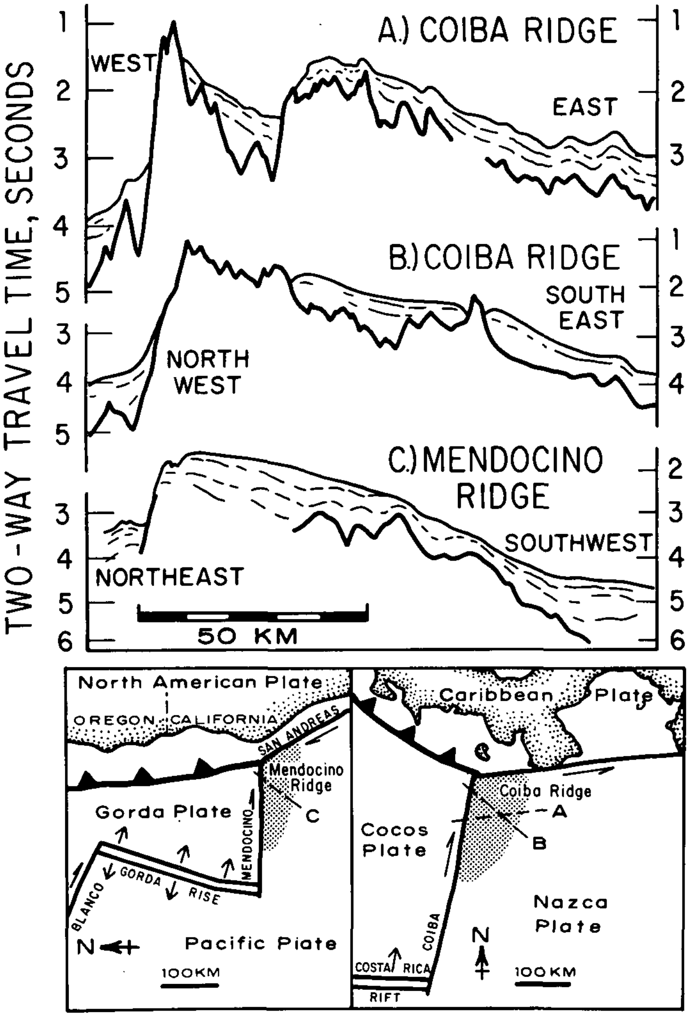


Figure 10. Comparison of profiler crossings and tectonic setting of Coiba Ridge (A and B) and Mendocino Ridge (C), the last from Silver (1971). Chartlets show plate boundaries and relative motions and location of profiles. (A is Scan 9; B is Vema 28 from Truchan and Aitken, 1973).

INTERPRETATION OF THE TECTONIC HISTORY

30 to 22 M.Y. B.P.: Initiation of Cocos-Nazca Spreading

The record of uplift, andesitic volcanism, and batholith emplacement in northwestern South America (Campbell, 1974a, 1974b) indicates that underthrusting of oceanic lithosphere, presumably part of the Farallon plate (Larson and Chase, 1972), has been occurring there throughout much of Late Cretaceous and Paleogene time. Isolation of the Caribbean plate and subduction along the southern part of the Middle America Trench is indicated by Eocene andesitic volcanism in southern Central America (Malfait and Dinkleman, 1972). Dating of calc-alkalic volcanic rocks in northwest Panama as Late Cretaceous (Fisher and Pessagno, 1965) suggests that development of an active plate margin between the Farallon and Caribbean plates may even have begun in late Mesozoic time. The geometry of this plate boundary and the geologic record on the isthmus, where Eocene calc-alkalic rocks are not widespread, indicate an eastward transition from subduction at the Middle America Trench to strike-slip motion with minor underthrusting in central Panama, causing obduction of a slab of Farallon plate there, and pure strike-slip motion at eastern Panama and northwestern Colombia (Fig. 11, a). Bandy (1970) described the rapid spatial transition, in sediments of Paleogene age, from bathyal and neritic facies in central Panama to abyssal facies in eastern Panama and adjacent parts of Colombia. He suggested that the paleoenvironments in the latter region were "a complex of basins not unlike those of the continental borderland of southern California," which is characteristic of a transform-fault continental margin.

