Iectonic evolution of the Cocos-Nazca spreading center

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ABSTRACT

Magnetic and bathymetric data from the eastern Pacific have been analyzed and a model for the evolution of the Galapagos region developed. The Farallon plate appears to have broken apart along a pre-existing Pacific-Farallon fracture zone, possibly the Marquesas fracture zone, at about 25 m.y. B.P. to form the Cocos and Nazca plates. This break is marked on the Nazca plate topographically by the Grijalva scarp and magnetically by a rough-smooth boundary coincident with the scarp. The oldest Cocos-Nazca magnetic anomalies parallel this boundary, implying that the early Cocos-Nazca spreading center trended east-northeast. This system soon reorganized into an approximately east-west rise–north-south transform configuration, which has persisted until the present, and the Pacific-Cocos-Nazca triple junction has since migrated north from its original location near lat 5°S. If correct, the combination of these simple geometric constraints produced the "enigmatic" east-trending anomalies south of the Carnegie Ridge.

The axes of the Cocos-Nazca spreading center and the Carnegie Ridge are essentially parallel; this can lead to paradoxical conclusions about interpretation of the Cocos and Carnegie Ridges as hotspot tracks. Hey and others (1977) have shown that recent accretion on the Cocos-Nazca spreading center has been asymmetric, resulting at least in part from small discrete jumps of the rise axis. I show here that the geometric objections to both the "hotspot" and "ancestral-ridge" hypotheses on the origin of the Cocos and Carnegie Ridges can be resolved with an asymmetric-accretion model. However, all forms of the ancestral-ridge hypothesis encounter more severe geometric difficulties, and these results support the hotspot hypothesis.

INTRODUCTION

The "instantaneous" plate motions in the east Pacific are apparently well known. Different people, working with different biases and often different data sets, have derived models quite consistent with each other, as well as being internally consistent (Hey and others, 1972, 1977; Herron, 1972; Morgan, 1973; Minster and others, 1974). These models predict both magnitudes and directions of relative plate motions and have been tested in many ways (Hey and others, 1972; Herron, 1972; Forsyth, 1972; Stover, 1973; Rea and others, 1973). Thus, on a gross scale, we appear to understand the present-day tectonic configuration. However, attempts to understand the details of the evolution of the present system have been less successful. The most obtrusive and controversial of the problem areas remains the Galapagos region, despite relatively high data density.

Herron and Heirtzler (1967) made the first guess at an evolutionary scheme for the Galapagos area, a guess that violated the rigid-plate hypothesis. Holden and Dietz (1972) pointed out this violation, but their reasoning was incorrect. They stated that the zone of compression suggested by Herron and Heirtzler (1967) and Raff (1968) is avoided by the requirement that two or possibly three of the rifts must spread obliquely, because "at triple junctions, seafloor spreading cannot be perpendicular to all three of the rifts" (Holden and Dietz, 1972, p. 267). In fact, spreading may be perpendicular to all three rifts without resulting zones of compression and without violation of the rigid-plate hypothesis.

Van Andel and others (1971) proposed that the aseismic Cocos and Carnegie Ridges were formed by rifting apart of a pre-existing ancestral ridge. This hypothesis has since undergone several modifications (Malfait and Dinkelman, 1972; Heath and van Andel, 1973; Rea and Malfait, 1974).

Holden and Dietz (1972) outlined a solution based on the hot spot hypothesis, in which the Cocos and Carnegie Ridges are regarded as hotspot traces formed as the Cocos and Nazca plates moved away from the Galapagos hotspot. This attempt, while instructive and partially successful conceptually, failed in detail for several reasons. Holden and Dietz misquoted Le Pichon (1968), confusing his America-Pacific pole with his Antarctica-Pacific pole and using that as a Nazca-Pacific pole. Using this invalid pole and an unreliable spreading-rate datum from Heirtzler and others (1968) (since reinterpreted) on the Pacific-Nazca rise, they calculated a spreading rate for the East Pacific (Pacific-Cocos) Rise north of the Pacific-Cocos-Nazca triple junction. This technique would only be valid if the Cocos-Nazca spreading center and triple junction itself did not exist. Solving for the Cocos-Nazca rotation rate, they predicted ages in the Panama basin that were so high they were used by Heath and van Andel (1973) to discredit the hotspot hypothesis.

After further elaboration of the hotspot hypothesis by Johnson and Lowrie (1972) and Hey and others (1973), Sclater and Klitgord (1973) examined both the hotspot and ancestral-ridge hypotheses and decided that both should be rejected, concluding that the Cocos and Carnegie Ridges "are not tectonically related" (p. 6973).

The difficulty in the Galapagos area arises primarily because the older magnetic anomalies have proven extremely difficult to correlate, surprisingly so considering the high data density and the ease with which the very young anomalies are correlated. An important problem is the reason for this difficulty in correlating older anomalies — either clearly recognizable anomalies were never formed here, or some mechanism has acted in this area to destroy them after they were formed.

On the basis of all available evidence, including new data presented here, I conclude that a model based on the hotspot hypothesis, with the modification of asymmetric accretion resulting at least in part from discrete jumps of the rise axis as discussed by Hey and others (1973) and demonstrated by Hey and others (1977), successfully meets the objection of Sclater and Klitgord (1973) and allows us to outline the history of the area from the break-up of the Farallon plate and birth of the Cocos-Nazca spreading center to the present. The "instantaneous" (a term Hey and others, 1977, have examined) configuration of plate boundaries and motions (Fig. 1) has generated a wedge of crust spread from the Cocos-Nazca spreading center, which is characterized by

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Geological Society of America Bulletin, v. 88, p. 1404–1420, 9 figs., October 1977, Doc. no. 71003.

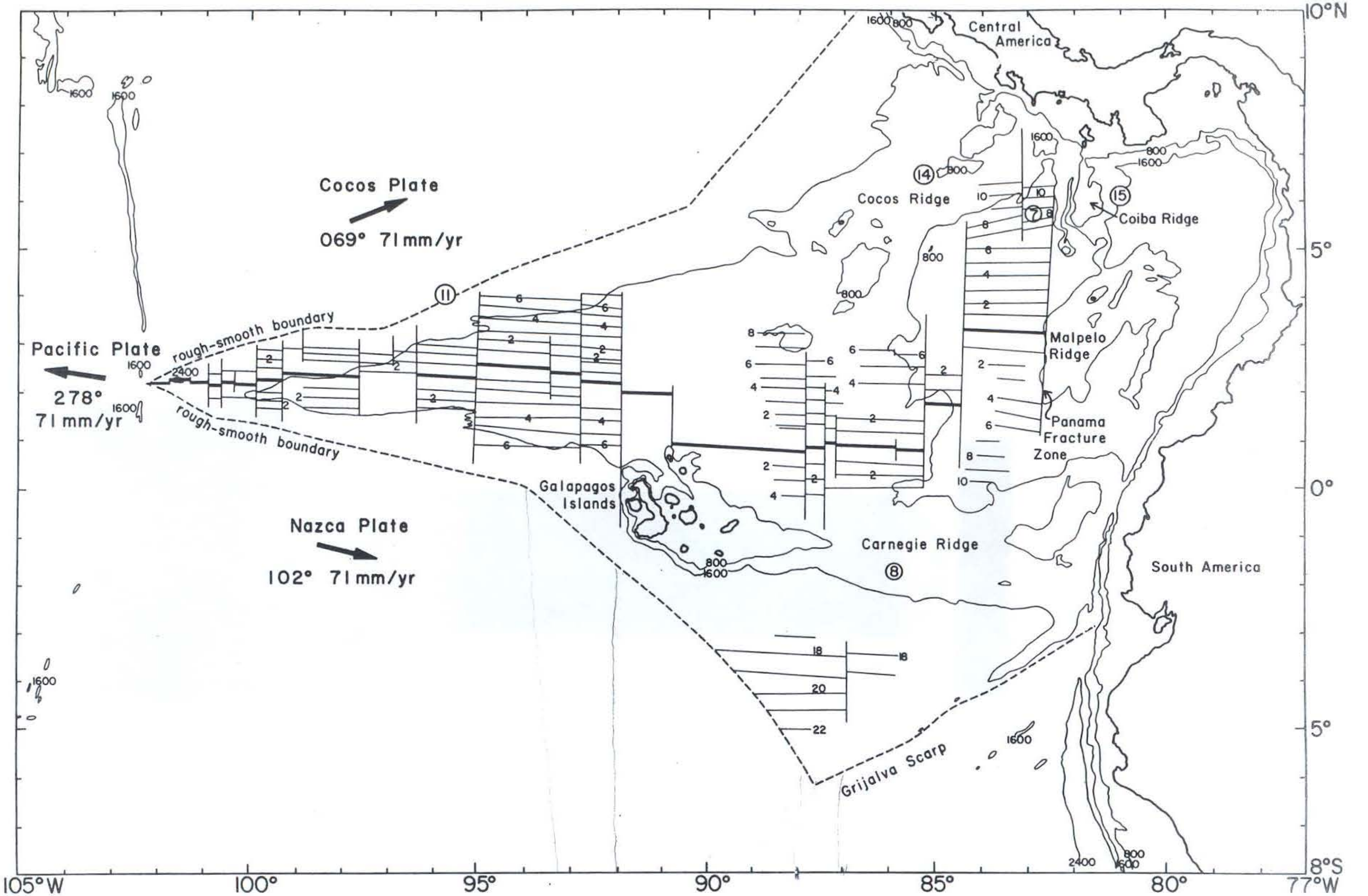


Figure 1. Diagram summarizing "known" aspects of Galapagos area. Bathymetry in fathoms from Chase and others (1971), van Andel and others (1971), Mammerickx and others (1974), and Johnson and others (1975). Dashed lines are rough-smooth boundaries. Light subparallel lines are isochrons dated in million years before present; heavier lines are active-rise axes. Isochron uncertainty increases with age. Circled numbers are DSDP ages from van Andel and others (1973). Plate motions are relative to triple junction.

a slow spreading rate, rough topography, and strong magnetic anomalies. This wedge, termed the Galapagos gore by Holden and Dietz (1972) and discussed in detail by Hey and others (1977), is surrounded by crust spread from the Pacific-Cocos and Pacific-Nazca spreading centers which has the smooth morphology common to fast-spreading rises and low-amplitude magnetic anomalies, as both these segments of the East Pacific Rise are oriented nearly parallel to the Earth's magnetic field vector. My model explains the location and orientation of the magnetic and bathymetric rough-smooth boundaries that thus bound the gore and implies that there are two genetically different magnetic and bathymetric boundaries in the area.

EVOLUTION OF PACIFIC-COCOS-NAZCA TRIPLE JUNCTION

McKenzie and Morgan (1969) assumed for simplicity that all rises spread symmetrically and nonobliquely. They were then able to show that all rise-rise-rise (RRR) triple junctions are stable under these assumptions. The stability criterion for the more general case of oblique spreading has been discussed by McKenzie and Sclater (1971), and for the yet more general case of asymmetric, oblique spreading by Johnson and others (1973). An RRR junction is stable (in the McKenzie-Morgan sense) only if a frame of reference exists in which the geometries of all three pairs of relative plate motions remain simultaneously unchanged. This frame of reference is thus fixed relative to the junction, which in general will be moving relative to the mantle. Figure 2 shows the instantaneous vector velocity triangle for the Galapagos triple junction. The vectors P-M, C-M, and N-M show the instantaneous velocities of the Pacific, Cocos, and Nazca plates relative to the Galapagos hotspot predicted by model PAM1 (Hey and others, 1977). The vectors C-P, N-P, and C-N show the predicted relative motions of these plates at the junction. The vector J-M shows the calculated velocity of the triple junction over the mantle (assuming hotspots to be fixed in the mantle). The vectors C-J, N-J, and P-J show the motions of the plates relative to the junction and thus predict the recent azimuths of the isochron flexures (rough-smooth boundaries) that separate crust spread from the various rises. The triangle is in velocity space. The dashed lines pc, pn, and cn in Figure 2 are an approximation to the frames of reference in which the respective relative geometries remain unchanged. These lines would be the perpendicular bisectors of the sides of the velocity triangle for the special case of symmetric, nonoblique spreading (McKenzie and Morgan, 1969), which is probably occurring on none of these rises at present, although I have constructed the frames of reference as though it were. More generally, frames of reference must be constructed parallel to their respective plate boundaries through points on the relative-motion vectors determined by the percentage of asymmetric spreading. The junction is stable only if these dashed lines intersect in a point, which shows the instantaneous velocity of the triple junction. The Cocos-Nazca spreading center away from the junction is probably now spreading slightly asymmetrically or jumping, with a maximum obliqueness angle, measured between the transform-fault azimuths and local perpendiculars to the rise axis, of about 10°. If this is also true at the junction, then in order for this junction to be continuously stable, the Pacific-Cocos and (or) the Pacific-Nazca spreading center must be accreting asymmetrically and (or) obliquely in a highly constrained geometry (although from our measurements this exact geometry is poorly defined). As asymmetric accretion has been reported on both rises (Heinrichs and Lu, 1970; Herron, 1972), and considering the uncertainties in rates involved, this could easily be a stable junction at present. Alternatively, it is possible that the junction could achieve long-term stability through discontinuous adjustments (such as rise jumps) to a geometry instantaneously unstable. McKenzie and Parker (1974) have pointed out that it is unlikely that a junction stable in velocity space will be stable in acceleration space. Short-term instabilities in velocity space could conceivably be resolved with compensating accelerations; a possible example of this is seen near the South America–Africa–Antarctica triple junction (Sclater and others, 1976). Instantaneously, the Pacific-Cocos-Nazca triple junction is moving about 5 mm/yr to the north and about 17 mm/yr to the west relative to the hotspot. It is interesting to note that the *junction* was creating the high escarpments bordering Hess Deep approximately 1 m.y. B.P., as the Cocos-Nazca spreading center is growing at a rate of about 68 mm/yr.

