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51. TWO-STAGE RIDGE PROPAGATION AND THE GEOLOGICAL HISTORY OF THE LAU BACKARC BASIN[1]

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ABSTRACT

Geophysical and geological data for the Central Lau Basin have been interpreted to constrain the tectonic evolution of the Lau Basin since 6 Ma. Seafloor morphology, residual magnetic anomaly lineations, and variations in seafloor acoustic backscattering indicate that two ridge propagation events have been responsible for the formation of the eastern floor of the basin. The earlier propagator formed the Eastern Lau Spreading Center and progressed into a horst-and-graben-dominated extensional terrain derived from the fragmenting Lau-Tonga composite arc. According to our interpretation of recompiled magnetic data, this propagating ridge probably initiated around 5.5 Ma at the southeastern end of a structure that became the Peggy Ridge. At present, the propagator has a tectonic rift tip at the southern end of the Valu Fa Ridge (23°S). This tip has advanced southward at a rate of 120 mm/yr, more than twice the rate reported for most other "open ocean" propagating ridges. The later propagator, referred to as the Central Lau Spreading Center, began from the southeastern limit of the Peggy Ridge between 1.2 and 1.5 Ma and has its present rift tip at 19°22′S. The western floor of the Lau Basin is dominated by irregular ridges and troughs, and our interpretation of the topography is that this crust, originally adjacent to the waning Lau Ridge arc, experienced a protracted period of extensional rifting and local easterly migrating arc magmatism before the advance from north to south of the first propagator. Backarc extension then transferred largely to the new spreading axis. Basement recovered from only two of the backarc sites (836 and 837) has unequivocal (and unmixed?) affinities to the present Central and Eastern Lau axial lithologies; all of the other basin sites have complex parentages. Sidescan sonar data suggest the persistence of some minor present-day extension within the western-rifted portion of the basin; thus, off-axis magmatism and/or extension outside of the present axis is not precluded.

INTRODUCTION

The seafloor of the Lau Basin between 24°S and the Peggy Ridge (17°20′S, 176°10′W to 15°30′S, 178°20′W) has been subdivided into two main crustal types based on seafloor morphology and structural characteristics. The western portion is dominated by a complex series of irregular and discontinuous horsts and grabens, and the eastern portion is characterized by a uniformly and regularly faulted mid-ocean-ridge pattern (Parson et al., 1992). It has been argued that, although the western portion of the Lau Basin appears to have developed by the localized formation of extensional basins, the easternmost crust was created by normal backarc seafloor spreading at the Eastern Lau Spreading Center (ELSC; Parson, Hawkins, Allan, et al., 1992). This relatively simple tectonic model is complicated in the north by the southerly propagation of the Central Lau Spreading Center (CLSC; Parson et al., 1990). This paper will demonstrate that (1) the majority of the easternmost Lau Basin was generated by the ELSC, and (2) the rapid penetration of a backarc spreading axis into the basin did not automatically terminate the extension in the attenuated pre-spreading crust.

MORPHOTECTONIC DOMAINS IN THE CENTRAL AND SOUTHERN LAU BASIN

Parson et al. (1992) published a new bathymetric map of the Lau Basin, along with the corresponding portion of long-range sidescan sonar (GLORIA) mosaic. We reproduce here a simplified version of this bathymetry of the Central Lau Basin for reference (Fig. 1). Detailed examination of this bathymetric data set integrated with the sidescan sonar data between 18°30′S and 21°S suggests an approximate subdivision into four regions, each characterized by distinct morphologies or morphotectonic criteria. These regions are described below and are outlined in Figure 1.

Western Horst-and-graben Terrain

In the western Central Lau Basin, between 18°30′S and 177°10′W, 18°30′S and 178°10′W, 21°S and 178°W, and 21°S and 176°40′W, lies an area of extreme and irregularly varying topography, producing a complex pattern of discontinuous ridges and basins. The shallowest areas reach water depths of less than 1000 m, whereas the deepest are greater than 3300 m. Individual platformal areas, some up to 30 km across, locally extend for more than 80 km in an overall north-south trend and restrict both the across-strike and along-strike interconnectivity of the basins. Locally, the ridges are weakly oriented and form a north-south fabric. Flanks to some of the ridges appear rectilinear and steep (>30°); they are probably fault controlled. This has an important bearing on the sedimentation characteristics of the area. Elsewhere, subequant, roughly conical morphologies persist.

Central Backarc Area

This zone has an irregular polygonal outline and includes the ELSC, its flanking crust, and the crust between the CLSC and the western horst-and-graben terrain (Fig. 1). This area is characterized by ridges between 100 and 200 m high, forming a closely spaced linear pattern with an interval of between 2 and 7 km and oriented at 010°. This fabric is imaged on GLORIA long-range sidescan sonar as closely spaced lineations subparallel to the ELSC. The ELSC itself has a well-pronounced axial trough that shoals toward the south from depths greater than 3000 m at its doomed rift tip at 19°20′S to around 2300 m at 21°S.

Central Lau Spreading Center Crust

A southward-tapering, wedge-shaped area of seafloor generated at the CLSC and described initially by Parson et al. (1990) is contained

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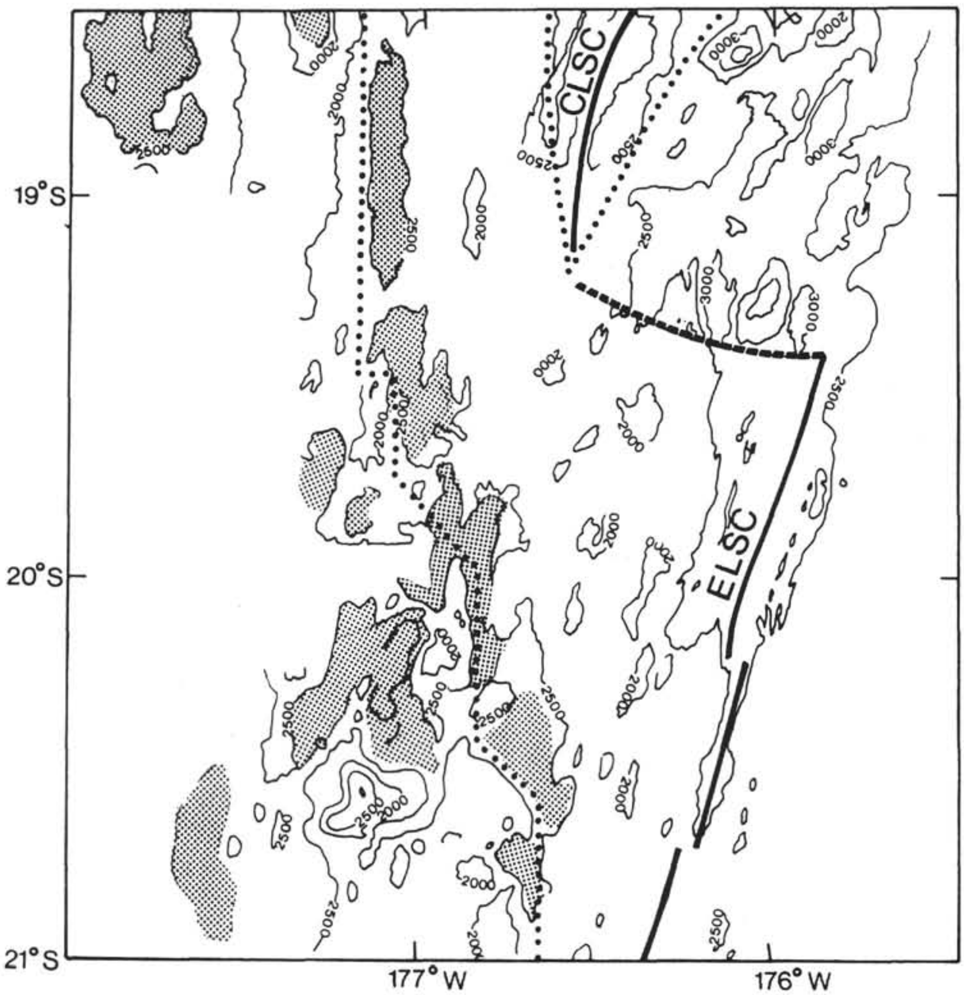