We agree with Hey's (1977) hypothesis that splitting of the Farallon plate into a northeasterly moving Cocos plate and an easterly moving Nazca plate began by spreading within the "Grijalva Fracture Zone" on the Farallon plate. Our identification of magnetic anomalies south of Panama (Fig. 9) implies that this occurred at least 27 m.y. B.P. Pacific-Farallon crust south of the Grijalva scarp is not much older than this (for example, a basement age of 28 m.y. B.P. at DSDP site 320 just south of Sarmiento Ridge), and Cocos-Nazca spreading may have begun in an active transform-fault section. Perhaps the effusive volcanism that built the Sarmiento and Alvarado Ridges, whose orientation is appropriate for Pacific-Farallon fracture zones (Mammerickx and others, 1975), was caused by similar but slight transverse extension there also. Subdivision of the old Farallon plate allowed subduction to be more normal to the margins of both Middle America and South America (Hey, 1977). A new "proto-Andean" phase of andesitic volcanism began in western Colombia (van Houten, 1976), but the effects of this change of plate motion were perhaps greatest at the Panamanian margin (Fig. 11 B): extensive Oligocene and early Miocene andesitic volcanism occurred in central Panama (Terry, 1956), and uplift of the eastern part of the isthmus from abyssal depths was initiated (Bandy, 1970; Bandy and Casey, 1973). Elsewhere in Central America there seems to have been a hiatus in andesitic volcanism (Malfait and Dinkleman, 1972).

A clear marine record of tectonic events 26 to 22 m.y. B.P. exists only to the south of Panama, where the northern flank of a spreading center that spread northward at 41 mm/yr is preserved. Along the surviving part of the southern flank, north of the Grijalva scarp, spreading at a relatively fast rate (40 mm/yr; Fig. 9) began about 24 m.y. B.P. and was initially orthogonal to the old fracture zone. Rearrangement into a pattern of east-west spreading centers and north-south transform faults did not occur here until about anomaly 6 time, 21 m.y. B.P.

22 to 17 M.Y. B.P.: Development of the Hot Spot

At the beginning of the Miocene the magnetic record on both flanks of the Malpelo rift becomes indecipherable, and a band of crust accounting for about 5 × 10^6 yr of spreading is represented by the rough topography of the Coiba-Malpelo gap and Malpelo Ridge on the north flank, and the eastern part of Carnegie Ridge on the south flank. Refraction data from Carnegie Ridge (Bentley, 1974) show that it is formed by a thickening of oceanic crustal layers most readily attributable to excessive volcanic extrusion and intrusion on the young oceanic plate — that is, to a hot spot adjacent to the spreading center. From the broad, massive form of the eastern Carnegie Ridge we infer that the hot spot was centered over the south (Nazca plate) flank of the spreading center (Fig. 11, B), as it is today at the Galapagos Islands. Indeed, the crust that we believe was contemporaneous with the southern part of Carnegie Ridge now forms the deep trough north of Malpelo Ridge (for example, Fig. 6, top). Perhaps tension on the flanks of a dome formed by the growing hot spot caused it to be downfaulted.

Both Malpelo Ridge and the eastern part of Carnegie Ridge are dominated by structural trends, mostly normal fault scarps, that strike 060° (van Andel and others, 1971, confirmed by recent Scripps surveys). If these faults are caused by differential contraction of a variable thickness of cooling volcanic rock (Heath and van Andel, 1973), then the 060° trend most likely represents the alignment of vents during the period that the hot spot was building these aseismic ridges. This trend persists to about long 85.5°W on Carnegie Ridge, which at a migration rate for the Nazca plate over the hot spot of 55 mm/yr (Hey and others, 1977) is predictably about