McKenzie and Parker (1974) have defined a triple-junction vector as a vector at right angles to the vector velocity triangle; the magnitude of the triple-junction vector is the area of the velocity triangle. The vector velocity triangle in Figure 2 is divided into three triangles by vectors P-J, C-J, and N-J. The area of each of these triangles represents the rate at which new material is created on the new parts of the respective rises. The magnitude of this

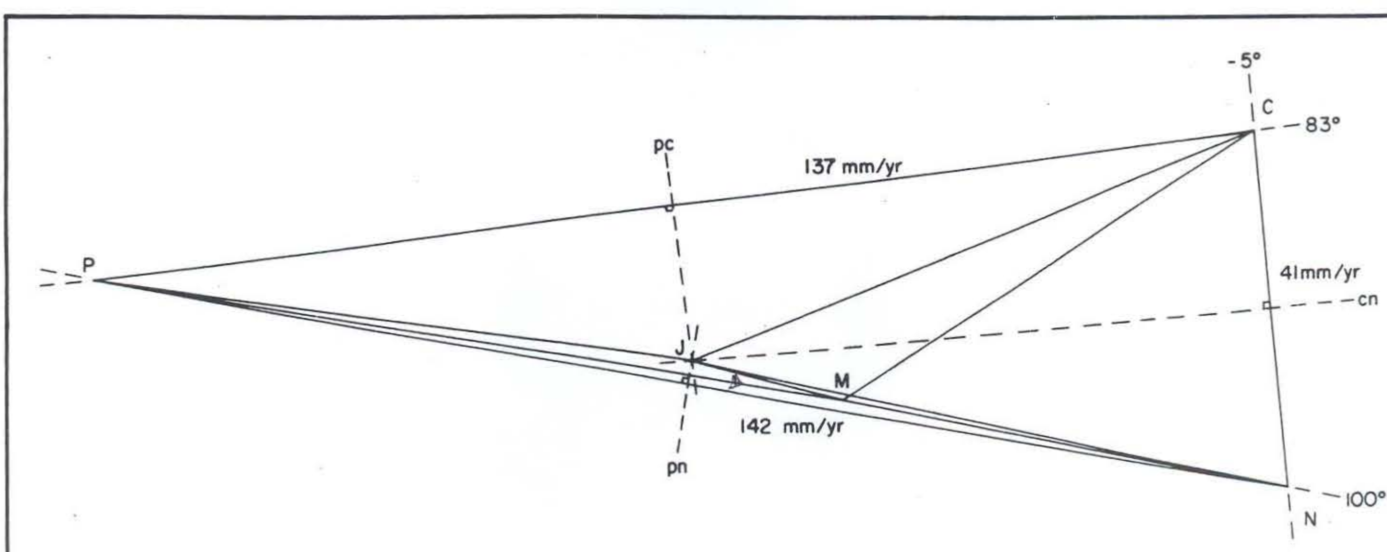


Figure 2. Instantaneous vector velocity triangle for Pacific-Cocos-Nazca triple junction. All instantaneous rates and azimuths are from model PAM1 (Hey and others, 1977). Vectors **P-C, C-N,** and **P-N** show relative plate motions at triple junction (rates and azimuths given refer to these motions). Vectors **P-M, C-M,** and **N-M** show plate motions relative to hotspot reference frame. Vectors **P-J, C-J,** and **N-J** show plate motions relative to triple junction. Vector **J-M** gives motion of junction relative to hotspots. Points along dashed lines pc, cn, and pn have vector velocities that leave geometry of **P-C, C-N,** and **P-N,** respectively, unchanged (McKenzie and Morgan, 1969). Triangle is in velocity space.

ıle-junction vector, then, is the rate at which new crust is created r' new parts of all three rise segments meeting at the triple ıc . (Note that the statement of McKenzie and Sclater [1971] out the change in length of an RRR system can be strengthened say that the total length of rises meeting at an RRR junction ıst increase with time, although a peculiar property of obtuse ctor velocity triangles is that the rise whose frame of reference ersects the obtuse angle is required to shrink in length — that is, ung isochrons will be shorter than old isochrons.) At present, the ocos-Nazca and Pacific-Cocos rises are creating new crust on eir new parts at a much greater rate than the Pacific-Nazca rise ig. 2). The relative (and absolute) importances of these rises as eators of new crust are thus in constant flux. Note that we are scussing accelerations in crustal formation, rather than velocities, both the Pacific-Nazca and Pacific-Cocos rises are creating more ust each year than the Cocos-Nazca rise. This emphasizes the imɪrtance of triple-junction geometry in plate evolution.

If the ages along the western rough-smooth boundary, that part ɪrmed by isochron flexures, were well known, we would know the ısition of the junction relative to the hotspot through time, as ıch point on that boundary was formed at the triple junction. parse data along the rough-smooth boundary allows us only to lace some broad constraints on that position. As the azimuths of ıe Pacific, Cocos, and Nazca plate motions over the mantle have emained essentially constant at least since the time marked by the ge of the northeastern end of the Cocos Ridge, (about 20 m.y. .P., if the instantaneous rates can be extrapolated that far into the ast), the triple junction must have been moving north relative to ıe mantle during that time. This requires either that the junction as originally located to the south and has migrated north to its resent position, or that the junction as well as the Cocos-Nazca ise jumps back to the south episodically after a period of northva gration. Note that rise jumps will affect the evolution and tat , of the triple junction only if the segment of the rise extendng into the junction jumps. Whether the junction has moved east ɪr west depends on the magnitudes of the eastward and westward omponents of motion of the plates. The azimuth of the eastern ɪart of the rough-smooth boundary (parallel to the old isochrons, igs. 3, 4) indicates either that the Cocos plate motion was slower ɪr that the Nazca plate motion was faster before about 23 m.y. B.P., assuming that the azimuths over the mantle have remained ɪpproximately constant. In either case, the junction was formerly ocated to the south and has been moving northward relative to the nantle.

A detailed knowledge of the triple-junction evolution must await a detailed (and accurate) isochron map. Before about 5 to 10 m.y. B.P., the triple junction was probably formed by the intersection of the Cocos-Nazca rise and fossil segments of the Pacific-Cocos and Pacific-Nazca rises. The evolution from that system to the present one was complicated by discontinuous jumps of the Pacific-Cocos and Pacific-Nazca rises (Sclater and others, 1971; Herron, 1972; Anderson and Sclater, 1972; Anderson and Davis, 1973). The peculiar pattern of the rough-smooth boundary near the Galapagos Islands may have formed during this transition, details of which are still unclear.

EVIDENCE FROM OLD MAGNETIC ANOMALIES

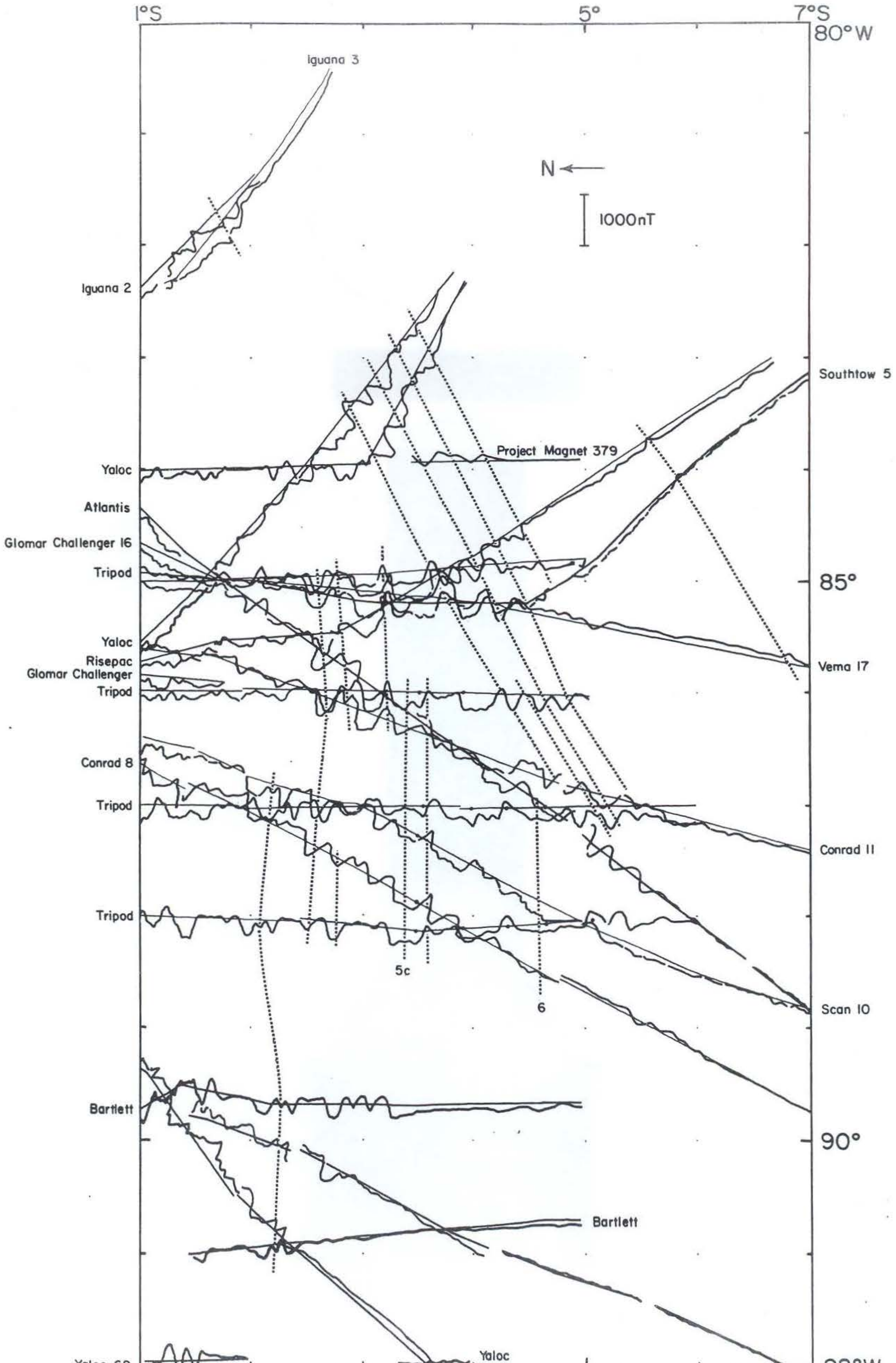
Figure 3 shows the old magnetic anomalies to the south in the central part of the area. There are several interesting anomaly patterns in this area. Perhaps most significant in unravelling the evolutior the pattern of the rough-smooth boundary, which suddenly w between long 92° and 88°W, its azimuth becoming much more south of east than it is farther west (Fig. 1). Between long 88° and 87°W the southern rough-smooth boundary azimuth changes drastically, swinging 90° to 100° to the northeast, and strikes approximately 060°, coincident with the Grijalva scarp (Fig. 4). The significance of this dramatic change in trend, first noticed by Raff (1968), will be explored in the section dealing with the evolution of the area.

The anomalies just north of the Carnegie Ridge trend approximately east-west. Over the Carnegie Ridge, anomaly amplitudes decrease, and identifications are impossible. South of the Carnegie Ridge the anomalies retain the east-west orientation (Fig. 3). South of lat 3°S some anomalies are oriented east-west and some northeast-southwest. The (presumably) oldest anomalies in the area are oriented approximately 063°, parallel to the southeastern rough-smooth boundary. If my correlations (Fig. 3, 4) are correct, the anomaly pattern in the confused area between the old anomalies trending northeast-southwest and the younger anomalies at lat 3°S trending east-west could be part of a rather extreme Zed pattern (Menard and Atwater, 1968). If the anomalies between about lat 3° and 4°S on the Tripod long 86° and 88°W profiles do in fact correlate as they appear to, implying an east-west trend rather than the fanning expected from the Zed pattern, sections of the anomaly pattern may be missing here and repeated to the north as a result of rise jumps.