Figure 1. Bathymetric compilation of the Central Lau Basin, adapted from Parson et al. (1992). Isobath interval is 500 m. The division of the study area into the four morphotectonic domains discussed in the text is identified by dotted lines. The geologic evolution of each of these areas is discussed in the text. Heavy lines locate present backarc spreading segments. ELSC and CLSC = Eastern Lau and Central Lau spreading centers, respectively. Stippled areas identify sub-basins formed in the western horst-and-graben terrain of the Lau Basin. Dashed bold line links propagating CLSC ridge tip and dying ELSC ridge tip.

between 18°30′S and 176°40′W, 18°30′S and 176°15′W, and 19°20′ and 176°30′W. The CLSC itself can be traced by a central, gently curving axial ridge, concave to the east, that lies consistently shallower than 2300 m throughout its length. This crest is flanked by shallow, subparallel, elongate linear basins that all deepen to at least 2800 m. The eastern margin of the wedge-shaped portion of crust appears to be interrupted by a series of short northeast-southwest-oriented dislocations, which right-laterally offset the CLSC crust at its junction with the northeastern Central Lau Basin.

Northeastern Central Lau Basin

This area of crust, north of the ELSC and east of the CLSC, carries some of the most complex topography of the basin. It is characterized by curved patterns of seafloor-spreading fabric, punctuated by a number of deep, crudely rhomb-shaped sub-basins that trend in a northeast line. One of these basins is deeper than 3500 m (18°37′S, 176°06′W) and represents one of the deepest parts of the Central Lau Basin. The basins are locally separated by irregularly shaped ridges and plateaux, which collectively have a weak northeasterly trend. Immediately to the east of the CLSC crust, GLORIA imagery shows a clockwise-deflected regular lineation pattern, suggesting a passive right-lateral shear deformation of the crust formed at the ELSC. We propose that this clockwise rotation of the backarc crustal fabric results from the rapid southward passage of the CLSC propagator, in agreement with the model of ridge propagation proposed by Hey (1977), illustrated in Figure 2A, and developed for the Lau Basin by Parson et al. (1990).

The CLSC and the northeastern Central Lau Basin have been described and discussed elsewhere (e.g., Parson et al., 1990), and few new data have been reported to challenge these earlier interpretations. The geological evolution of the crustal boundary between the western horst-and-graben terrain and the central backarc area, however, is of particular importance in the early tectonic development of the basin. The morphology and geological characteristics of this boundary, therefore, are described in detail here. Throughout this boundary zone, a series of irregularly shaped basins is observed that extends from 18°30′S to 21°S in a broad band approximately 15 km wide and oriented at 167°. We indicate their approximate extent in Figure 1. Individually, the four most northerly basins have a linear form and a north-south orientation, but the southern examples are nonlinear and largely amorphous. These basins, similar in depth range, are deepest at their southern ends, where they typically plunge to 2900 m. They appear to be mostly steep sided and are probably fault bounded. One exception to

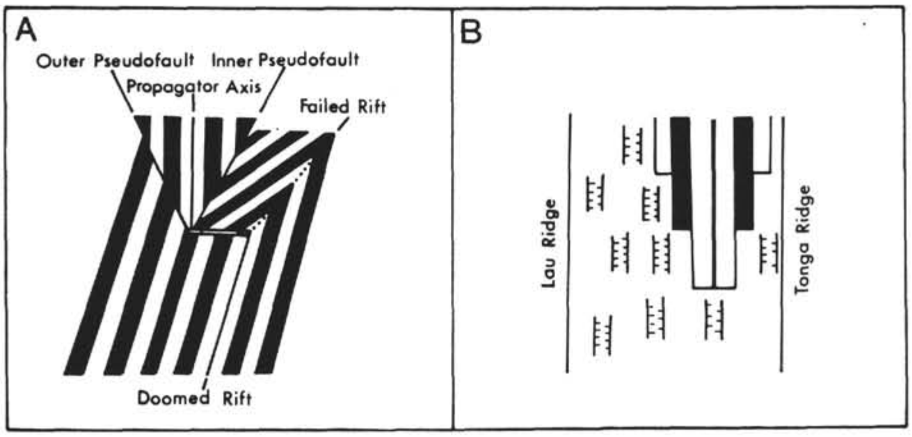

Figure 2. **A.** Simplified tectonic model for the development of sheared ocean floor at the line of the instantaneous transform zone (ITZ, marked by closely spaced double lines) between propagating and retreating spreading ridge tips. Adapted after Hey (1977). **B.** Schematic illustration of a ridge propagation into attenuated, rifted, non-oceanic crust, with implications that exploitation of weaknesses in the crust allow the "stepped" or intermittent propagation.

this is the broad flat-floored triangular trough centered at 20°25′S, 176°45′W. From north to south, the basins describe a weak easterly stepping locus across the basin, and this crude en echelon arrangement of lows marks a well-defined boundary between the irregular horst-and-graben topography to the west and the more subdued, regularly lineated seafloor to the east.

The propagation of the CLSC southward into the Lau Basin has been discussed elsewhere (Parson et al., 1990), and details will be only reviewed here. In essence, the southerly advance of the CLSC rift tip results in the progressive, concomitant retreat of the ELSC "doomed" rift tip and a simultaneous right-lateral shear of the intervening crust, developed during the passage of the instantaneous transform zone (the migrating transform relay linking the two rift tips) across preexisting crust generated at the doomed rift. Some evidence for sheared crust also comes from the easterly deflection of some of the magnetic lineations in the instantaneous transform zone; this is discussed in the following section.