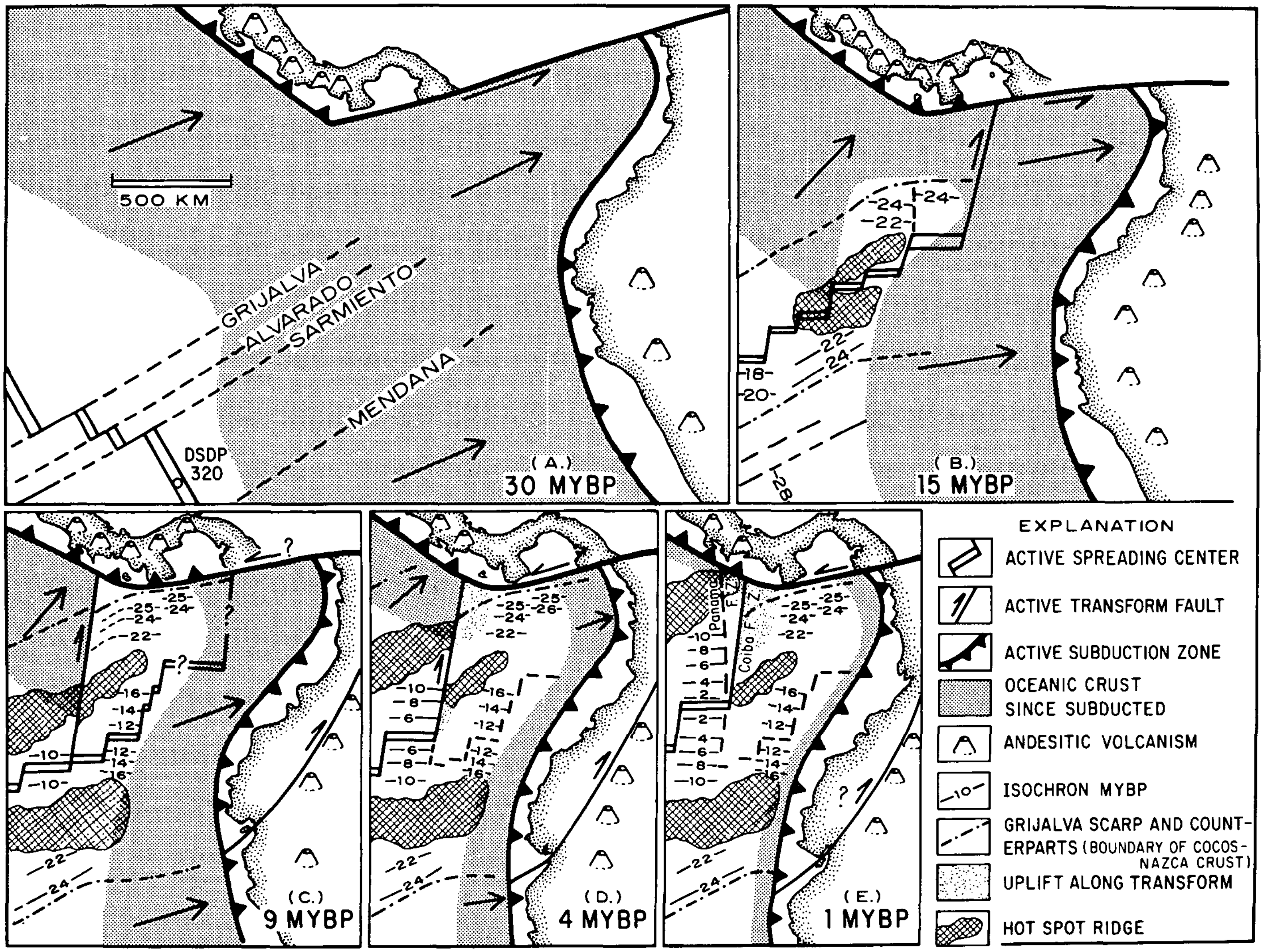


Figure 11. Tectonic reconstructions tracing inferred history of eastern Panama Basin. (A) Middle Oligocene: Farallon plate interacting with Caribbean and South American plates, just before splitting into Nazca and Cocos plates. (B) Middle Miocene: Malpelo and Carnegie Ridges are being formed by hot spot centered on Nazca plate near axis of Nazca-Cocos spreading and are being continuously separated by spreading at boundary. (C) Late Miocene: slowdown of spreading on Malpelo rift, rejuvenation of fracture zone at long 83°W, and cessation of subduction at Panama Trench. (D) Early Pliocene: continued northward migration of Cocos Ridge, stagnation of Malpelo Ridge, and uplift of Coiba Ridge near Nazca-Cocos-Caribbean triple junction. (E) Pleistocene: Cocos and Carnegie Ridges have just arrived at Middle America and Ecuador Trenches, and triple junction has jumped west from Coiba to Panama fracture zone.