I was able to find a highly tentative correlation (Fig. 6) between the long 88°W anomalies and the time scale of Heirtzler and others (1968). Because my conclusions about the timing (although not the geometry) of the Cocos-Nazca spreading-center evolution are heavily based on this correlation, they should be regarded as equally unsure. If valid, the spreading half-rate at long 88°W was about 41mm/yr between about 17 and 23 m.y. B.P. The long 88°W profile was chosen as the standard because it runs nearly parallel to the spreading direction, thus minimizing the number of fracture zones crossed, and because each short segment of anomalies along it is duplicated on one or another of the nearby profiles. Rea and Malfait (1974) have suggested an alternative interpretation, based on correlation of anomalies on the *Atlantis II*, 54a trackline, which cuts diagonally across this area at an angle of about 35° (Fig. 3). I am suspicious of correlations based on a profile so oblique to the north-south spreading direction, particularly in an area characterized by jumping rise axes and a dense and complex fracture-zone pattern. In addition, the anomaly between about lat 4.4° and 4.8°S on the Tripod long 88°W profile (Fig. 3), which I have tentatively identified as anomaly 6, a large negative (normal) anomaly, has been identified by Rea and Malfait (1974) as the large positive (reverse) anomaly between anomalies 12 and 13 (see their Fig. 2, 4). (Note that anomalies in this area are "upside down" because of their equatorial location.) This is perhaps an indication of how tenuous these correlations are. Handschumacher (1976) supports my anomaly 6 interpretation. My correlations are approximately valid only if the numerous rise-axis jumps I think have occurred have been small and periodic enough that the resultant anomaly pattern appears to have been produced by asymmetric spreading. I emphasize that my geometrical arguments are independent of the timing involved.

Figure 5 shows the old anomalies to the north in the central part of the area. The magnetic rough-smooth boundary azimuth becomes more northerly north of the Galapagos Islands. Northeast of about lat 6°N, long 90.5°W, the orientation of this boundary is uncertain, although it probably becomes more northerly (Fig. 5). The oldest anomalies in this area may also be parallel to the rough-smooth boundary. If the oldest anomalies to the south are parallel to that rough-smooth boundary (Fig. 4), we expect the same relationship to the north, as the oldest anomalies to the south should correlate with the oldest anomalies to the north. Unfortunately, if the hypothesis of persistent north-south relative motion in this area is correct, most, if not all, of the older anomaly pattern on the Cocos plate probably was subducted in the Mid-America Trench (Fig. 7), perhaps eliminating a critical test of my model. If any of this older Cocos crust remains unsubducted, it will be found east of long 88°W just south of the trench, according to my model.

My correlations on the *Glomar Challenger* Leg 16 profile differ from those of Sclater and Klitgord (1973). (This point is discussed in the section below [Fig. 9]). Farther north, in the area from lat


1°S
5°
7°S
80°W
85°
90°
92°W
N
1000nT
Iguana 3
Iguana 2
Project Magnet 379
Southtow 5
Yaloc
Atlantis
Glomar Challenger 16
Tripod
Yaloc
Risepac
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Conrad 11
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Yaloc 69
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Vema 21
Atlantis

5° to 9°N, long 85° to 90°W, surveyed by the *USNS Bartlett,* I am generally unable to correlate anomalies from profile to profile. Although old anomalies on the Nazca plate are oriented east-west, and the rise axis forming these anomalies was probably oriented roughly east-west, and young anomalies on the Cocos plate are also east-west, the older anomalies on the Cocos plate should not be oriented east-west today if the plate motions that Hey and others (1977), Morgan (1973), and Minster and others (1974) have derived can be extrapolated into the past; the reason is that the old anomalies on the Cocos plate have been rotated about a pole near lat 20°N, long 114°W, at a rate of about 1.4°/m.y. Thus, we expect the trend of the older anomalies to swing around toward the northeast. The difficulty in correlating anomalies to the north may thus result from each profile crossing several fracture zones now oriented northwest-southeast. The numerous small offsets of the rise axis (Fig. 3, 4, 5 of Hey and others, 1977) may indicate that fracture zones are common in this area, which we would expect in an area characterized by jumping rise segments.

Figure 7 of Hey and others (1977) shows anomalies from a detailed survey over the eastern (Costa Rica) rise segment (Grim, 1970a, 1970b). During the past 6 m.y., the rise axis was oriented east-west. The trend of the older anomalies swings slightly toward the northeast, but correlations remain convincing. I think anomaly 5 can be identified on the profiles at long 82.5°, 83°, and 83.5°W. The trend of the (presumably) older anomalies continues to become more northeasterly and the correlations become more tenuous the older the anomalies, in contrast to the easily correlatable younger anomalies. The gradual swinging around of anomalies in this area is the effect expected from the rotation of the Cocos plate.

Correlation of old anomalies on the Cocos plate with the time scale is complicated by the lack of a continuous profile across the entire sequence. I used a composite profile consisting of the Tripod long 88°W profile from the axis to the course change at lat 3.3°N and two short north-south profiles, run by the *USNS De Steiguer* on the way to and from the triple-junction survey (Hey and others, 1972), which were designed to tie in with this Tripod profile (Fig. 5, 6). The preferred model is shown in Figure 6. I am not overly enthusiastic about these correlations but prefer them to the alternatives I discussed in detail previously (Hey, 1975).

Figure 3. Magnetic anomalies in southern part of area, all plotted perpendicular to track except *Bartlett* profiles, which are projected onto 000°. Positive (reversed) toward east. Dotted lines show proposed correlations. Note rough-smooth boundary.

EVOLUTION OF GALAPAGOS AREA

The evidence from morphology and magnetic anomalies allows us to place general constraints on evolutionary models. The major aspects of the geometrical evolution we understand are (1) the period when the Cocos and Nazca plates were one plate (the Farallon plate), (2) the early (and brief) period of spreading along the northeast-trending Cocos-Nazca spreading center following the break-up of the Farallon plate, (3) the rapid reorganization of this system into a north-south–opening system which has persisted until the present, (4) the northward migration of this system from the original triple junction at about lat 5°S to the present location at about lat 2°N, during which time the east-west–lineated anomalies south of the Carnegie Ridge were formed, (5) the occasional jumps of the rise axis resulting in asymmetric accretion of material to the Cocos and Nazca plates, and (6) the formation of the Cocos and Carnegie aseismic ridges as hotspot traces on the Cocos and Nazca plates. Much of the information my model is based on is summarized in Figure 1. We are building toward the reconstruction shown in Figure 7.

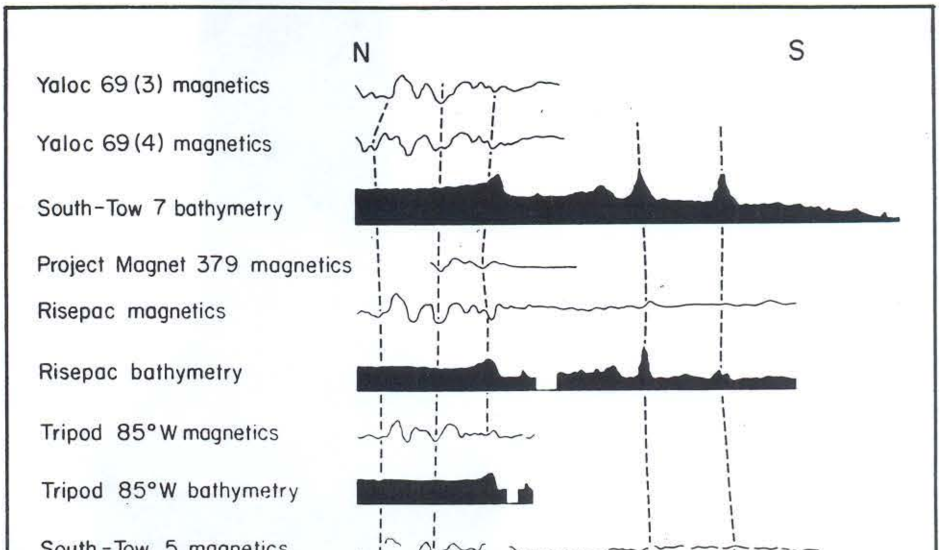

Figure 4. Profiles cutting southeastern rough-smooth boundary projected onto 330°, perpendicular to that boundary. Magnetic and bathymetric amplitudes are functions of projection angles. Prominent scarp is Grijalva scarp. Farther south are Sarmiento and unnamed topographic trends. Dashed lines are proposed correlations.

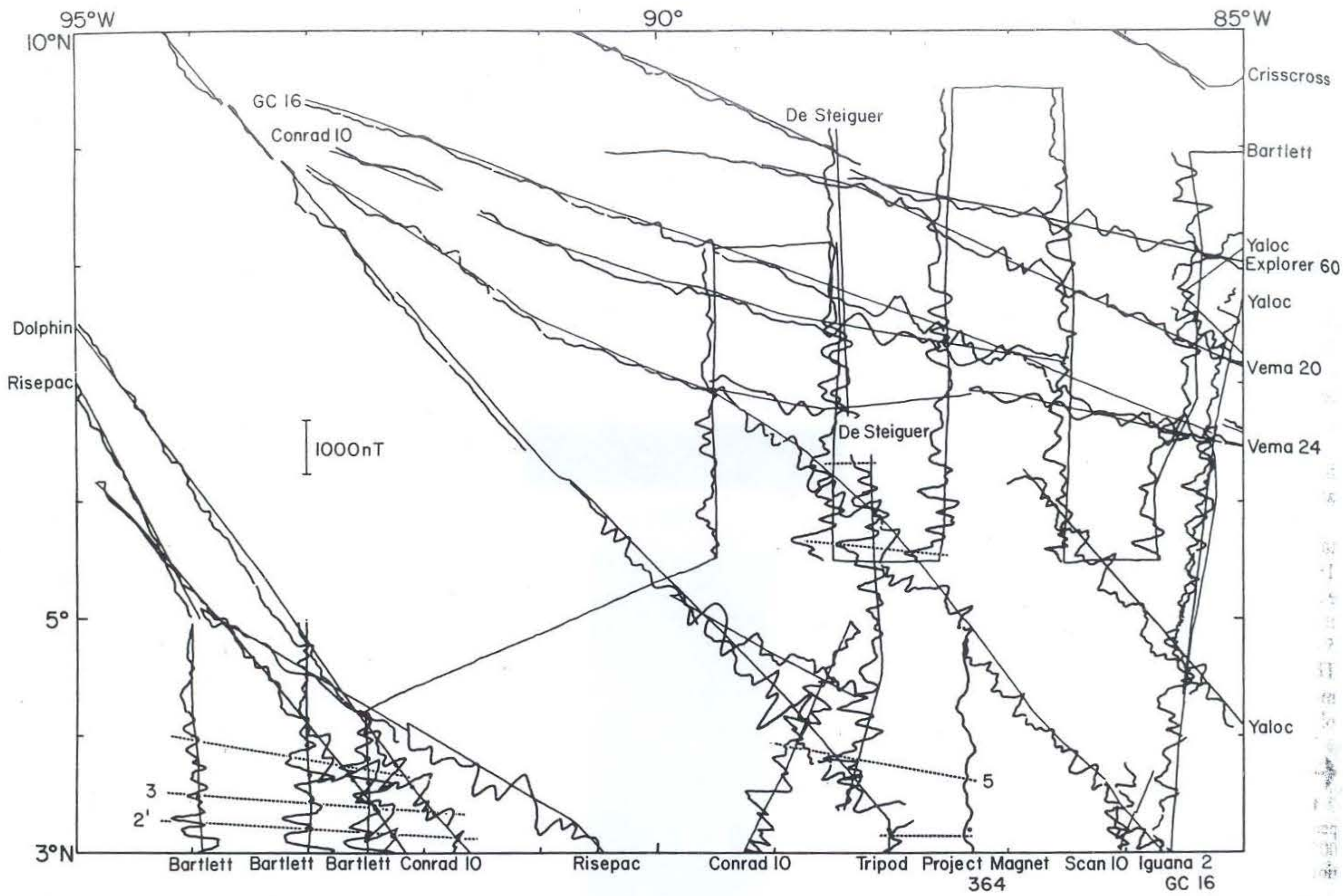

Figure 5. Magnetic anomalies in north-central part of area. ***De Steiguer*** and ***Bartlett*** profiles projected onto 000°. All others plotted perpendicular to track. Note rough-smooth boundary.