MAGNETIC DATA

A compilation of the marine and aeromagnetic data for the Lau Basin has been recently published and discussed by Murthy (1990) and Murthy and Parson (1991). Their interpretations follow the suggestions of previous workers in the Lau Basin (e.g., Malahoff et al., 1982, in press) that normal seafloor spreading was the mechanism by which the *entire* floor of the Lau Basin had been created. Making this assumption, however, and attempting to correlate poor magnetic anomalies lying close to the magnetic equator, has led to a succession of workers presenting strikingly different interpretations of the data. Estimates for the oldest magnetic anomaly, interpreted as recording the initiation of seafloor spreading in the basin, have ranged from Anomaly 5 (10 Ma; Sclater et al., 1972) to Anomaly 3 (5 Ma; Weissel, 1977). Here we reproduce our modified compilation of Murthy (1990) for reference, along with a revised interpretation (Figs. 3B and 4).

Some portions of the magnetic fabric are more easy to interpret than others. A number of broad magnetic lineations oriented between north-south and up to 30° east of north are identifiable in the central, south, and eastern part of the compilation. They continue for up to 150 km along strike, and we think they represent true seafloor-spreading magnetic anomalies, which are discussed in more detail below. The principal interpretative difficulties lie with the westernmost portion of the basin floor, to the west of a line passing from 18°00′S, 177°20′W to 21°S, 176°45′W (line X–X′ in Figs. 3 and 4). In this area, the magnetic anomaly pattern is characterized by a chaotic but overall neutral or negative signature. No continuous magnetic lineations can be unequivocally mapped, and only weak (<200 nT) anomalies appear as discrete, isolated areas. The pattern is not one easily interpreted as resulting from normal seafloor spreading. Although it is possible that linear anomalies formed at a highly segmented or unstable spreading axis could produce such a complex and nonsystematic magnetic anomaly pattern, we do not incline to this reasoning; instead, we discuss possible alternative origins below.

The clearest magnetic lineations occur in the center of the basin, to the east of 177°00′W (Fig. 3). Positive anomalies as high as 350 nT and negative anomalies as low as 450 nT can be traced continuously over distances of up to 250 km north-south. Surprisingly, close to the ELSC axis, the magnetic fabric is less clear; indeed, the central anomaly is extremely difficult to trace (Figs. 3B and 4). We are uncertain as to why the axial anomaly is so poor. This may be partially as a result of the propagation of the CLSC, the dying back of the ELSC, the distortion during curvature of ELSC anomalies in the Instantaneous Transform Zone, a sudden decrease in spreading rate, or a combination of these factors (Fig. 4). We recognize some similarities between the poor magnetic signature of the last million years of spreading on the ELSC and the irregular patterns identified in the western basin (i.e., discontinuous lineations). We suggest, however, that the subdued and low amplitude signals in the horst-and-graben terrain contrast in detail with the higher intensity (>350 nT) anomalies along the ELSC.

To interpret the anomaly pattern for as continuous a time (flow)-line as possible, we selected four portions of the magnetic compilation orthogonal to the strike of the lineations. Collectively, these portions form a composite merged profile from the ELSC axis to the westernmost (and hence the oldest identifiable) anomaly (Figs. 4–5). In each of the portions, we have selected a number of closely spaced and parallel profiles for consistency. We have great confidence in the identification of Anomalies 2 and 2A, and although Anomaly 3 is less clear, is still readily identifiable (Fig. 5). Although the Jaramillo anomalies are not clearly marked as continuous lineations, locally they are each readily identifiable. Some portions of the magnetic anomaly pattern are described here in detail to support our interpretations. In general, we refer to magnetic anomaly identifications to the west of the ELSC. To the east, a less clear set of anomalies appears to result from the westerly encroachment of the Tofua Arc volcanism, or from the deep burial of the ELSC crust by volcaniclastic sediments. Our data is also more sparse in the extreme eastern Lau Basin. For the most part, unambiguous identification can be made of the Jaramillo

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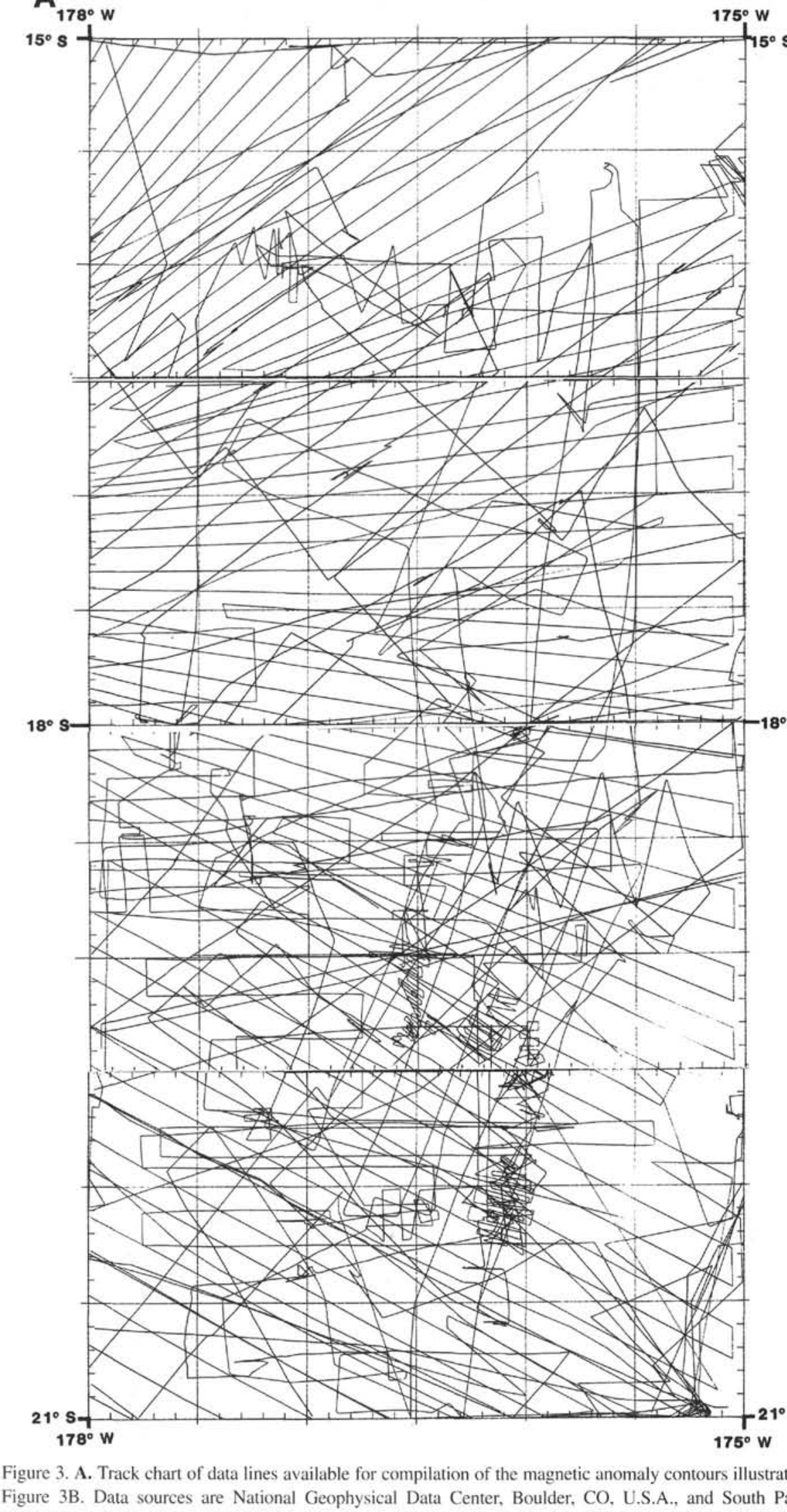