12 × 10^6 yr old at this longitude. On the northern flank, 060° faults and ridges on Malpelo Ridge were once continuous with those on Cocos Ridge, where they also extend to about long 85.5°W (Fig. 1; Truchan and Aitken, 1973). The longitudinal change in relative volumes of Cocos and Carnegie Ridges suggests that at about 12 m.y. B.P. the hot spot was under the northern (Cocos plate) flank of the spreading center. On younger parts of both Cocos and Carnegie Ridges, structural lineations trend east-west. We do not understand the somewhat paradoxical observation that while the hot spot was apparently beneath the Nazca plate volcanic vents were aligned almost parallel to the relative motion of the Cocos plate and hot spot (Hey and others, 1977), and when it was apparently beneath the Cocos plate, then the 090° alignment of vents was parallel to the motion of the Nazca plate. Perhaps the pattern of ancient hot-spot vents is as inexplicable as the so-called "Darwinian" alignments of the recent Galapagos volcanoes (McBirney and Williams, 1969), which are oblique to the Galapagos rift and to the absolute motion of the Nazca plate.

17 to 11 M.Y. B.P.: Separation of Malpelo and Carnegie Ridges

The oldest magnetic anomaly we think we can recognize between Malpelo and Carnegie Ridges is anomaly 5C (about 17 m.y. B.P.); the oldest that we are confident of and can model adequately is 5B (Fig. 3). By 16 m.y. B.P. the Malpelo rift segment had migrated away from the hot spot, and "normal" oceanic crust was being created by segments of spreading center that trended 100° and were offset along orthogonal transform faults (Fig. 11, B). By about 12 m.y. B.P. normal crust was being created north of Carnegie Ridge in the Costa Rica rift segment, east of the Malpelo rift. The outlines of the younger margins of the eastern Carnegie Ridge, northeastern Cocos Ridge, and Malpelo Ridge form a crude east-west and north-south staircase, suggesting that although the alignment of vents during the ridge-building phase may have been 060°, a pattern of approximately north-south spreading became established as soon as normal crustal accretion ensued.

The fracture zone traces of transform faults active during this interval cannot be convincingly traced on older crust beyond the aseismic ridges. Although they may be obscured by later tectonism north of Malpelo Ridge and by acoustically opaque chert on the Carnegie platform (Heath and van Andel, 1973), it seems probable that an entirely new pattern of offset spreading centers was formed after the disrupting episode of hot-spot ridge-building volcanism. The only likely exception is the Yaquina graben, which may have developed from the short transform fault postulated at long 79.5°W north of Malpelo Ridge (Fig. 7). If that was its predecessor, then this transform fault had greatly increased in length by 8 m.y. B.P. (when it became extinct); this could have been accomplished by earlier cessation of spreading east of the Yaquina graben and transfer of the northeast corner of the Nazca plate to the Cocos plate, but available data are too sparse to check this hypothesis.

11 to 8 M.Y. B.P.: Abandonment of Malpelo Rift

Halving of the spreading rate on the Malpelo rift 11 m.y. B.P. heralded the end of spreading in the eastern Panama Basin 3 m.y. later. During this period of slow spreading on the Malpelo rift (Fig. 11, C), spreading at a rate consonant with its angular distnace from the Nazca-Cocos pole of rotation continued on the Costa Rica rift. Relative motion along transform faults must have been occurring on the previously inactive sections of long 82°W or the fracture zones at long 83°W between these two segments. We do not know if slow-down and cessation of spreading on the segment from long 83° to 82°W was synchronous with that on the Malpelo rift at long 81.5° to 80.5°W, because of inadequate magnetic data across the former. Van Andel and others (1971) postulated that the northern part of the transform fault at long 84.5°W is being similarly rejuvenated at present, as the northern flank of the Costa Rica rift gradually transfers from the Cocos to the Nazca plate, although there is no evidence of a contemporary slow-down of spreading on the Costa Rica rift.