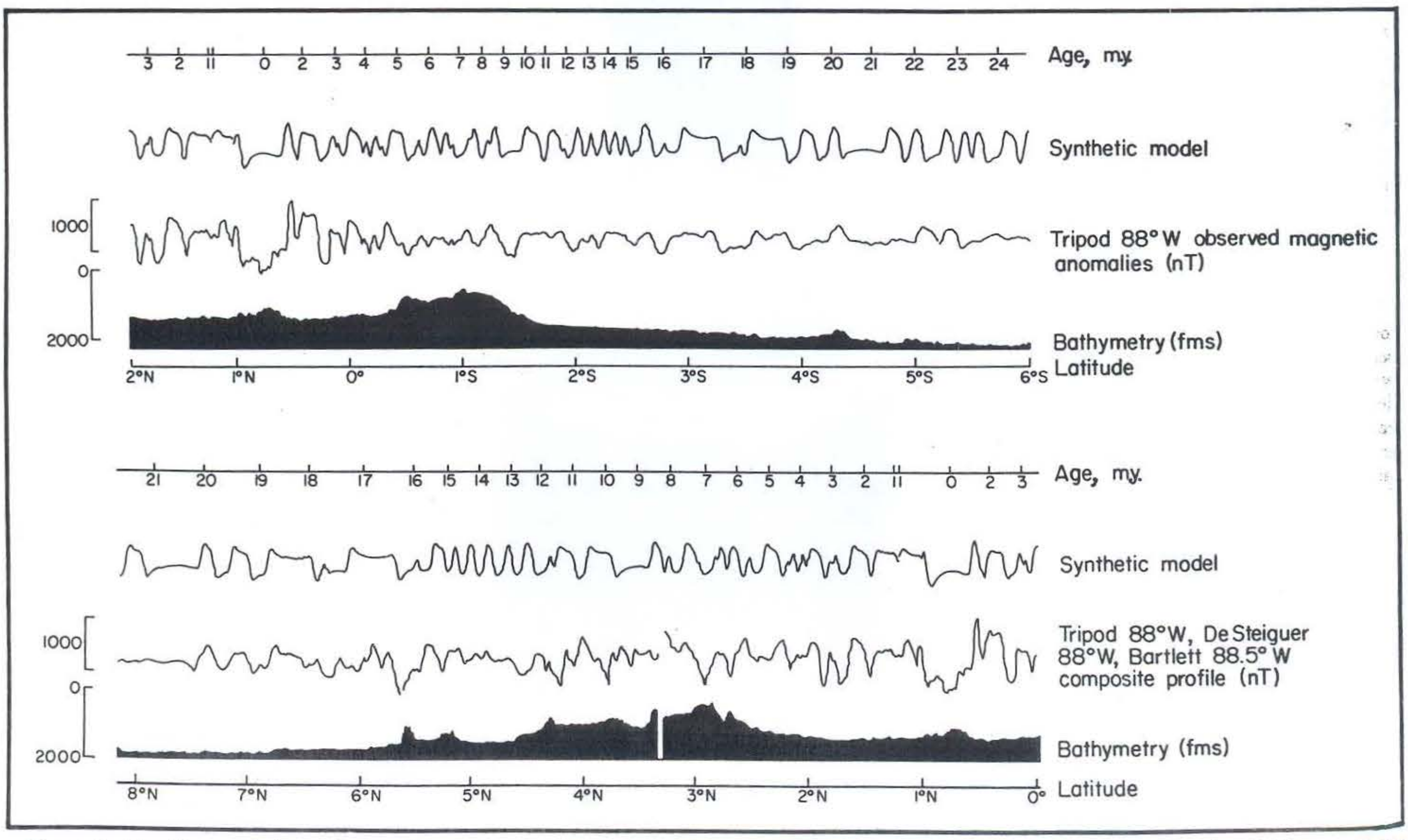

Figure 6. Possible correlations of anomalies across Cocos-Nazca spreading center. Age sequence 7 to 17 m.y. on Nazca plate as implied by correlation on Cocos plate.

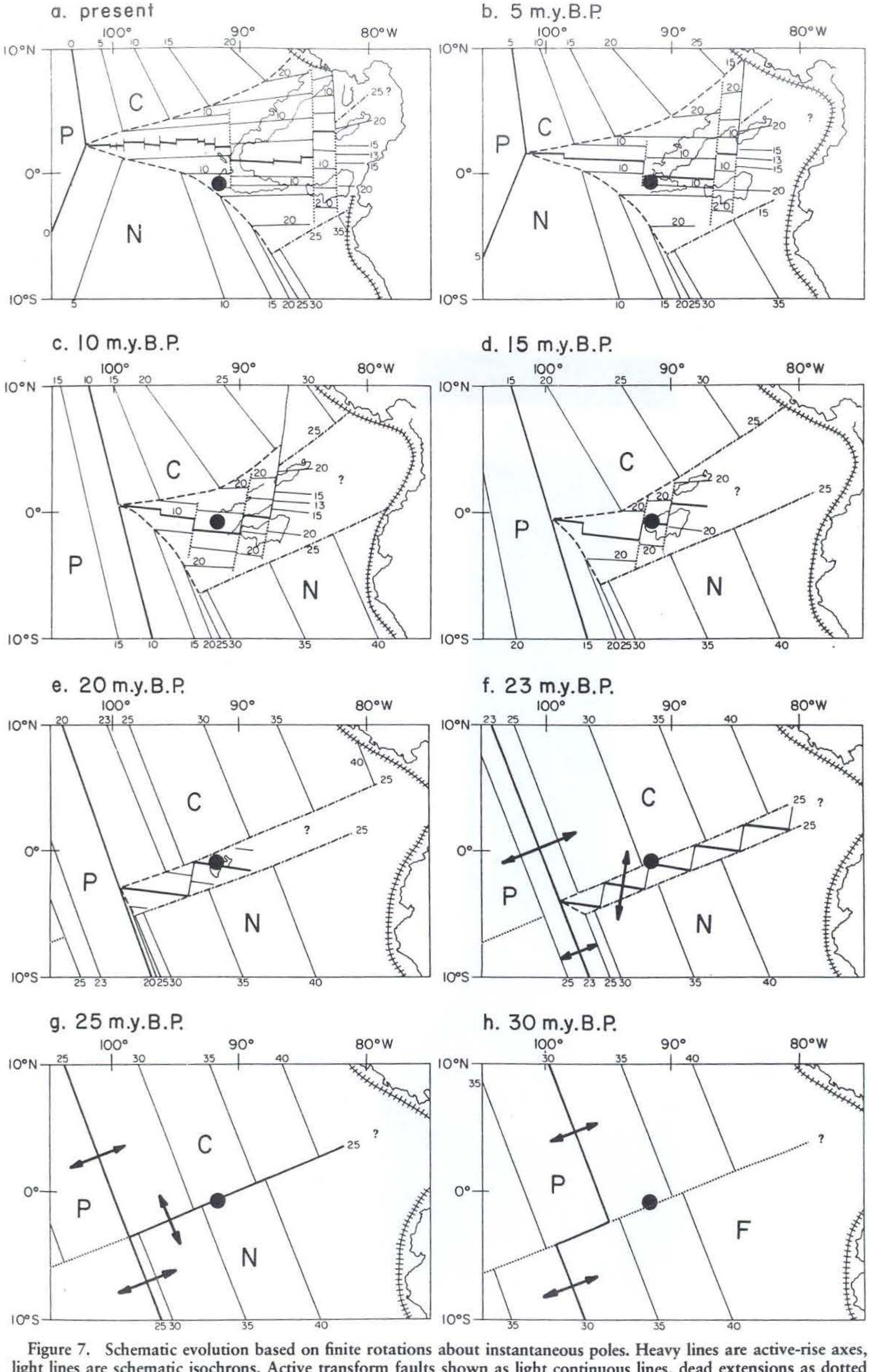

Figure 7. Schematic evolution based on finite rotations about instantaneous poles. Heavy lines are active-rise axes, light lines are schematic isochrons. Active transform faults shown as light continuous lines, dead extensions as dotted lines. Dash-dot line denotes rough-smooth boundary marking original Cocos-Nazca rifting. Dashed lines mark rough-smooth boundaries formed at triple junction. Hachured line represents Mid-America–Peru-Chile trench system. Aseismic ridges delineated by 2,000-m isobath from van Andel and others (1971). Central and South America were arbitrarily separated at Golfo de San Miguel in eastern Panama. Solid circle represents Galapagos hotspot. Arrows in f, g, and h show changes in relative plate motions. Stage illustrated in f exaggerated to show development more clearly.

Several kinds of evidence indicate that the present north-south spreading pattern of the Cocos-Nazca rise has persisted for a long time. Hey and others (1977) have presented extensive evidence that this pattern has certainly held for the past 3 m.y. and probably for at least the past 9 m.y. The anomalies south of the Carnegie Ridge (Fig. 3) have been correlated with each other in an east-west direction (Herron and Heirtzler, 1967; Raff, 1968; Herron, 1972); I have made a tentative correlation of these anomalies with the reversal time scale. The east-west trend supports the contention that the rise axis has been oriented east-west for more than 9 m.y.; if my correlations are correct, this basic geometric configuration has held for about 23 m.y. Also, the transform faults and fracture zones are oriented north-south (Fig. 1 here; van Andel and others, 1971, Fig. 2). (I am trying not to use hotspot inferences in this section, but note that if the Carnegie and Cocos Ridges are hotspot traces and the total volume output of the hotspot has been roughly constant, the saddle in the Carnegie Ridge near long 86°W [Fig. 7, a] may correlate with the bulge in the Cocos Ridge directly to the north, indicating perhaps that during the time interval of formation of these features [which we expect to be the same age] the hotspot was primarily under the Cocos rather than the Nazca plate. Accepting this correlation, the Cocos-Nazca relative motion has been approximately north-south at least since the time of formation of these features. This is a simplistic argument that ignores the effect of asymmetric accretion; I will show below that asymmetric accretion is mandatory if the hotspot interpretation is to be viable here.)

All of the evidence mentioned above suggests that the Cocos-Nazca spreading center has been oriented nearly east-west and spreading approximately north-south for quite a while, possibly 23 m.y.

Rough-Smooth Boundaries

Further evidence about the geometrical evolution of the area, particularly the early evolution, comes from the rough-smooth boundaries, which bound the gore to the west, north, and south (Fig. 1). Near the triple junction, these boundaries are formed by the isochron flexures marking the change in anomaly trend from east-west to north-south, paralleling the rise axes. The azimuths of these rough-smooth boundaries are compatible with those predicted by our triple-junction analysis (Fig. 2). The vectors **P-J**, **C-J**, and **N-J** (Fig. 2) show the instantaneous motions of the Pacific, Cocos, and Nazca plates relative to the junction and thus indicate the boundaries of crust spread from the Pacific-Cocos, Pacific-Nazca, and Cocos-Nazca rises for as far back in time as the instantaneous motions are good. (This boundary on the Pacific plate should also be marked by a change in trend both of magnetic anomalies and bathymetry, but this change should be smaller and harder to detect than the boundaries on the Cocos and Nazca plates.) Each point on the rough-smooth boundary in this area was formed at the triple junction.

East of the Galapagos Islands, the southern rough-smooth boundary is oriented northeast-southwest (Figs. 3, 4), while the orientation of the northern rough-smooth boundary becomes more northerly (Fig. 5). The southeastern magnetic rough-smooth boundary is coincident with the Grijalva scarp (Fig. 4). Note that only if the anomalies from two spreading systems abut the rough-smooth boundary could that part of the boundary have been formed at a triple junction. Because the magnetic anomalies on the Nazca plate east of long 87.5°W are oriented parallel to the southeastern rough-smooth boundary (Fig. 4), this part of the boundary was not formed at a triple junction, but rather at a "double junction," the Cocos-Nazca spreading center. The southeastern rough-smooth boundary is thus an isochron that marks the time of origin of the Cocos-Nazca spreading center and the rifting apart of the Farallon plate to form the Cocos and Nazca plates. If my correlations are correct, and if there was no drastic change in spreading rate before about 22 m.y. B.P., the Cocos-Nazca spreading center was born about 25 m.y. B.P. This coincides with a time of renewed tectoni[c] activity in Mexico and Central and South America, as well a[s] elsewhere around the Pacific margin and the world. This activit[y] was summarized by Dott (1969, p. 875), who concluded tha[t] "circum-Pacific land history would predict discovery of evidence o[f] a discontinuity of spreading about 25 to 30 million years ago."

If the azimuth of the Nazca plate motion has remained approximately constant for the past 25 m.y., which is supported by th[e] constant trend of the Sala y Gomez Ridge, the azimuth of the newborn rise axis must have been slightly greater than the present 060 trend of the rough-smooth boundary on the Nazca plate. Thi[s] azimuth is within the range of possible Pacific-Farallon fracture zone azimuths. Thus, it is possible that the Cocos-Nazca spreading center was born when an old Pacific-Farallon fracture zone opene[d] about 25 m.y. B.P. in response to a new stress pattern in the area. The present position and azimuth of the Marquesas fracture zon[e] on the Pacific plate (Mammerickx and others, 1974) make it th[e] most likely candidate of the great Pacific fracture zones. (Others ar[e] certainly possible. Mammerickx and others, [1975], correlated th[e] Sarmiento scarp [shown in Fig. 1 of Hey and others, 1977] with th[e] Marquesas fracture zone, and the Grijalva scarp with an unnamed fracture zone north of the Marquesas fracture zone. If their correlation proves valid, then, under my hypothesis, the Farallon plate must have broken apart along this smaller feature rather than along one of the great fracture zones. Handschumacher [1976] has suggested that the Grijalva scarp may correlate with the Galapagos fracture zone on the Pacific plate.) Possible causes of the new stress pattern include the birth of the Galapagos hotspot, the intersection of a line of weakness with the hotspot, or perhaps the intersection of one of the aseismic ridges with the trench system, disrupting the subduction process. It is intriguing to note that as a result of the Farallon plate break-up, subduction became approximately perpendicular to both the Mid-America and Peru-Chile Trenches, whereas before the breakup at least one of these trenches must have had a large strike-slip component. Of all the great fracture zones that could have opened (and because fracture zones separate areas sinking at different rates they are lines of concentrated strain), the Marquesas was (I think) most favorably situated to allow this change.