Figure 3. **A.** Track chart of data lines available for compilation of the magnetic anomaly contours illustrated in Figure 3B. Data sources are National Geophysical Data Center, Boulder, CO, U.S.A., and South Pacific Commission, Suva, Fiji. **B.** Contoured residual magnetic anomaly compilation of the Central Lau Basin between 16°30′S and 21°S. Contours at 100-nT intervals. Negative anomalies are shaded in light stipple. Line X–X′ separates weakly north-south-oriented anomalies in the east from random fabric in the west. Labels 2A, 2R, and 2 locate the most obvious magnetic lineations. Filled circles locate the Peggy Ridge crest, dashes locate the Central Lau Spreading Center, and plus signs locate the Eastern Lau Spreading Center. For discussion, see text.

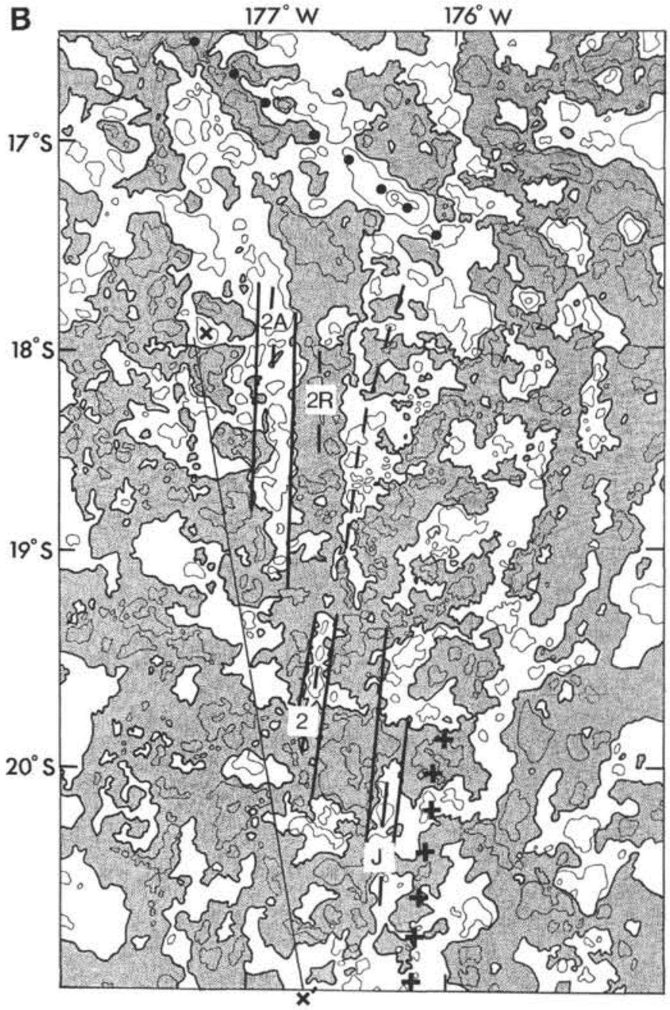

Figure 3 (continued).

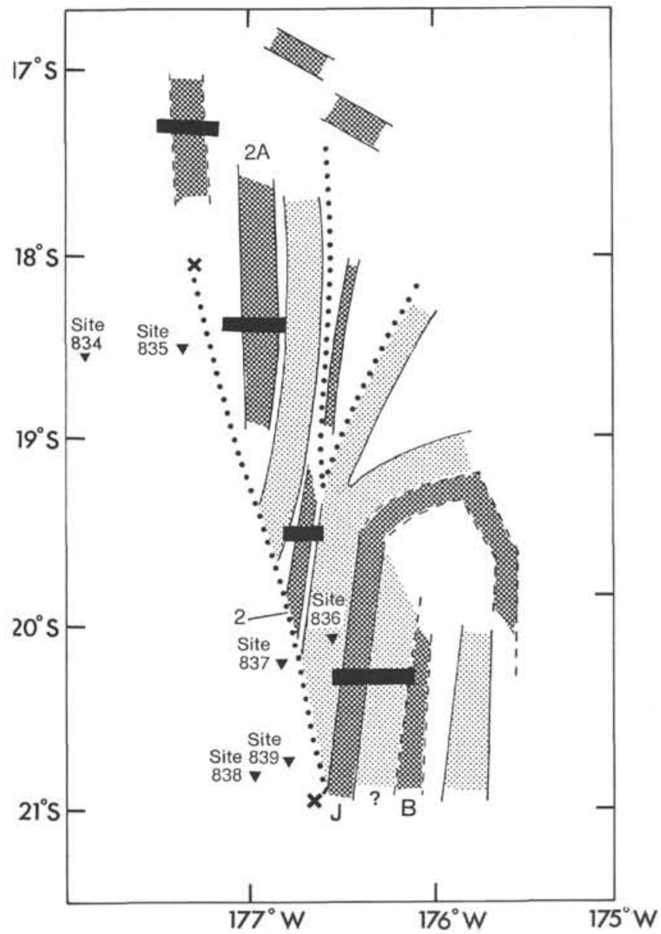

Figure 4. Interpretation of the residual magnetic anomaly compilation illustrated in Figure 3. The general pattern of north-south lineations are interrupted by the 167°-trending limit of "true" seafloor spreading anomalies (filled circle patterns), the southerly tapering wedge of the CLSC (dashes), and the curved lineations to its east. Polarity inversion boundaries are dashed where extrapolated. Line X–X′ as in Figure 3B. The four bold lines lying east-west mark the positions of the selected magnetic anomaly sections we used to construct a composite flow-line anomaly from the ELSC to the westernmost anomaly at 177°30′W. The composite profile is illustrated in Figure 5. J = Jaramillo, and B = Brunhes.