A consequence of the greatly different spreading rates of the Costa Rica rift and segments to the east (for example, the Malpelo rift) is that the length of the active transform fault at long 83°W between rise-crest segments decreased, because of faster northward movement of the Costa Rica rift spreading center. When spreading on the eastern segments stopped, at 8 m.y. B.P., the rise-crest offset at long 83°W was about 50 km, but by then the entire length of the northern fracture zone at long 83°W had been converted to an active transform fault at least 100 km long, forming the new Cocos-Nazca plate boundary between the active Costa Rica rift and a triple junction (Nazca-Cocos-Caribbean) near Coiba Island.

As either a cause or a consequence of the cessation of spreading east of long 83°W, subduction ceased along the southern margin of Panama in late Miocene time. At that time, major andesitic volcanism ended to the east of Coiba Island, although it continued in the western Panamanian provinces of Bocas del Toro and Chiriqui (Terry, 1956). The plate boundary south of the isthmus, which had been a strike-slip boundary between the Caribbean and Farallon plates during Paleogene time, was reconverted to a strike-slip boundary (between the Caribbean and Nazca plates) after an 18 to 20 × 10^6 yr episode of subduction by the Cocos plate. Slow underthrusting of the northern margin of the isthmus by the Caribbean plate may have continued until the present (Bowin, 1976). Major andesitic volcanism in the Colombian Cordillera Central ceased at 7 m.y. B.P., soon after spreading stopped at the Malpelo rift, and restarted as the current Pliocene-Pleistocene phase of postorogenic volcanism only after a hiatus of several million years (van Houten, 1976). Because we have not been able to define the former Nazca-Cocos plate boundary east of the Yaquina graben and do not know where it intersected the South American (or Caribbean?) plate, it is dififcult to relate the Oliogence-Holocene record of andesitic volcanism in Colombia to changes in the position of the Nazca-Cocos boundary and in the direction of motion of oceanic lithosphere. Previous attempts at this exercise (Malfait and Dinkleman, 1972; van Houten, 1976) have used histories of oceanic plate motions (from van Andel and others, 1971, and Rea and Malfait, 1974) that are quite different from that proposed in this paper.

8 M.Y. B.P. to Present: Readjustment of Plate boundaries and Uplift of Coiba Ridge

Since late Miocene time the main tectonic event has been continued asymmetric spreading on the Costa Rica rift at a rate of about 66 mm/yr (Fig. 11, D). This has increasingly separated the once-continuous Malpelo and Cocos Ridges (Johnson and Lowrie, 1972). Spreading on the Costa Rica rift has also shortened the active transform fault at long 83°W between the rift and the triple junction. Since this long transform fault began as a fracture zone contemporaneous with the long 82°W and the Yaquina graben fracture zone, and with the southern part of the fracture zone at long 83°W, we believe that it was initially parallel to them and extended from the eastern end of the Costa Rica rift with an orientation of 010° along the foot of the steep western scarps of Coiba Ridge and the similar unnamed ridge at lat 3°N, long 82.5°W (Fig. 1). A line of troughs, now partly filled with sediment (for example, the easternmost graben of Fig. 5, C) marks this now-extinct fault, which we propose to call the Coiba fracture zone. With this plate geometry, the tectonic setting of Coiba Ridge was precisely similar to that prevailing today near the Mendocino triple junction, and we believe that the close structural similarity of Coiba Ridge and Mendocino Ridge (Fig. 10) is explained by their similar genesis — namely, minor underthrusting on a long transform fault between a spreading center and a trench-transform-transform triple junction. A minor component of underthrusting along this rejuvenated fracture zone is predictable, because rotation of the Cocos plate throughout its history changes the orientation of old lineations on it (Hey, 1977), so that although the older part of the fracture zone at long 83°W was initially parallel to the direction of Cocos-Nazca plate motion, it would not be when rejuvenated 15 m.y. later even if the direction of plate motion remained the same. This same effect, rather than a change in spreading-center orientation, probably accounts for the lack of parallelism between magnetic anomalies north and south of Malpelo Ridge (Fig. 8).

Uplift along the east side of the Coiba fracture zone was variable; it was greatest on the old crust to the north, where the west rim of Coiba Ridge was uplifted about 3 km; uneven where it intersected the pre-existing rough topography and complex structure of the Coiba-Malpelo gap; and about 1.5 km along its southern extent, near lat 3°S. Additional uplift, perhaps accompanied by volcanism, may have been caused by propinquity of the heat source and magma chamber beneath the Costa Rica rift. Recent uplift and volcanism on Malpelo Island (McConnel, 1943), whose latitude the Costa Rica rift is now approaching as it travels north along the western side of the fracture zone, may be attributable to this effect.