There appear to be two lineated bathymetric highs parallel to the Grijalva scarp and south of it (Fig. 4). These topographic peaks produce small magnetic anomalies that are apparent only because of the extreme smoothness of the surrounding field. These trends project into similar features farther west on the *Vema* 17 and *Conrad* 11 profiles (Figs. 3, 4). In my interpretation, the Grijalva scarp resulted from early rifting along a northeast-trending Pacific-Farallon fracture zone to form the Cocos-Nazca spreading center. Thus, with Mammerickx and others (1975), I speculate that the features south of the scarp also mark old Pacific-Farallon fracture-zone traces.

The reorganization of the early system into the present east-trending Cocos-Nazca spreading system could be responsible for the dextral rise offset pattern east of the Galapagos Islands, as this sort of pattern is expected from the proposed reorientation. A continuous reorientation from the northeast trend to offset east-west segments should have produced a Zed pattern. I see no evidence for this, although the confused nature of the anomalies makes it a possibility. If there is no Zed pattern, the rise reorientation must have followed a hiatus in spreading on the old northeast-southwest system, followed by a new east-west rise–transform system breaking through the old pattern — a discontinuous evolution as opposed to a continuous one. The available data do not permit this distinction. The remarkably linear character of the southeastern rough-smooth boundary (considering that much of the data is pre-satellite navigation) suggests that the reorientation did not include breaks outside this boundary.

Note that in my interpretation the eastern segment of the rough-smooth boundary was formed by an entirely different process than part to the west. The central section, between long 88° and W where the boundary suddenly enlarges, could have been n several ways, as described in Hey (1975). The geometry the southeastern rough-smooth boundary has one other interesting implication. If the Nazca plate motion has been approximately due east, the southerly position of the rough-smooth boundary implies that the original position of the triple junction was several degrees south of its present location, as was discussed in the triple junction section above.

Early Evolution

Thus, the available evidence suggests that the Farallon plate broke apart along a pre-existing fracture zone, possibly the Marquesas (Fig. 7, h) at about 25 m.y. B.P. (Fig. 7, g), that this early northeast-trending system was soon reorganized into an approximately north-south–opening configuration (Fig. 7, f), and that the Pacific-Cocos-Nazca triple junction has since migrated north. Figure 7 shows how these simple geometric constraints combine to produce the old east-trending anomalies south of the Carnegie Ridge, the origin of which has been considered an enigma (see, for example, Herron, 1972). This highly schematic evolution is based on finite rotations about the instantaneous rotation poles of model PAM1 of Hey and others (1977) and is drawn with the most simplifying assumptions I could make: the unaesthetic patterns that resulted in particular areas and times probably indicate errors in these assumptions. The trend of the oldest isochrons (Fig. 4) implies that before the geometrical reorganization of the Cocos-Nazca system, either the Nazca plate motion was faster or the Cocos plate motion was slower than at present. For this reconstruction, I have assumed that the Nazca motion was faster; thus the early triple junction migrates east. I arbitrarily eliminated the Marquesas transform fault with a rise jump at 25 m.y. B.P. There must have been a reorganization of some sort to permit a stable evolution of the triple junction. Learning the details of this transition would be an obvious refinement to this model. Obviously, the Pacific-Cocos and (or) Pacific-Nazca spreading direction must be different from the older Pacific-Farallon direction. Therefore, at least one of those rises must have either spread obliquely or changed azimuth. This reconstruction assumes oblique spreading; it is more probable that one of the rises (Pacific-Nazca) rotated. I have shown this schematic evolution as continuous and without invoking unwarranted highly asymmetric accretion on the Cocos-Nazca rise. Thus, the rough-smooth boundary azimuth on the Nazca plate between long 88° and 93°W indicates a time of very rapid accretion on the Cocos-Nazca rise relative to the Pacific-Nazca rise. This segment of the boundary appears to intersect the southeastern rough-smooth boundary at an angle of about 100°. If this angle were 90°, which is possible, then under my assumptions this would mean no spreading on this segment of the Pacific-Nazca rise. If this angle were 90°, of course, we might instead speculate that this part of the rough-smooth boundary represents an old Cocos-Nazca transform fault, perhaps extending into a rise-fault-fault (RFF) triple junction. I have speculated further about this (Hey, 1975, p. 120–122). Because of the geometric properties of rough-smooth boundaries discussed above, a detailed knowledge of the anomalies abutting the rough-smooth boundary would distinguish between the various explanations and would completely determine the evolution of those segments of the Pacific-Cocos and Pacific-Nazca spreading centers extending into the triple junction. The Pacific-Farallon isochrons and plate boundaries are extremely schematic, although a paleobathymetric study by van Andel (1974) indicates they may be fairly accurate. I could have juggled various azimuths and rates and ked asymmetric accretion and discontinuous jumps of the triple junction and produced a much more pleasing picture, but I think it is more useful at this time to focus attention on remaining problems.

The plate motions over the mantle computed by Hey and others (1977), Morgan (1973), and Minster and others (1974) indicate that the Cocos-Nazca spreading center must be migrating northward and (or) spreading highly asymmetrically. Holden and Dietz (1972) pointed out that the present location of the rise axis in the southern part of the gore implies that it has either spread asymmetrically or jumped back to the south one or more times in the past. Their argument is valid only if the entire gore was produced at the triple junction, as their model assumes. If, however, the eastern parts of the rough-smooth boundaries are isochrons marking the birth of the Cocos-Nazca spreading center (Fig. 4), the geometrical requirement for symmetry east of about long 88°W is different from that west of long 88°W, where their argument is valid. To the east, the average trend of the rise–transform-fault system must bisect the gore for symmetrical accretion to have occurred (assuming that the complete anomaly sequence is enclosed by the original isochrons), but at any given point the rise axis need not, and in general, for finite-length east-west rise segments, cannot bisect the gore. The average trend of the present plate boundary indicates that more material has been added to the Cocos plate than to the Nazca plate; thus, the conclusion of Holden and Dietz (1972) is probably still valid.

A stronger argument supporting this conclusion is the essentially continuous nature of both the Cocos and Carnegie Ridges. If these aseismic ridges are hotspot traces, then the rise axis must have remained near the Galapagos hotspot by some mechanism. As our plate motions indicate that the axis must migrate north relative to the hotspot to spread symmetrically, it must have periodically jumped back to the south or else have spread asymmetrically to stay near the hotspot. (Note that this last point requires some circular reasoning, as I will use the hypothesis of asymmetric accretion to justify the assumption that the Cocos and Carnegie Ridges are hotspot traces.) Evidence from the young magnetic anomalies for recent discrete jumps of the rise axis to the south at long 88°W and 92.5°W has been presented by Hey and others (1977, Figs. 12, 13). We suspect that such jumps have happened during all times in which the plate-boundary geometry has been basically the same as today. Whether these jumps were large or small, were periodic or random in time, and involved long or short rise segments, this is certainly a mechanism that can explain the absence of correlatable older anomalies here. Our bias is that the mechanism responsible for this absence is probably directly related to the presence of the Cocos and Carnegie aseismic ridges in this area.

HOTSPOT MODEL FOR EVOLUTION OF GALAPAGOS AREA

There are currently two basic alternative hypotheses about the origin of the Cocos and Carnegie Ridges: the hotspot hypothesis and the ancestral-ridge hypothesis. In the hotspot hypothesis (Wilson, 1963; Morgan, 1971), the Cocos and Carnegie Ridges were formed from outpourings of basalt from the Galapagos hotspot onto the Cocos and Nazca plates, respectively, and thus they mark the azimuths of motion of these plates relative to the hotspot. The ridges must then have been separate entities throughout their existences, whereas in the ancestral-ridge model (van Andel and others, 1971; Malfait and Dinkelman, 1972; Heath and van Andel, 1973; Rea and Malfait, 1974), the present Cocos and Carnegie Ridges were derived from a single ancestral Carnegie Ridge, which began to split from east to west about 25 m.y. B.P.

Hey and others (1977) have presented evidence from recent plate motions that the Cocos and Carnegie aseismic ridges are hotspot traces. Inverting all available relative-motion data from the Pacific, Cocos, Nazca, and Antarctica plates, and assuming that the recently formed parts of the Hawaiian, Austral, Tuamotu, and Juan de Fuca traces (all of which are very nearly along small circles about the same axis) define Pacific plate motion relative to fixed hotspots, we computed the motions of the other plates over fixed hotspots. This analysis predicts that if the Galapagos were a hotspot fixed relative to the Pacific hotspots, there should be aseismic ridges trending away from it with azimuths nearly exactly those of the Cocos and Carnegie aseismic ridges. This is discussed in detail in Hey and others (1977); we consider it a powerful argument that at least the recently formed parts, and thus probably all, of these aseismic ridges are hotspot traces.

To test this model, we assigned ages at 1-m.y. intervals to segments of the Cocos and Carnegie Ridges by (outrageously) extrapolating the instantaneous motions for the Cocos and Nazca plates predicted by model PAM1 back for 25 m.y. Finite rotations about these poles (in a negative time sense) should move segments of the Cocos and Carnegie Ridges as well as isochrons on the Cocos and Nazca plates back to approximate (because they are finite rotations about instantaneous poles) annihilation at the time and place they were formed. The results of finite rotations about the instantaneous poles at the instantaneous rates for the past 6 m.y. are presented in Figure 8. The Cocos Ridge and Carnegie Ridge segments are moved backward to "originate" near the Galapagos Islands. The young isochrons are brought together by these rotations, to reunite at the position of the Cocos-Nazca spreading center at the time they were formed. This indicates that our model is approximately correct, at least in the recent past. Small misfits occur between 2 and 6 m.y. B.P.; rise-axis jumps or asymmetric spreading have been identified (Hey and others, 1977; Hey and Vogt, 1977) in all areas of misfit of the proper sense and magnitude to resolve the misfit. Thus, I will continue to develop a model of evolution based on the hotspot hypothesis, with the modification of asymmetric accretion discussed by Hey and others (1977).

Figure 7, part e shows aseismic ridges forming on the Cocos and Nazca plates at the Galapagos hotspot. Whether the Galapag hotspot initiation predated, was contemporaneous with, or pos dated the Farallon break-up is unknown — it is included in parts g, and h of Figure 7 as a convenient reference point. The fir aseismic ridge segment shown forming on the Cocos plate is tl Malpelo Ridge (we ignore the Coiba Ridge for now), and it ove laps with the Carnegie Ridge.

Cocos and Carnegie Ridge Morphology

There is overlap of the Cocos and Carnegie Ridges between 2 and 15 m.y. B.P. in this reconstruction, perhaps indicating that th present motions cannot be extrapolated so far into the past or th eventual intersection with the trenches has altered the origin shapes of the ridges. At about 15 m.y. B.P. (Fig. 7, d) the Coco Nazca spreading center may have jumped south of the hotspo leading to the saddle in the Carnegie Ridge and the bulge in th Cocos Ridge. Alternatively, these features could have been pro duced by the northeastward migration of the rise-transform "stai case" over the hotspot. By about 10 m.y. B.P. (Fig. 7, c) the north ward migration of the central segment of the axis had brought nearly to the hotspot, and the Carnegie Ridge was just starting t form again. Note the corresponding decrease in Cocos Ridge vo ume starting at about this time. Note also the east-trendin anomalies south of the Carnegie Ridge. In Figure 7, part b, the fo sil Pacific-Nazca rise (also called the Galapagos rise and Foss ridge) has jumped west (Herron, 1972; Anderson and Sclate 1972), and the fossil Pacific-Cocos rise system (also called man other things, mostly variations on Clipperton-Mathematicia