Subchron (0.9 Ma), although the Brunhes axial anomaly is surprisingly unclear and appears to be discontinuous. No doubt exists as to the position of the ELSC in this part of the Lau Basin, where the axis is confirmed both on bathymetric and sidescan sonar data (Parson et al., 1990). North of 19°30′S, the Jaramillo anomaly is clearly seen to take an easterly curved path as it is sheared laterally to the right by the southerly passage of the Instantaneous Transform Zone associated with the CLSC. Outside of this, the negative central portion of the Matuyama Subchron is also similarly deformed. A clear portion of Anomaly 2 (1.8 Ma) is identified passing through 19°30′S at 176°40′W. To the west of this, well-developed Anomaly 2R stretches from 17°40′S, 176°40′W to 19°45′S, 176°55′W (Figs. 4–6). Anomaly 2A (Gauss Chron) is relatively clear, but Anomaly 3 is less prominent, as is Anomaly 3R. All of these anomalies end at a line running approximately 167°, coincident with that separating the morphotectonic domains of the first two areas discussed above.

According to these identifications, an average half-spreading rate of approximately 50 mm/yr has persisted over the past 5.5 m.y. We have, accordingly, constructed a synthetic magnetic anomaly profile to support our interpretations, using the IOSDL two-dimensional modeling package "MAGIC" that we present in Figure 5. This half-spreading rate exceeds by some 14 mm/yr previous estimates derived from both regional (Weissel, 1977) and detailed studies (M. Sinha and C. Williams, pers. comm., 1988). New data recently derived from GPS studies, however, based on stations on the Lau, Vava'u, Tonga, and Samoan island groups, indicates that 100–110 mm/yr of opening is likely to be the present figure for full rate extension in the northernmost Lau Basin (Bevis et al., 1991; Schutz et al., 1991).

To assess variations in spreading rate since 5.5 Ma, we have compared the age and the distance of the magnetic polarity reversals from the onset of the Brunhes axial anomaly, at 0.73 Ma (Fig. 6). For this exercise we assumed symmetric spreading. The spreading history can be divided into two sections: the pre- and post-Jaramillo normal events (0.9 Ma). A transition zone between these sections spans the time between the Olduvai and the Jaramillo, and we will discuss this period in more detail below. Before the end of the Olduvai reversed period, the widths of the anomalies indicate a consistent half-spreading rate of approximately 49.5 mm/yr, (Fig. 6). Post-Jaramillo, the identification of the magnetic anomalies is more equivocal, and our estimate for the spreading rate in the last million years is not as reliable. Our measurement of the width of the Jaramillo Subchron appears to support a significantly higher half spreading rate, perhaps as high as 85 mm/yr, although the event is probably too short to give a more than an approximate spreading rate. The accurate mapping of the reversal boundaries, however, is absolutely critical for this exer-

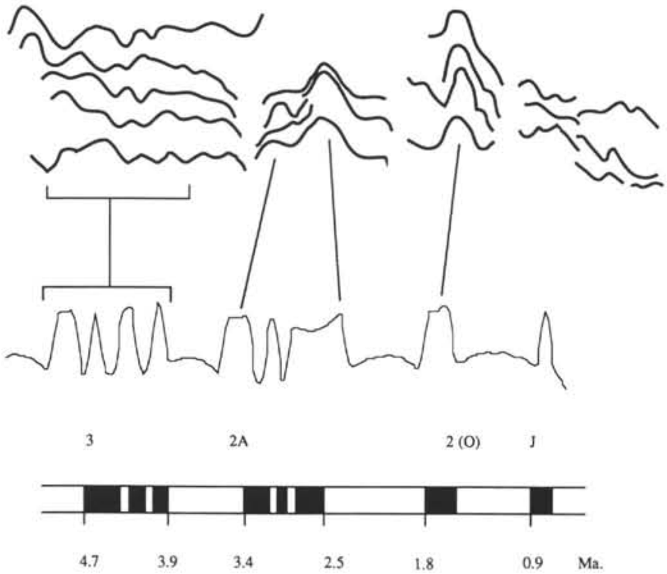

Figure 5. Composite magnetic anomaly profiles (2, 2A, and 3) derived from the temporally consecutive sections of ELSC-spread crust indicated in Figure 4. O = Olduvai, and J = Jaramillo. Normal/reversed block model provided for reference, as are the ages (in millions of years) for the onset and end of anomalies. Parameters used in the model are as follows: strength of present field in nt = 5000; inclination of present field in degrees = 58°; declination of present field, positive east = 13.5°; present strike of spreading axis = 0°; half-spreading rate in mm/yr = 25.0; latitude at the time of seafloor formation = 19°S; strike of the spreading axis at the time of its formation = 0°; intensity of magnetization (modulus) for seafloor older than Brunhes = 30 amp/m.

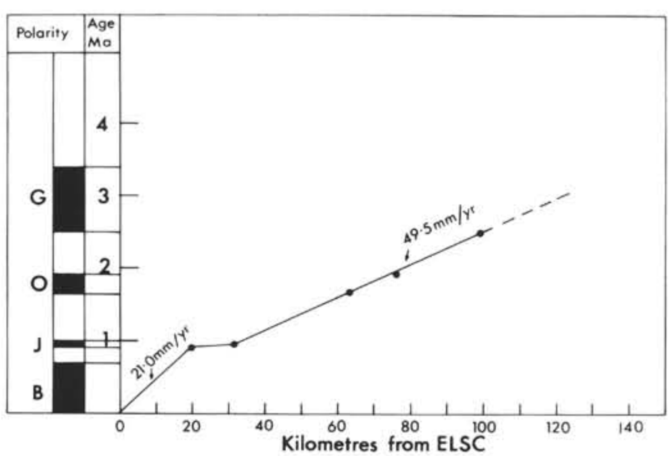

Figure 6. Plot of distance from ELSC of magnetic anomalies in the Central Lau Basin. Anomaly reversal scale indicated for reference purposes. B = Brunhes, J = Jaramillo, O = Olduvai, and G = Gauss.

cise and is clearly not possible close to the axis of the ELSC. Therefore, we prefer to treat this interpretation of the most recent history of spreading with some skepticism.

The reversed polarity section of seafloor between the end of the Olduvai and the base of the Jaramillo subchrons suggests that a slowing of the half-spreading rate to about 46 mm/yr may also have occurred. Because the reversed magnetic anomaly boundaries are the only fixed time points on our geological time scale, it is impossible to ascertain exactly at which time during the chron/subchron that the rate change may have occurred.