The now-active transform fault at long 83°W, to which we restrict the name "Panama fracture zone" (Molnar and Sykes, 1969), lies about 50 km west of the Coiba Ridge scarp, and has a different orientation (about 358°) to the older Coiba fracture zone, and to the now-active segments of the Ecuador fracture zones (oriented about 005°; Fig. 1). This small but well-defined lack of parallelism implies that the plate east of the Panama fracture zone has a slightly different motion from that east of the Ecuador fracture zones — that is, that the northeastern corner of the Nazca plate, forming the whole of the eastern Panama Basin, has become a separate platelet, detached from the rest of the Nazca plate. This is more convincingly demonstrated by seismicity along that part of the fracture zone at long 83°W south of the Costa Rica rift, although there are no epicenters between the southern part of this fracture zone and the flanks of the Ecuador Trench.

We believe that the jump of the triple junction from the vicinity of Coiba Island (Fig. 7) to near the Burica Peninsula, at the boundary of Costa Rica and Panama (that is, the jump of transform faulting from the Coiba to the Panama fracture zone, and the creation of a separate platelet), occurred quite recently. The jump transferred a triangle of crust between the Coiba and Panama fracture zones from the Cocos plate to the new platelet (Fig. 11), yet Cocos plate underthrusting of that part of western Panama between Coiba Island and the Burica Peninsula may have continued into Pleistocene time, as there are now extinct volcanoes of that age in the cordillera there (Terry, 1956). If we were able to identify magnetic anomalies in the transferred triangle, where lineated anomalies apparently of sea-floor–spreading origin do occur (for example, on profiles 47 and 22 of Grim, 1970b; see Hey and others, 1977, Fig. 6) we could date the triple-junction jump more precisely, by examining their displacement across the Panama fracture zone. Existing marine magnetic data are not dense enough to allow this.

Uplift of the Coiba Ridge probably ceased after the westward jump of the triple junction. Geomorphological evidence suggests that the Burica Peninsula has been recently tilted to the northeast by about 3° (Terry, 1956); this is approximately the dip of the east flank of Coiba Ridge, suggesting that the Burica Peninsula may be a recent miniature analogue of Coiba Ridge.

COMPARISON WITH OTHER TECTONIC INTERPRETATIONS

Our observations and analyses strongly support the general model of Hey (1977) for the development of the entire Cocos-Nazca spreading center. We have added details of tectonic events in its early history and their geologic effects and have discovered that some events occurred at different times than he predicted. For example, we have established from our identification of magnetic anomalies south of Panama that normal Nazca-Cocos spreading was taking place at least 26 m.y. B.P., whereas Hey suggested that it began about 25 m.y. B.P., and for the first 2×10^6 yr was orthogonal to Farallon plate fracture zones rather than approximately north-south. Also, the Malpelo rift spreading center between Malpelo and Carnegie Ridges was still active at 8.5 m.y. B.P. (Hey, 1977), although its rate of spreading had decreased sharply by 11 m.y. B.P.

The great difference between our interpretation of the structure of the eastern Panama Basin and that of van Andel and others (1971) and Heath and van Andel (1973) is that we see it as the result of rather common oceanic-plate processes (sea-floor spreading, plate-boundary jumping, and hot-spot volcanism) that have also occurred in the western Panama Basin, whereas they considered the eastern basin to be significantly different in structure, having giant dilational cracks, a pervasive northeast-southwest fault pattern, and perhaps even continental fragments. Our perception of a plate tectonic order in this apparently complex chaos results from access to a wealth of new marine geophysical data which, above all, allow mapping of east-west structural trends and isochrons parallel to those in the western basin, as well as increased knowledge of the nature of the aseismic ridges (for example, Heath and van Andel, 1973) and of tectonic evolution along the rest of the Nazca-Cocos boundary (Hey, 1977; Hey and others, 1977; Anderson and others, 1976).

In addition to factual disagreements with the conclusions of Hey (1977) and van Andel and others (1971), we harbor different prejudices about the causes of the events whose effects we observe.