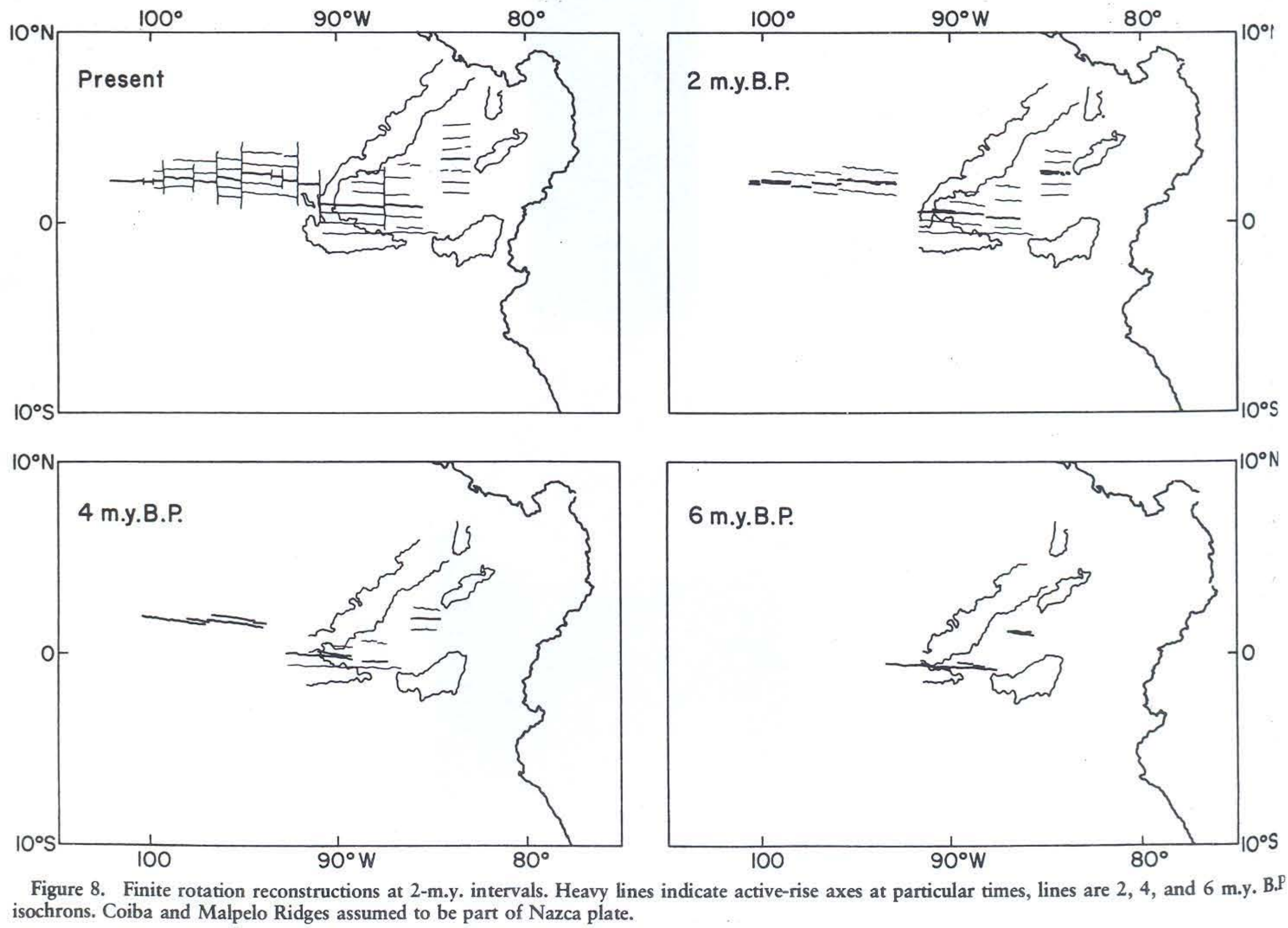

Figure 8. Finite rotation reconstructions at 2-m.y. intervals. Heavy lines indicate active-rise axes at particular times, lines are 2, 4, and 6 m.y. B.P isochrons. Coiba and Malpelo Ridges assumed to be part of Nazca plate.

ridge) has also been reorganized (Sclater and others, 1971; Herron, 1972; Anderson and Davis, 1973). This reorganization is highly problematic, primarily because the anomalies produced on the north-trending Pacific-Cocos and Pacific-Nazca rises are quite small. If my analysis and assumptions are valid, Figure 7 implies that the segment of fossil Pacific-Nazca rise extending into the triple junction jumped west between 10 and 5 m.y. B.P. The triple junction thus also jumped west at this time. By about 5 m.y. B.P. the entire rise-transform "staircase" had migrated north of the hotspot. Thus, for the first time the hotspot was entirely under the Nazca plate (although some material may have been leaking onto the Cocos plate along the Galapagos Island transform fault, creating the "broad low zone 2000 to 2600 m deep studded with pinnacles and small seamounts and, near the Galapagos pedestal, a few larger volcanoes" described by van Andel and others, 1971, p. 1491).

Galapagos Islands

This might account for the youth of the Galapagos Islands —perhaps only when the hotspot is feeding material exclusively to one plate are large volcanic edifices built above sea level. Cox and Dalrymple (1966) concluded, on the basis of K-Ar dating, that the present islands are all Pliocene and younger; they also saw a general age increase away from the western islands, consistent with the hotspot hypothesis. Thus, following a suggestion by Ken Deffeyes, I speculate that biological evolution, rather than proceeding slowly on a "succession of Galapagos islands" (Holden and Dietz, 1972), may have proceeded quite rapidly in the past 3 to 5 m.y. in the essentially closed system of the present islands to produce the "peculiar organic beings" remarked upon by Darwin (1839). The present tectonic configuration is shown in Figure 7, part a; note the recent a[illegible]mp to the south at long 92.5°W.

Malpelo Ridge

The Malpelo Ridge was possibly once part of a hotspot trace in the northeastward-moving Cocos plate (note its parallelism with the Cocos Ridge), which was recently transferred to the Nazca plate by a westward shift of the eastern Cocos-Nazca plate boundary (Johnson and Lowrie, 1972). A possible cause for such a shift is a collision of the Malpelo Ridge with a trench (for which there is no evidence), as several other aseismic ridge–trench intersections may be interpreted as implying interference with the subduction process (Menard, 1966; van Andel and others, 1971; Vogt, 1973; Vogt and others, 1976). The abrupt changes in morphologic and seismic expression of the Mid-America and Peru-Chile Trenches where they are intersected by the Cocos and Carnegie Ridges, respectively (van Andel and others, 1971; Vogt and others, 1976), support this hypothesis. Between these aseismic ridges, although there is evidence for an ancient trench system, the present system shallows and seismicity decreases. Van Andel and others (1971), who proposed this mechanism to explain the origin of the Coiba Ridge, suggested, on the basis of earthquake epicenters outside the offset Cocos-Nazca spreading center segments, that the Cocos-Nazca boundary may be about to shift to the long 85°W fracture zone, as the Cocos Ridge has again reached the trench. Although we see no recent decrease in spreading rate on the Costa Rica rift segment, we concur in this surmise. Note that this is a model of a discontinuous evolution of a triple junction, as opposed to the continuous-evolution schemes discussed by McKenzie and Morgan (1969). Note also that while this mechanism may explain either the Malpelo Ridge or the Coiba Ridge, it cannot explain both without a major modification, such as an east-west fault between the ridges. The bathymetry suggests that such a fault may exist (see Fig. 2 of van Andel and others, 1971); Jordan (1975) found this trend compatible with his computed Caribbean-Nazca motion azimuth. This hypothetical fault may thus represent an active or inactive plate boundary.

Figure 7, part d shows the geometry just before the postulated transferral of the Malpelo Ridge to the Nazca plate. (At this time the Cocos-Malpelo ridge is still far from any known trench. Another possible explanation for the transferral is that the rise axis between the Malpelo and Carnegie Ridges migrated too far from the hotspot, and it became advantageous in terms of minimum energy considerations to break somewhere else. We see possibly the same phenomenon manifested in the recent discrete jumps of the rise axis toward the hotspot.) Subsequent continued motion of the Cocos plate, containing the Cocos Ridge, northeastward and the Nazca plate, now containing the Malpelo Ridge, eastward would eventually lead to the observed right-lateral offset of the two aseismic ridge segments. I have used an age of 13 m.y. B.P. for this transferral (computed from the observed offset by extrapolating the present spreading rate back) in this reconstruction. Thus in Figure 7, part d, the Malpelo Ridge is part of the Cocos plate, separated from the Carnegie Ridge by an actively spreading rise. Just west of the Malpelo Ridge is the proto-Panama fracture zone. In Figure 7, part c, the Panama fracture zone has become the easternmost Cocos-Nazca plate boundary, leaving an extinct (13 m.y. B.P.) axis and the Malpelo Ridge on the Nazca plate.

This hypothesis predicts that ages along the Cocos and Malpelo Ridges increase from southwest to northeast, with the southwestern tip of the Malpelo Ridge (where truncated by the Panama fracture zone) just older than the northeastern tip of the Cocos Ridge. All variations of this model of Malpelo Ridge formation predict the existence of an extinct-rise axis between the Malpelo and Carnegie Ridges. Lliboutry (1974) has concluded that the Galapagos hotspot formed the Cocos and Malpelo Ridges on the Cocos and Nazca plates and that the Carnegie Ridge may be "an extinct ridge like the Alpha Cordillera" (p. 300). His conclusions are based on the relative rotation poles of Chase (1972), whose Cocos-Nazca and Nazca-Antarctica poles do not fit our data. Tom Jordan (1973, personal commun.) has suggested that Chase's model vector may represent a "local minimum" and thus be invalid.

Coiba Ridge

I investigated the role of the Coiba Ridge in this evolution by computing finite rotation reconstructions variously assuming it to be a part of the Cocos plate, Nazca plate, "Malpelo plate" (assumed to have rotated about the Cocos pole before 13 m.y. B.P. and then about the Nazca pole to the present), South American plate, and North American plate. One obvious refinement would be to use the Caribbean motion rather than North American motion for Central America. Unless the Caribbean is moving east at several centimetres per year, which is doubtful (Jordan, 1975), my conclusions would remain unchanged. For the Cocos and Nazca rotations I used the poles from our model PAM1 (Hey and others, 1977); for the North and South American rotations, I used the poles of Minster and others (1974). None of the models indicate a reason for the hypothesized Cocos-Malpelo ridge split. They do indicate that if the Coiba Ridge is oceanic, then it has not been exclusively a part of either the Cocos or Nazca plates if my Malpelo Ridge interpretation is correct. The lack of a rough-smooth boundary between the Coiba and Malpelo Ridges implies that the Coiba Ridge is oceanic.

Finite Rotation Complications

Note that the triple junction moves much faster in these reconstructions than predicted by our instantaneous triple-junction analysis (Fig. 2), which demonstrates a problem inherent in finite rotations about instantaneous poles. This discussion follows from a suggestion of Jason Morgan and extends the results of Le Pichon (1968), McKenzie and Morgan (1969), and Le Pichon and others (1973).

We have assumed for these reconstructions that the Cocos and Nazca plates have rotated relative to a fixed reference frame, the mantle, about the instantaneous Cocos-Mantle and Nazca-Mantle rotation poles of model PAM1. (Although these particular poles were computed with the assumption that hotspot traces indicate plate motions relative to the mantle, the generalization made here does not depend on that assumption.) The Cocos-Nazca pole must then be fixed relative to the mantle (or other hypothetical fixed reference frame) in order that the closure equation remain satisfied. Thus the Cocos-Nazca pole must move relative to the Cocos and Nazca plates and so cannot be valid to describe Cocos-Nazca relative motion, except instantaneously, at present. Therefore, the apparent azimuth of Cocos-Nazca relative motion must change with time, unless the motion of the pole relative to the plate boundary is exactly along a great circle perpendicular to the transform faults, in which case the radii of curvature of the transform faults must change.

Thus, it is impossible, for the purpose of finite rotations, to fix both the azimuths and radii of curvature of transform faults and the relative-rotation pole describing motion on that plate boundary to a frame of reference in which the motions of the two plates meeting at that boundary are constant. This effect causes the apparent anticlockwise rotation of the Cocos-Nazca plate boundary shown in Figure 7. Because the same argument applies to the Cocos-Pacific and Pacific-Nazca poles as well, the triple-junction configuration may have changed considerably with time. Therefore, the reconstructions described here, which are based on finite rotations, are offered only as an approximation to reality.

Objections to Hotspot Hypothesis

Sclater and Klitgord (1973) briefly examined the hotspot hypothesis and concluded that "the geometry of the [Cocos and Carnegie] ridges and the offset between the currently active Galapagos and Costa Rica spreading centers make this hypothesis untenable" (p. 6962). They rejected the ancestral-ridge hypothesis on the basis of their magnetic anomaly interpretations. If the Cocos and Carnegie Ridges were once joined and have since been rifted apart, the offset sections must be the same age. Because they identified anomalies 4, 4′, and possibly 5 on the *Glomar Challenger* Leg 16 profile (Fig. 9) just south of the Cocos Ridge due north of where they identified anomaly 2′ near the Carnegie Ridge, they concluded that this hypothesis must be wrong (unless the Carnegie Ridge is a fossil trench, which they, and we, think unlikely). The same objection holds for the hotspot hypothesis if, as we have shown, the Cocos-Nazca relative motion in the recent past was north-south.

A restatement of this argument provides some illumination: the geometry of the Cocos and Carnegie Ridges demands that east-west isochrons intersect the ridges at different longitudes if the isochron spacing is equal north and south of the rise axis; thus, if accretion has been symmetric, the Cocos and Carnegie Ridges at a given longitude cannot lie on crust of the same age. This geometric requirement led Sclater and Klitgord to conclude that the Cocos and Carnegie Ridges are not tectonically related and thus to reject both the ancestral-ridge and hotspot hypotheses. Our restatement of the problem, however, suggests an alternative interpretation.