INTERPRETATION

We think that the magnetic fabric described above, and the seafloor topography in the central portion of the Lau Basin, are consistent with a model of southerly ridge propagation of the ELSC from the earliest geological evolution of the Lau Basin to the present day. The present propagating rift tip of the ELSC lies at the southern limit of the Valu Fa Ridge (i.e., 23°00′S; Fig. 7). Unlike the propagation of the CLSC into preexisting backarc crust generated at the ELSC, however, this initial propagator has advanced into a region of attenuated crust of heterogeneous character that probably comprises a mixture of relict arc fragments, rift graben, and volcanic constructs derived from easterly migrating arc magmatism. From our interpretation of the magnetic fabric discussed above to provide the average half-spreading rate of 100 mm/yr (Fig. 6), and by extrapolating the possible ages of the crust back in time, we can then estimate that the intersection of the ELSC propagator with its probable initiation point (a ridge-transform intersection at the Peggy Ridge) occurs at around 16°30′S, 177°15′W. The southernmost point to which the ELSC has been mapped is 23°S and is referred to as the Valu Fa Ridge (von Stackelberg and von Rad, 1990). If this, indeed, represents the propagating tip, then the ridge has propagated approximately 660 km. Furthermore, if we assume a constant spreading rate before Anomaly 2A (3.4 Ma) equal to that after Anomaly 2A, then we can date the initiation of the propagator at 5.5 Ma. Thus, the rate of propagation of the ELSC through the Lau Basin would have been approximately 120 mm/yr. This is more than twice as fast as the rates estimated for many "mid-ocean" propagating ridges (Hey, 1977) but approached by propagation rates associated with microplate evolution (Naar and Hey, 1986). We suggest that this relatively rapid rate may be because the ridge is penetrating into highly attenuated and weakened "proto"-backarc crust. Rift propagation under these conditions may be more analogous to the rapid rifting and breakup of continents before the formation of ocean-continent transition zones than to ridge advance through oceanic crust. The en echelon pattern of north-south elongate basins that step easterly from north to south further suggests that propagation occurred in an intermittent or "staggered" manner (Bonatti, 1985; Fig. 2B). Periods of advance appear to have alternated with periods of spreading and incipient development of transform offsets.

The magnetic fabric for the youngest portion of the CLSC is very unclear, resembling that described above for the most recent ELSC crust. We are unable, therefore, to make more than a speculative estimate for the age of the CLSC propagator. If we assume similar propagation and spreading rates as that of the ELSC, on the basis of their similar propagator tip angles, then the CLSC appears to be approximately 1.5 m.y. old.

We propose a model to summarize and illustrate the evolution of the Lau Basin by the advance of the two propagators, the ELSC and the CLSC, and present this model in Figure 8. The seven stages schematically record the disintegration of the Fiji/Tonga/Lau proto-arc through splitting and rifting, the initiation and establishment of the backarc spreading axis, its subsequent segmentation, and the development of the new line of arc volcanism. Figure 8A denotes the tectonic setting of the Pacific–Indo-Australian plate boundary at 10 Ma, approximately 3 m.y. after the cessation of backarc spreading in the South Fiji Basin. Volcanism was active in the Lau group from 13–14 Ma (Woodhall, 1985) to 3 Ma (Gill, 1976). Figure 8B illustrates schematically the earliest stages of arc fragmentation. Normal extensional faulting is distributed in a nonsystematic fashion across the arc. Arc volcanism (as reported by Woodhall [1985] and Gill [1976]) continued throughout this period. By 6 Ma (Fig. 8C), the proto-arc had separated into its two components along an irregular line of rifting. Although some minor arc volcanism persisted on the westernmost (remnant) arc of the Lau Ridge, significant arc constructs developed within the incipient basin as it formed between the separating halves of the remnant arc. A number of rift graben or sub-basins also started to form, some developing into short-lived spreading

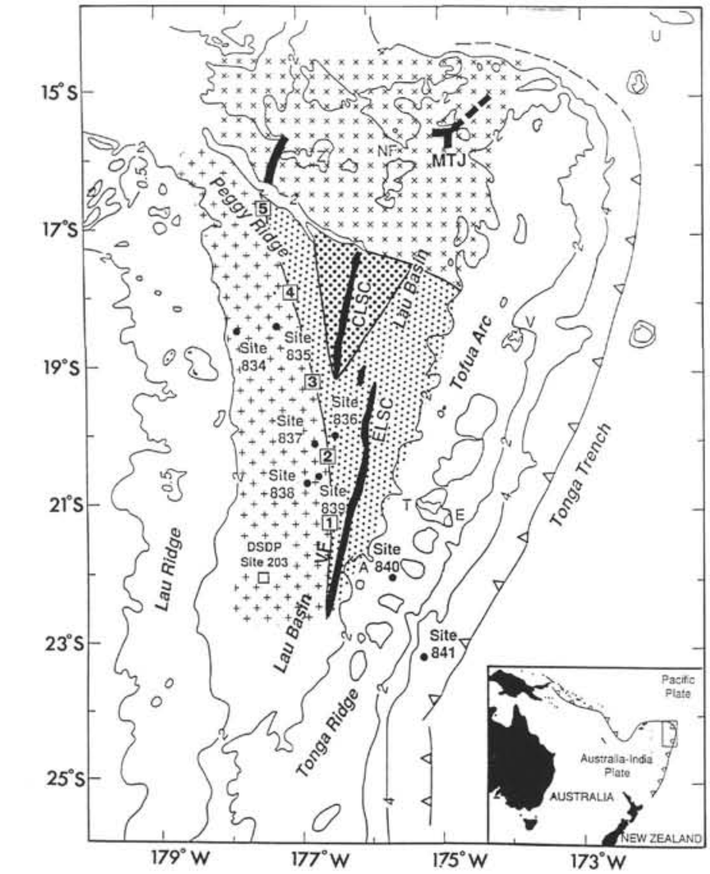

Figure 7. Crustal domains of the Lau Basin between 14°30′S and 22°15′S, overlain on a regional bathymetry of the Lau Basin, and the locations of Sites 834 through 841. Figure adapted from Parson, Hawkins, Allan, et al. (1992). + = crust of attenuated and rifted paleo- and active arc complexes (the "horst-and-graben terrain" of Parson et al., 1992); x = attenuated crust in the northern Lau Basin as a possible equivalent to the western basin terrain. The lightly stippled pattern locates the distribution of crust interpreted to have been generated at the ELSC; the densely stippled pattern locates crust generated at the CLSC. Numbers in boxes are ages (in Ma) at which the ELSC propagator would have reached that latitude on its progression south, assuming constant spreading and propagation rates. Islands shown are Niuafo'ou (NF), 'Eua (E), Vava'u (V), Tongatapu (T), and 'Ata (A). MTJ = Mangatolu Triple Junction, and VF = Valu Fa Ridge. Contour intervals in kilometers.