SPECULATIONS ON CAUSES

What Initiated Cocos-Nazca Spreading?

There are several hypotheses explaining the splitting of the Farallon plate that marked the initiation of Cocos-Nazca spreading, but some require a timing of events that is at odds with our observations. Hey (1977) suggested that the split was caused by tension about a nascent hot spot, and Heath and van Andel (1973) favored fragmentation as a result of collision of an ancestral Carnegie Ridge with the South American subduction zone. However, the earliest Cocos-Nazca spreading that we recognize produced apparently normal oceanic crust, unaffected by any developing hot spot for at least 5 × 10^6 yr, and all the aseismic ridges of the Panama Basin are clearly younger than the initiation of Cocos-Nazca spreading. Handschumacher (1976) proposed that splitting of the Farallon plate in the equatorial region was a consequence of the collision of the Pacific-Farallon spreading center with the Pacific–North America subduction zone off western North America. We find this an attractive idea, because the events were approximately synchronous (at 27 to 26 m.y. B.P.), and we can envisage that after the spreading center collision had greatly changed the geometry of the Farallon plate, then the forces controlling its motion would have had different effects. Specifically, we hypothesize that before the spreading-center collision, the intact, rigid Farallon plate was moving eastward, orthogonally toward the long North and South American subduction zone, with oblique subduction in the shorter Middle America segment. After the collision had split the plate into northern (Gorda plate) and southern (Cocos plus Nazca plate) sections, then the southern section was subjected to divergent gravitational stresses from orthogonal subduction at the northwest-southeast Middle America Trench and the north-south Peru-Chile Trench, which split the plate along an intervening line of weakness, the Grijalva fracture zone. This inactive lineament was converted, by the change in plate motion into an extreme type of "leaky" fracture zone, namely an obliquely spreading rise crest. Van Andel (1971) first speculated on the likelihood of fracture zones evolving into spreading centers in this manner.

What Caused Miocene Cessation of Nazca-Cocos Spreading East of Long 83°W?

The most popular explanation for cessation of spreading in the eastern Panama Basin is that the northern subduction zone became "plugged" as it attempted to swallow one of the aseismic ridges migrating toward it on the Cocos plate (van Andel and others, 1971; Malfait and Dinkleman, 1972; Hey, 1977). The greatly overthickened nature of the crust beneath the hot-spot ridges (Bentley, 1974) makes this plausible, although seismicity and observations with a deep-tow instrument at the eastern margin of Carnegie Ridge (Huestis and Lonsdale, 1976) and with a submersible at the northeastern end of Cocos Ridge (Heezen and Rawson, 1977) establish that underthrusting of these ridges is now occurring. Van Andel and others (1971) suggested that plugging of the Panama Trench began with an aseismic ridge (their Ridge X), for which we find little evidence in recent bathymetric or seismic profiler data, and continued with Coiba Ridge. We have explained Coiba Ridge as a consequence, rather than a cause, of the shift in plate boundaries, and we postulate that it is a tilted slab of normal oceanic crust (rather than an overthickened hot-spot ridge), which would afford little obstacle to the subduction process. Malpelo Ridge is clearly not a candidate for trench plugging, because it is far from the margin today and has never been closer. Knowledge that Malpelo Ridge was once adjacent to both Cocos and Carnegie Ridges allows us to reconstruct their former extent and to estimate how much of them has been subducted. The answer we get is that neither ridge has pentrated more than 40 km into the subduction zone, and we deduce from the present rates of motion of the Cocos and Nazca plates (Hey and others, 1977) that they have arrived at the trench within the past 1 × 10^6 yr (Fig. 11, E), long after spreading stopped on the Malpelo rift.

Hey (1977) suggested as an alternative explanation that spreading on the Malpelo rift ceased because it migrated too far from the hot spot. This is unconvincing, because long segments of the now-active boundary are now farther from the Galapagos than the Malpelo rift was when it became extinct.