Resolution of Objections

Although the point raised by Sclater and Klitgord (1973) is entirely valid — that is, for either model to hold, the Cocos and Carnegie Ridges must lie on crust of the same age — the data they present do not preclude this possibility. Hey and others (1977) constructed a model with highly asymmetric accretion during intervals in the past several million years. In that model, jumps of the rise axis to the south have resulted in more material being added to the Cocos plate than to the Nazca plate. This model overcomes the objection of Sclater and Klitgord by discarding their tacit assumption that material must have been added symmetrically to the two plates.

Although Hey and others (1977) have shown that asymmetric accretion has occurred in the past few million years and that occasional discrete jumps of the rise axis have occurred, it is impossible to demonstrate convincingly at this time that on a profile such as *Glomar Challenger* Leg 16, the Cocos and Carnegie Ridges abut anomalies of the same age. The observed data certainly do not preclude this possibility, despite the highly asymmetric location of the rise axis relative to the two aseismic ridges. Note that at long 88°W the single young rise jump so far identified resolves to a great extent, if not entirely, the same apparent geometrical argument against the hotspot hypothesis used by Sclater and Klitgord (1973) at long 86°W. The crust abutting the Cocos and Carnegie Ridges at long 88°W is about the same age on the Cocos and Nazca plates (5 to 6 m.y.), although the rise axis is quite asymmetrically located between the aseismic ridges (Fig. 6). No anomaly older than the Jaramillo event may be identified with any confidence south of the rise axis on the *Glomar Challenger* Leg 16 profile, a probable consequence of an evolution marked by occasional jumps of the rise axis. Our hypothesis, that the asymmetric location of the spreading axis within the rough-smooth boundary requires that asymmetric accretion has occurred, is attractive in that it removes the sole geometric objection of Sclater and Klitgord to both the ancestral-ridge and hotspot hypotheses.

Thus, even if the correlation of Sclater and Klitgord (1973) is valid, it does not invalidate my model. In addition, I question the validity of their correlation. Figure 9, part B shows six profiles that I think illustrate the 2 to 6 m.y. B.P. sequence of anomalies. One of these profiles is the *Glomar Challenger* Leg 16 profile, which Sclater and Klitgord correlated differently. Their correlation and mine are shown for comparison (Fig. 9, A). I think my correlation is at least as good. As their correlation is the basis for Sclater and Klitgord rejecting the hotspot hypothesis, and I demonstrate that there is reasonable doubt that their correlation is correct, I think that the hotspot hypothesis should not be rejected on this basis and that their conclusion that the Cocos and Carnegie Ridges are tectonically unrelated is at least premature and probably wrong. The proposal of Anderson and others (1975) that the Galapagos "melting anomaly originated 3 to 4 m.y. B.P. and generated the Galapagos Islands and the Carnegie Ridge, at least from longitude 85°W to the Galapagos Islands where anomaly 2′ consistently abuts the Carnegie Ridge" (p. 692) is based on the Sclater-Klitgord correlation; Anderson and others (1976) now instead support my correlation. Even if the Sclater-Klitgord correlation is correct, it does not invalidate my model but merely demands a much higher degree of asymmetric accretion.

Thus, both the hotspot and ancestral-ridge models are viable if our asymmetric evolutionary scheme is correct. Is there any reason to discard one of these models?

ANCESTRAL-RIDGE MODEL FOR EVOLUTION OF GALAPAGOS AREA

The ancestral-ridge hypothesis (van Andel and others, 1971; Malfait and Dinkelman, 1972; Heath and van Andel, 1973; Rea and Malfait, 1974), posits that the Cocos and Carnegie Ridges were originally joined and later rifted apart, with rifting beginning in the east and gradually moving west. In most versions of this hypothesis, an ancestral Carnegie Ridge collided with South America approximately 25 m.y. B.P. "Presumably as a result of the collision, the ancestral Carnegie Ridge began to split from east to west, and the fragments split off drifted north to form the Cocos and more easterly ridges of the northern Panama Basin" (Heath and van Andel, 1973, p. 901). This model leads to severe geometrical difficulties. Consider the geometry immediately after the first segment of the Cocos Ridge was rifted apart from the ancestral Carnegie Ridge (see, for example, Fig. 7 of Heath and van Andel, 1973). There are only three ways in which this initial segment of the Cocos-Nazca spreading center could have been bounded to the west: (1) by the rotation pole describing Cocos-Nazca opening, (2) by a triple junction (or higher order junction; Hey, in prep.), or (3) by a transform fault (possibly with a component of opening or closing) extending into a triple (or higher order) junction. There are no other ways for a spreading center to end. None of the figures in the papers of van Andel and others, Malfait and Dinkelman, or Heath and van Andel show such a triple junction or bounding transform fault; thus, we infer, as did Holden and Dietz (1972), that in their models this initial rise segment was bounded by the Cocos-Nazca rotation pole. Therefore, the pole of rotation describing opening on the newly developing rift zone must have propagated to the west as the rise axis propagated westward. The Cocos and Carnegie Ridges are essentially joined today at the Galapagos Islands, which would imply that the Cocos-Nazca rotation pole is located just west of the islands today. This would imply, in the rigid-plate hypothesis, that the Cocos-Nazca motion between the islands and the triple junction would be a closing motion — that is, a spreading center would not exist; the rise crest west of the islands would necessarily be a compressional feature. The presence of young magnetic anomalies between the islands and the junction (Herron and Heirtzler, 1967; Hey and others, 1972) invalidates this hypothesis. Also, as Sclater and Klitgord (1973) pointed out, this model would demand that the Cocos-Nazca spreading rate increase dramatically to the east, while in fact the actual small increase in spreading rate is only compatible with a pole much farther west. Thus, this relatively simple hypothesis is untenable.

Sclater and Klitgord (1973) discussed a more complicated variation of this hypothesis, in which the pole of rotation is located not at the Galapagos Islands but farther to the west. This version, and all other versions of the ancestral-ridge hypothesis, encounter the difficulty described below.

Objections to Ancestral-Ridge Hypothesis

In the ancestral-ridge hypothesis, the age of initiation of the rifting episode that split each segment of the ancestral ridge is given by the isochron at the base of that segment of the aseismic ridge, in the same way that the isochron at the continental margins of South America and Africa gives the age of initiation of rifting of the South Atlantic. Van Andel and others (1971) thus postulated that rifting just east of the Galapagos Islands started at about 2 m.y. B.P., because the foot of the Cocos Ridge lies "somewhat north of anomaly 3 in its central portion, and north of anomaly 2 near the Galapagos" (van Andel and others, 1971, p. 1503). Hey and others (1977) have identified anomalies west of the islands older than those found at the bases of the aseismic ridges; thus, a spreading rise must have existed west of the islands before the segment existed which, in the ancestral-ridge hypothesis, rifted apart the segments of the aseismic ridges just east of the islands. This argument, furthermore, does not depend on our anomaly correlations. The Cocos-Nazca pole of rotation is located west of the triple junction (Herron, 1972; Morgan, 1973; Minster and others, 1974; Hey and others, 1977); opening rates to the west of the Galapagos Islands are lower than those to the east of the islands. The age of initiation of spreading in the ancestral-ridge hypothesis east of the islands is given by the isochron at the base of the aseismic ridges. The age of initiation of spreading west of the islands is given by the isochron abutting the rough-smooth boundary that bounds crust spread

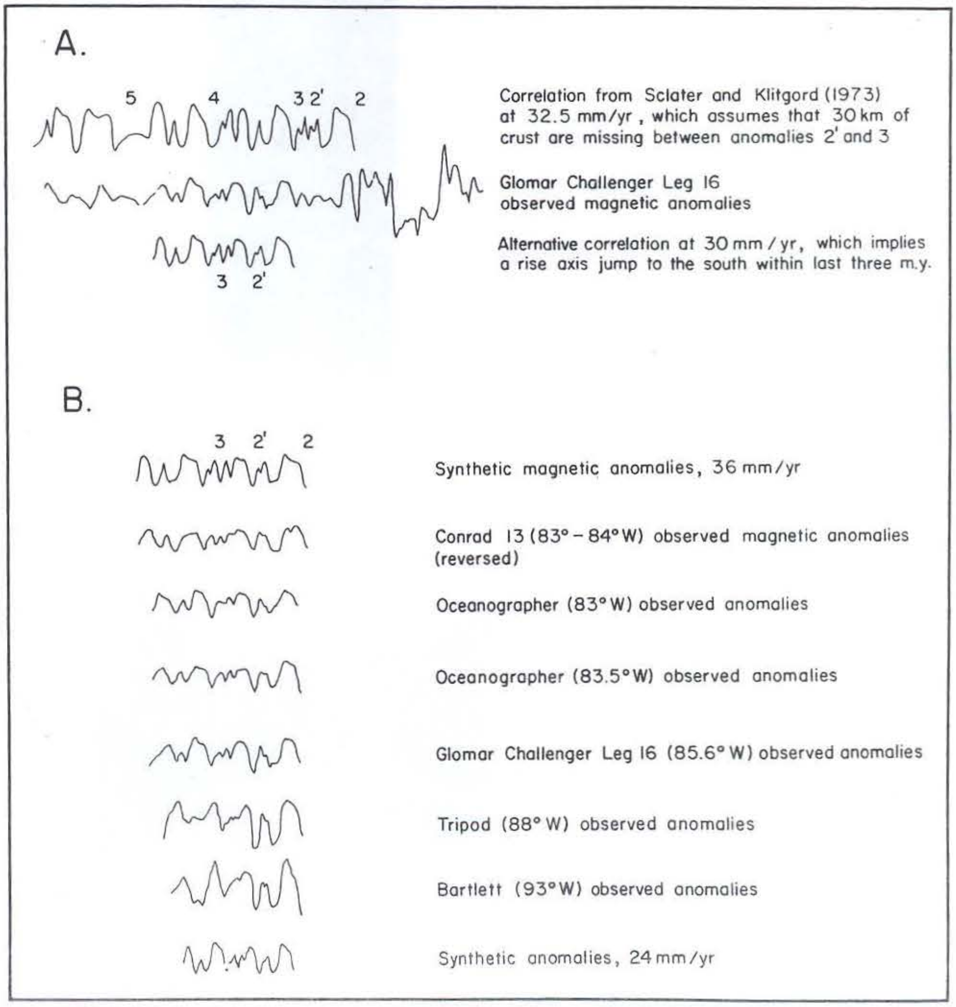

Figure 9. A. Alternative correlations of *Glomar Challenger* Leg 16 magnetic anomalies. B. Profiles across Cocos-Nazca rise, showing characteristic sequence of 2 to 6 m.y. B.P. anomalies. Profiles arranged from east to west and correlated with reversal time scale of Talwani and others (1971). Note inclusion of *Glomar Challenger* Leg 16 profile in this set.

from the Cocos-Nazca spreading center. The distance between the northern and southern rough-smooth boundaries west of the islands is considerably greater than the distance between the Cocos and Carnegie Ridges just east of the islands (Fig. 1, 7). Therefore, in the ancestral-ridge hypothesis, spreading must have started west of the islands before it started east of the islands. However, the ancestral-ridge hypothesis demands that rifting began first in the east and proceeded to the west, as the distance between the aseismic ridges increases to the east. Thus, an (unstated) implication of all forms of this hypothesis is that there was, at least for a short time, rifting west of the islands and rifting several degrees east of the islands, but negligible or no rifting immediately east of the islands. Implicit in all forms of the ancestral-ridge hypothesis, therefore, is the postulation of at least one additional plate for which there is no evidence other than that it must have existed if the ancestral-ridge hypothesis is to be viable. That this hypothesis drives us to such extremes in an effort to find a configuration that can resolve its geometrical weaknesses while there is a much simpler model available seems almost reason enough to reject the ancestral-ridge hypothesis.

We emphasize that this argument depends only on our explanation of the origin of the rough-smooth boundary, for which we think the evidence is incontrovertible, and on the increase in spreading rate from west to east along the Cocos-Nazca spreading center, for which the evidence is equally incontrovertible.

There are other reasons for discarding the various forms of the ancestral-ridge hypothesis:(1) in many versions of this hypothesis, the relation of the Galápagos Islands to the Cocos and Carnegie Ridges is coincidental, as the islands are Pliocene and younger (Cox and Dalrymple, 1966; Swanson and others, 1974); (2) the versions of van Andel and others (1971), Malfait and Dinkelman (1972), and Heath and van Andel (1973) fail to explain the presence of strong magnetic anomalies trending east-west north of the Cocos Ridge and south of the Carnegie Ridge — in fact, they (implicitly) predict that there should be no such anomalies. Note that these anomalies are predicted by our model (Fig. 7). If these east-west anomalies were formed on east-west segments of the Cocos-Nazca spreading center, and the Nazca plate has behaved rigidly with its motion over the mantle shown by the Carnegie Ridge, then these anomalies must have been formed on rise segments south of the hotspot. The latitude of the old triple junction at the time of the Farallon break-up is approximately defined by the position of the southernmost of these anomalies, at about lat 5.5°S. These "enigmatic" east-west anomalies were produced as the rise-transform system migrated north (Fig. 7). The only version of the ancestral-ridge hypothesis that purports to explain these anomalies is that of Rea and Malfait (1974), who adapted the hypothesis (McKenzie and Sclater, 1971; Kroenke, 1974) of flood-basalt plateau formation during periods of rapid magma generation yet slow spreading to this area. This version, as well as all other versions of the ancestral-ridge hypothesis, implicitly demands the existence of at least one additional plate that no longer exists. In addition, the oldest Cocos-Nazca anomalies south of the Carnegie Ridge parallel the magnetic rough-smooth boundary and Grijalva scarp (Fig. 4), which is sufficient to invalidate the hypothesis of Rea and Malfait. In addition, the bathymetric ridges south of and parallel to the Grijalva scarp (Fig. 4) are incompatible with their model.