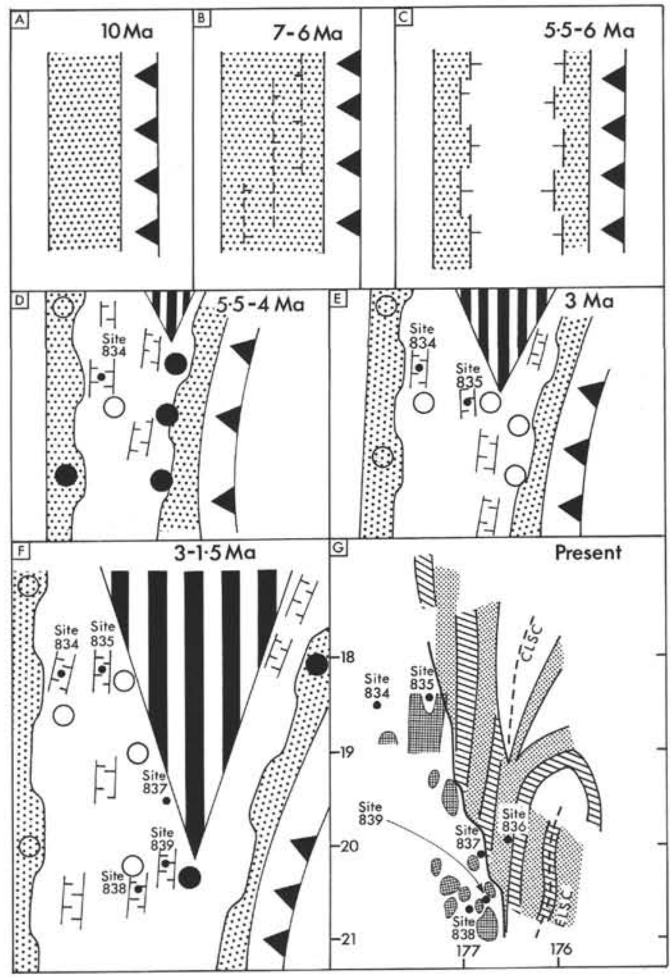

Figure 8. Schematic summary of tectonic evolution of the Central Lau Basin since 10 Ma in cartoon form. Stippled pattern denotes original Lau/Tonga/Fiji/New Hebrides proto-arc. The Pacific–Indo-Australian plate boundary is denoted by the standard subduction symbol of large filled triangles. Filled circles are possible active arc constructs (seamounts), open circles are extinct arc constructs, and small filled circles locate Leg 135 sites. The rift graben is denoted by short, paired parallel lines; active tectonism is denoted by ticks on the downthrown side. The propagating backarc ridge (ELSC) is denoted by the alternative striping of crust in the central-eastern portion of the Lau Basin. In Figure 8G, the cruciform ornament locates present topographic highs, and the hachured/stippled ornament locates magnetic striping from Figure 4. For a complete discussion of Figures 8A–8G, see text.

centers. As the Lau Basin developed from 5.5 to 4 Ma (Fig. 8D), arc volcanism began to wane on the Lau Ridge and to migrate eastward within the backarc basin, and the first of the two backarc propagators advanced into the northern parts of the basin. Figure 8E illustrates a more southerly position of the ELSC propagator, the largely extinct backarc rifting and extension phase in the western portion of the basin, and the speculated initiation of subsequent arc volcanism along the western margin of the Tonga Ridge. Figure 8F illustrates the increased dominance of extension at the ELSC, with most of the crustal attenuation in the western basin at an end. Figure 8G is a cartoon summary of the present-day geologic setting for the Lau Basin. The second propagator, the CLSC, was initiated at around 1.5 Ma and is advancing southward at the expense of the ELSC. Arc volcanism has developed fully along the western Tonga Ridge, and extension and volcanism have all but ceased in the western Lau Basin horst-and-graben terrain.

Following the model of Hey (1977) applied to ridge propagation and spreading axis reconfiguration, two pseudofaults would develop, one either side of the margins of the advancing ELSC ridge. The pseudofault developed at the western flank of the southerly propagating ELSC can be traced through the zone of en echelon troughs described above. The locus of the eastern pseudofault is difficult to ascertain precisely; it runs approximately parallel to the western limit of the Tofua volcanic arc, however, and must be largely buried by sediments derived from it. It is likely that the Tofua Arc migrated westward across the crust generated east of the ELSC; and the lack of good magnetic anomaly data in this area means that a degree of asymmetrical spreading in the ELSC cannot be ruled out. This model of ridge propagation from the north would help to explain the greater width of the Western Lau Basin in the south, which would naturally result from a more prolonged period of attenuation pre-spreading. At the latitude of the southernmost tip of the ELSC, the Lau basin is approximately 200 km wide. At the point of initiation of the propagator, the Western Lau Basin is less than 100 km wide.

IMPLICATIONS FOR THE DRILLING RESULTS OF LEG 135

The new model of Lau Basin backarc evolution has considerable significance for the petrogenesis of basement rocks recovered during Leg 135. Interpretation of the preliminary findings of the drilling (Parson, Hawkins, Allan, et al., 1992) indicated that, although extension was taking place, only local magmatic basins were formed throughout the western basin before the beginning of "true" backarc seafloor spreading. In this part of the basin, therefore, it was proposed that a two-fold division of crustal types, separated by an approximately north-south line, occurred (Parson, Hawkins, Allan, et al., 1992). It was clear that, although Site 836 was located on crust that had been generated at the ELSC, the positions of Sites 837, 838, and 839 were close to the proposed boundary between the two crustal types. Our new model helps to locate these latter sites with great accuracy. Although Site 834 must clearly lie within the extended crust to the west of the Lau Basin, Site 835 must also be close to the boundary between it and the ELSC crust to the east. We describe here the possible effects of each of the propagators on the geological evolution of backarc Sites 834–839. A summary of crustal types developed through the passage of the propagators is presented as Figure 7. This figure also indicates the extrapolated positions of the ELSC propagator tip at intervals of one million years between 5.5 Ma and the present day.

Site 834

Basement ages for Site 834 range between 3.8 Ma for the shallowest recovered hard rock and 5.6 Ma at the base of the hole, and are derived from a combination of paleomagnetic and biostratigraphic control. The older age corresponds with that for the suggested initiation of the ELSC propagator at the (proto-) Peggy Ridge, probably some 200 km from Site 834. At 3.8 Ma, the propagating rift tip would have advanced to a position just south of 18°S, some 100 km from the site, and almost its closest approach (Fig. 7 and Table 1). At Site 834 a consistently high percentage of ash units in the sedimentary section was present until the middle late Pliocene (around 2.5 Ma), at which time predominantly pelagic conditions abruptly returned. At this time, the propagating rift tip would have been located somewhere around 20°S, some 200 km to the south of the site. It seems likely, therefore, that the abrupt cessation of volcaniclastic deposition was related to local activity, rather than connected with the ELSC propagator. The initiation of the CLSC propagator, at around 1.5 Ma, does not seem to have resulted in any first-order signature in the volcaniclastic record at Site 834.

Site 835

The youngest basement age for rock recovered at Site 835 is 3.5 m.y., based on the biostratigraphic ages of the immediately overlying sediments. However, for discussion about these dates see Rothwell et al., this volume. The latitude of the ELSC propagating tip at 3.5 Ma is estimated to be around 18°30′S, the same as that for Site 835. Our bathymetric control for the area to the north of Site 835 is poor, but we are confident that the site is located in a northerly widening basin, perhaps similar to those described above that define the western pseudofault of the ELSC. We tentatively speculate, therefore, that Site 835 could contain crustal components from both extended and rifted arc terrain associated with the earliest extensional phase of Lau Basin opening, as well as those from the propagating ELSC rift. We emphasize here the clear difference in the geochemical characteristics of basement at each of these two sites. Site 834 samples contain components of MORB-like lithologies, whereas Site 835 contains predominantly arc-like affinities.