The explanation we prefer is a variant of the trench-plugging hypothesis that relies on the apparent coicidence of the northern boundary of crust formed by Cocos-Nazca spreading with the extinct Panama Trench. We suggest that the trench was plugged by a broadside encounter with the northern counterpart of the Grijalva scarp and ridge. Subduction ceased not just because of the difficulty of underthrusting a ridge and the younger, less dense lithosphere behind it (much greater obstructions have been subducted at other trenches), but because there was a convenient nearby line of weakness, the Coiba fracture zone, that could become the new plate boundary. This again emphasizes the role of fracture zones as deep lines of weakness in the lithosphere, which we believe was also significant in the 27 m.y. B.P. break-up of the Farallon plate. The counterpart of the Grijalva scarp and ridge was plastered onto the isthmian slope west of long 80°W but survives as an eastward, basin-enclosing extension of that slope between long 79.7° and 78.2°W, where the isthmian margin is embayed (Fig. 1). Because this enclosed basin falls within the territorial waters of the Republic of Panama, reflection profiles across it are not available to us, and other tectonic interpretations are possible (for example, it may be a borderland basin defined by strike-slip faulting). However, gravity data, which have a narrow low over the former trench (Hayes, 1966), suggest that the boundary of oceanic plate lies along the north flank of the basin and that the enclosing ridge is a structure on the oceanic crust. To the west, it is possible that the large ridge and northwest-facing scarp that trends 060° across Coiba Ridge (A in Fig. 10) is an extension of the same structure, that at these longitudes changes orientation and becomes parallel to the extant Grijalva scarp.

What Caused the Readjustment in Plate Boundaries from Coiba to Panama Fracture Zone?

It has been suggested that collision of the aseismic hot-spot ridges of the Panama Basin with its bordering subduction zones might have profound tectonic effects of regional significance. We have deduced that the Cocos Ridge and Carnegie Ridge both encountered their subduction zones for the first time within the past 1 × 10^6 yr. The event that we can most readily relate to these confrontations is the isolation of the northeast corner of the Nazca plate, to form a separate platelet, and the consequent jump of transform faulting from the Coiba fracture zone, which is parallel to the Ecuador fracture zones, to the Panama fracture zone, which is not parallel to any Nazca-Cocos transform faults.

CONCLUSIONS

The eastern Panama Basin was formed by north-south spreading at the Cocos-Nazca plate boundary 27 to 8 m.y. B.P. For much of this period, spreading was highly asymmetric. There are probably no remnants of crust created by earlier east-west spreading at the Pacific-Farallon spreading center, except on the obducted margins of Panama and Colombia, but large parts of the eastern basin have been gradually transferred from the Cocos to the Nacza plate. The entire region may now be a separate small plate, with different motion from the bulk of the Nacza plate.

Part of a pattern of extinct spreading centers and transform faults that were abandoned by shifts in the plate boundaries have been mapped. The fossil rise crest at the Malpelo rift had a full-spreading rate of only 25 mm/yr for the 3 m.y. before spreading ceased. The Yaquina graben is a fossil transform fault offsetting the Malpelo rift. Another fossil transform fault forms a deep trough near long 82°W.

The pattern of spreading was disrupted about 22 m.y. B.P. by development of a hot spot and its attendant effusive volcanism: this first built Malpelo Ridge and the eastern part of Carnegie Ridge, and then the Cocos and western Carnegie Ridge; today it is building the Galapagos Islands. Malpelo Ridge was separated from Carnegie Ridge by a 9-m.y. period of normal (highly asymmetric) Nacza-Cocos spreading, and from the Cocos Ridge by an 11-m.y. period of continued fast spreading on the Costa Rica rift, while the more eastern Malpelo rift segment slowed down and became extinct. Coiba Ridge is not a hot-spot trace, but was formed by uplift beside a long meridional transform fault during late Miocene and Pliocene time. The transform fault subsequently jumped westward to the Panama fracture zone. Coiba Ridge was an indirect result of the cessation of subduction along the Panama Trench. The cause of this event was probably plugging of the trench with the northern counterpart of the Grijalva scarp, a fragment of which may still exist south of the Gulf of Panama.

The land geology of Panama and western Colombia, which has become much better known through the recent efforts of the Office of Interoceanic Canal Studies (see, for example, Bandy, 1970; Bandy and Casey, 1973; Case and others, 1971; Case, 1974), is compatible with our plate-tectonic model, and the volcanic and sedimentary stratigraphy there is a valuable check on the timing of events that we have inferred mainly from marine magnetic data.

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