Furthermore, fairly strong circumstantial evidence favoring the hotspot hypothesis is that a self-consistent model of plate motions relative to the hotspots exists such that the predicted plate motions are parallel to the aseismic ridges and the relative motion data are satisfied. These poles and rates were used to reconstruct the plates and aseismic ridges in time with finite rotations by assuming the Cocos and Nazca poles to have remained stationary relative to the mantle over the past 6 m.y. (Fig. 8). The isochrons and aseismic ridges are brought to annihilation at the time and position of their formation, supporting our model, as previously discussed. If the ancestral-ridge hypothesis were correct, segments of the Cocos and Carnegie Ridges should come together east of the islands, then move backward together to annihilation along the Carnegie Ridge azimuth, since in that model the motion of a segment of the Cocos Ridge would be defined by the Cocos pole after it was rifted from the ancestral Carnegie Ridge, but by the Nazca pole before rifting. Also, if the ancestral-ridge hypothesis were correct, the parallelism of the Cocos Ridge to the Cocos over-the-mantle motion would be a coincidence. Since our model satisfies all of the available data and predicts that the Cocos motion over the mantle should be parallel to the Cocos Ridge, there is reason to suspect that the Cocos ridge was indeed formed according to the hotspot hypothesis. Note that the sedimentary history of the Cocos and Carnegie Ridges, interpreted by van Andel and others (1971) to indicate that segments of these ridges were initially created in proximity and separated later, is compatible with the hotspot hypothesis (Tj. van Andel, 1975, personal commun.). Thus, we conclude that the hot-spot explanation for the origin of the Cocos and Carnegie Ridges is correct. Where the assumption of this hypothesis is critical to our conclusions, I have tried to clearly state that fact to aid readers with biases different from ours.

PROBLEMS AND SPECULATIONS

Two problems should be noted. One is that our model demands greater than 35% asymmetric accretion, more than a 2:1 accretion ratio, near long 86°W. This is calculated from the location of the rise axis relative to the centers of the aseismic ridges and is thus averaged over the past 15 m.y. or so at this location. This ratio is quite high, although comparable to that found (averaged over a much shorter time) in the FAMOUS area (Needham and Francheteau, 1974), and even one-sided accretion has always been considered theoretically possible (see, for example, Morgan, 1972). Klitgord and Mudie (1974) concluded, on the basis of a detailed deep-tow magnetic survey near long 86°W, that accretion here has been slightly asymmetric during the past 1 m.y. or so, with rates higher on the north flank. They also concluded, however, that for the past 3 m.y. accretion has been essentially symmetric, and that "there definitely were no detectable jumps in the last 3 My" (p. 579). Their conclusion is apparently based on the same correlation of anomalies made by Sclater and Klitgord (1973) and Sclater and others (1974). I have questioned this correlation and an alternative is presented here (Fig. 9). My correlation, discussed in more detail in Hey (1975) and supported by Anderson and others (1976), implies highly asymmetric accretion, presumably produced by one or more jumps of the rise axis, within the past 3 m.y., resulting in about 150 km of new Cocos crust and 50 km of new Nazca crust, roughly 50% asymmetric accretion, during this period. This is, perhaps not coincidentally, roughly the average ratio of asymmetric accretion required over the past 15 m.y. or so in order that the hotspot model be viable. Although the magnetic record here is obviously complex, I think that this coincidence supports my correlation (Fig. 9) and contention of a recent axis jump, and I predict that detailed study will reveal other jumps to have occurred here as well. I further hypothesize that as spreading on this segment of the rise seems to have been essentially symmetric over the past 1 m.y. or so, there will be another discrete shift of the rise axis to the south within the next few million years. The Cocos-Nazca spreading center near long 86°W has been the site of several of the most detailed geophysical surveys yet made (Sclater and Klitgord, 1973; Detrick and others, 1974; Klitgord and Mudie, 1974; Sclater and others, 1974; Williams and others, 1974). Comparison with a detailed study of a "normal" rise might reveal details of the asymmetric accretion process, if my interpretation is correct. Particularly intriguing are the chains of small mounds parallel to and 20 to 30 km south of the rise axis (Klitgord and Mudie) associated with high heat flow (Williams and others), as my model demands that this egment of the rise axis jumps south about 17 km/m.y., averaged ov... veral million years. These chains of mounds may therefore be ... rsors of an incipient rise jump.

Finally, in my model it is a coincidence that there is today a spreading center trending nearly exactly due east-west, nearly exactly at the equator. This was not true in the recent past and will not be true in the near future, in my interpretation, unless accretion here becomes essentially one-sided. I consider this problem to be either profound or nonexistent.

CONCLUSIONS

Crust has been asymmetrically accreted to the Cocos and Nazca plates by spreading on the Cocos-Nazca spreading center. It is possible, with an asymmetric-accretion model, to overcome the geometric objection of Sclater and Klitgord (1973) to both the hotspot hypothesis and the ancestral-ridge hypothesis for the origin of the Cocos and Carnegie Ridges. The ancestral-ridge hypothesis, however, encounters more severe geometric difficulties.

The old Cocos-Nazca spreading center was briefly oriented east-northeast–west-southwest (approximately 070°). The Pacific-Cocos-Nazca triple junction has moved at least several degrees north since the formation of the Cocos-Nazca spreading center; at present, it is apparently in a stable RRR configuration and is migrating northwestward. The east-west–lineated anomalies south of the Carnegie Ridge are a simple and direct consequence of the evolutionary scheme we have proposed, rather than an enigma.

The following tentative conclusions require further confirmation.

The Cocos-Nazca spreading center was born about 25 m.y. B.P. as the Farallon plate broke apart along a pre-existing (Marquesas?) fracture zone to form the Cocos and Nazca plates. As a result of this break-up, subduction was allowed to become approximately pe... dicular to both the Mid-America and Peru-Chile Trenches. ... original northeast-trending rise system was reorganized into its present geometric configuration by about 23 m.y. B.P.

The Malpelo Ridge may once have formed the northeastern extension of the Cocos Ridge, which has been transferred to the Nazca plate by a discontinuous jump to the west of the Cocos-Nazca-Caribbean triple junction.

ACKNOWLEDGMENTS

This work is permeated with the ideas of Jason Morgan. The finite rotations of Figures 7 and 8 were computed with his "Ultramap" program. In addition to those acknowledged in the preceding paper (Hey and others, 1977), I thank Leonard Johnson, Allen Lowrie, Jerry van Andel, and Carl Bowin for helpful suggestions and David Rea for a preprint. This work was partly supported by the International Decade of Ocean Exploration, National Science Foundation Grant ID 071-04207-A04. The National Science Foundation and the National Aeronautics and Space Administration provided inflationary traineeships, and Princeton University, Woods Hole Oceanographic Institution, the University of Texas, and the University of Hawaii provided further support. This paper is part of a dissertation presented in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Princeton University.

REFERENCES CITED

Anderson, R. N., and Davis, E. E., 1973, A topographic interpretation of the Mathematician ridge, Clipperton ridge, East Pacific rise system: Nature, v. 241, p. 191–193.

A...on, R. N., and Sclater, J. G., 1972, Topography and evolution of the ...ast Pacific rise between 5°S and 20°S: Earth and Planetary Sci. Letters, v. 14, p. 422–441.

Anderson, R. N., Clague, D. A., Klitgord, K. D., Marshall, M., and Nishimori, R. K., 1975, Magnetic and petrologic variations along the Galapagos spreading center and their relation to the Galapagos melting anomaly: Geol. Soc. America Bull., v. 86, p. 683–694.

Anderson, R. N., Moore, G., Schilt, S., Cardwell, R., Tréhu, A., and Vacquier, V., 1976, Heat flow low near a fossil ridge on the north flank of the Galapagos spreading center: Jour. Geophys. Research, v. 81, p. 1828–1838.

Chase, C. G., 1972, The N-plate problem of plate tectonics: Royal Astron. Soc. Geophys. Jour., v. 29, p. 117–122.

Chase, T., Menard, H. W., and Mammerickx, J., 1971, Bathymetry of the North Pacific: La Jolla, Calif., Scripps Inst. Oceanography and Inst. Marine Resources, 10 sheets, Mercator projection.

Cox, A., and Dalrymple, G. B., 1966, Paleomagnetism and potassium-argon ages of some volcanic rocks from the Galapagos Islands: Nature, v. 209, p. 776–777.

Darwin, C., 1839, Journal of researches into the geology and natural history of the various countries visited by H.M.S. Beagle, under the command of Captain Fitzroy, R.N. from 1832 to 1836: London, Henry Colburn, 615 p.

Detrick, R. S., Williams, D. L., Mudie, J. D., and Sclater, J. G., 1974, The Galapagos spreading centre: Bottom-water temperatures and the significance of geothermal heating: Royal Astron. Soc. Geophys. Jour., v. 38, p. 627–637.

Dott, R. H., Jr., 1969, Circum-Pacific late Cenozoic structural rejuvenation: Implications of sea floor spreading: Science, v. 166, p. 874–876.

Forsyth, D. W., 1972, Mechanisms of earthquakes and plate motions in the East Pacific: Earth and Planetary Sci. Letters, v. 17, p. 189–193.

Grim, P. J., 1970a, Connection of the Panama fracture zone with the Galapagos rift zone, eastern tropical Pacific: Marine Geophys. Researches, v. 1, p. 85–90.

——1970b, Bathymetric and magnetic anomaly profiles from a survey south of Panama and Costa Rica: U.S. Dept. Commerce, Environmental Science Services Administration, ESSA Tech. Memor. ERLTM-AOML 9, 87 p.

Handschumacher, D. W., 1976, Post-Eocene plate tectonics of the eastern Pacific, *in* The geophysics of the Pacific Ocean basin and its margin: Am. Geophys. Union Mon. 19, p. 177–202.

Heath, G. R., and van Andel, Tj. H., 1973, Tectonics and sedimentation in the Panama basin: Geologic results of Leg 16, Deep Sea Drilling Project, Vol. 16: Washington, D.C., U.S. Govt. Printing Office, p. 899–913.

Heinrichs, D. F., and Lu, R. S., 1970, Magnetic and gravity measurements south of Baja California: EOS (Am. Geophys. Union Trans.), v. 51, p. 761–762.

Heirtzler, J. R., Dickson, G. O., Herron, E. M., Pitman, W. C., III, and Le Pichon, X., 1968, Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents: Jour. Geophys. Research, v. 73, p. 2119–2136.

Herron, E. M., 1972, Sea-floor spreading and the Cenozoic history of the east-central Pacific: Geol. Soc. America Bull., v. 83, p. 1671–1691.

Herron, E. M., and Heirtzler, J. R., 1967, Sea-floor spreading near the Galapagos: Science, v. 158, p. 775–780.

Hey, R. N., 1975, Tectonic evolution of the Cocos-Nazca rise [Ph.D. thesis]: Princeton, N.J., Princeton Univ., 169 p.

Hey, R. N., and Vogt, P. R., 1977, Rise axis jumps and sub-axial flow near the Galapagos hotspot: Tectonophysics, v. 37, p. 41–52.

Hey, R. N., Deffeyes, K. S., Johnson, G. L., and Lowrie, A., 1972, The Galapagos triple junction and plate motions in the East Pacific: Nature, v. 237, p. 20–22.

Hey, R. N., Johnson, G. L., and Lowrie, A., 1973, Recent apparent asymmetric spreading near the Galapagos hotspot: EOS (Am. Geophys. Union Trans.), v. 54, p. 244.

——1977, Recent plate motions in the Galapagos area: Geol. Soc. America Bull., v. 88, p. 1385–1403.

Holden, J. C., and Dietz, R. S., 1972, Galapagos gore, NazCoPac triple junction and Carnegie/Cocos ridges: Nature, v. 235, p. 266–269.

Johnson, G. L., and Lowrie, A., 1972, Cocos and Carnegie ridges — Result of the Galapagos "Hot Spot"?: Earth and Planetary Sci. Letters, v. 14, p. 279–280.

Johnson, G. L., Hey, R. N., and Lowrie, A., 1973, Marine geology in the environs of Bouvet Island and the South Atlantic triple junction: Marine Geophys. Researches, v. 2, p. 23–36.

Johnson, G. L., Vogt, P. R., Hey, R. N., Campsie, J., and Lowrie, A., 1976, Morphology and structure of the Galapagos rise: Marine Geology, v. 21, p. 81–120.