Table 1. Comparison of drilling ages of basement recovered from Leg 135 backarc sites.

Site	Drilling age (m.y.)	Predicted age of closest approach of ELSC to site
834	3.8–5.6	3.6
835	3.5[a]	3.6
836	0.7	0.9
837	2.0	2.0
838	N/R (≤4.0[b])	1.65
839	>2.2–1.25	1.7

Notes: Data taken from Parson, Hawkins, Allan, et al. (1992). ELSC = Eastern Lau Spreading Center. N/R = normal/reversed polarity.

[a] Best estimate of basement age based on biostratigraphic and paleomagnetic interpretations, but see Rothwell (this volume).

[b] Predicted basement age, assuming constant sedimentation rates.

Site 836

The most easterly backarc site, 836, is located less than 50 km from the ELSC. The thin sediment sequence overlies crust with a clear negative magnetic signature, interpreted to have formed immediately pre-Jaramillo. Our estimated age for the basement, therefore, is marginally older than 0.9 Ma. The youngest basement rocks recovered at Site 836, however, were reported to be around 700 k.y., based on biostratigraphic evidence from the overlying sediments (Parson, Hawkins, Allan, et al., 1992). Site 836 lies 50 km west of the zero age crust of the ELSC. Thus, we are able to estimate an average half-spreading rate of 71 mm/yr for the younger portion of the Brunhes normal polarity period.

High-resolution, 3.5-kHz seismic profiles across the basin within which Site 836 is located have been used to identify variations in sediment thickness (Parson, this volume). Sediment thicknesses in the floor of the basin range from greater than 70 meters at the basin flanks to negligible thicknesses in the center of the basin. This variability may result from restricted connectivity of sediment supply between basins or from sediment reworking by currents scouring the basement surface. We speculate, therefore, that the sedimentation history may have been interrupted or delayed at its commencement. The biostratigraphic ages derived from the base of Site 836, therefore, could be minimum and misleading if interpreted as implying a younger basement age.

Site 837

Site 837 was occupied on the eastern flank of one of the basins that we suggest locates the western pseudofault of the ELSC. Our interpretation of the detailed morphology of Basin 837 is that its eastern flank clearly forms an extension of crust generated at the ELSC. According to our assumptions of a constant propagation rate for the ELSC, the rift tip would be located at the latitude of Site 837 at around 2.0 Ma. This corresponds exactly with the biostratigraphic age of the youngest basement rocks recovered at the site. Analysis of basement lithologies recovered at Site 837 indicates they are andesitic basalts with clear arc affinities. T_1O_2 and FeO^* levels in these lithologies were recorded as high as 1.4% and 11.8%, respectively, but do not approach concentrations recorded in FeTi-type basalts sampled at propagator tips in active oceanic settings (Hey, 1977). In detail, Site 837 lies on the eastern flank of Basin 837, on the tip of a north-northeast-trending ridge that continues in an apparently unbroken path into crust, which is predicted to be derived from backarc spreading at the ELSC. Isotope data (Hergt, this volume) produced from basement sampled at Site 837 indicates that the rocks recovered from this site, along with those from Site 836, require an Indian Ocean MORB component, although it is not an essential component for the other backarc sites. One implication of this is that Sites 836 and 837 appear to tap a mantle source uncontaminated by Pacific MORB influence and thus represent a later phase of the evolution of the marginal basin at the plate boundary. This is clearly at odds with the major and trace geochemistry, which places basement lithologies at Site 837 within the western Lau Basin domain.

Site 838

Site 838 is located on the western flank of an irregularly shaped ridge that clearly lies within that portion of the Western Lau Basin dominated by rift graben and horst structures. Basement was not reached at the site, and the oldest sediment recovered yielded a biostratigraphic age of 2.6 Ma. Reexamination of the seismic sections collected during Leg 135, however, indicates that an acoustic basement surface is recognizable at Site 838 at around 0.34 s two-way traveltime (TWT) below seafloor (see Parson, this volume). Assuming a constant sedimentation rate of 177 mm/kyr (Parson, Hawkins, Allan, et al., 1992), this basement surface (which appears to be clearly downfaulted on a series of structures into the basin) could be as old as 4.0 m.y. If our estimates for propagation rates are correct, then the ELSC rift tip at this time would have been more than 300 km to the north (Fig. 8). The considerable thickness of volcaniclastic sediment at the site, the failure to reach basement, and the age suggested by the sediment succession supports our suggestion that the site overlies an area of extended arc terrain, which existed well before the ELSC approach.

The predicted age for the closest approach of the propagator tip to Site 838 is around 1.7 Ma, which coincides with the time of a sharp reduction of the supply of coarse debris and turbiditic material (Parson, Hawkins, Allan, et al., 1992). Immediately following the estimated time of passage of the tip, the sedimentation was dominated by clayey nannofossil oozes derived from pelagic sedimentation.

Site 839

Site 839 lies on the extreme westernmost margin of Basin 839, one of the topographic lows occurring along the eastern margin of the extended horst-and-graben terrain of the Western Lau Basin.

Basin 839 overlies seafloor that, because of its morphology, we would ascribe to the Western Lau Basin extended crust. The site is located in one of the basins that we suggest marks the locus of the pseudofault of the ELSC. The youngest basement rocks recovered at the site were reversely magnetized and are interpreted as belonging to the negative chron immediately predating the onset of the Olduvai Subchron at 1.88 Ma. Our estimates for the age of the closest approach of the propagator to Site 839, however, is approximately 1.7 Ma. The emplacement of basement at Site 839, therefore, is unlikely to be related to the ELSC. Basement at Site 839 contains a heterogeneous mixture of arc-like (Tofuan) basalts and andesitic basalts and therefore is clearly part of the pre-spreading arc terrain.

The nine basement lithology units identified at Site 839 have been subdivided geochemically into three groups: a primitive, MgO-rich group, represented by two units; a basaltic group, represented by two units; and an evolved group of basaltic andesites, represented by units from the base to the second highest unit. All lithologies are 1.7 m.y. old or older and have been tentatively extrapolated to 2.2 Ma at the base of the hole (based on paleomagnetic data). It is unlikely that the rift tip of the ELSC passed closer than 30 km at 1.7 Ma, according to our propagation model above, so the volcanic effect of dike emplacement and extrusion at Site 839 is likely to have been minimal. Volcanism associated with the advancing tip cannot be ruled out, however. Lava flows related to the present propagating tip of the CLSC can be observed on GLORIA records extending well ahead (up to 40 km) of the morphologic propagating tip (Parson et al., 1990), and reports of dike and sill emplacement over distances of more than 100 km are not unusual.

Units 1 and 4, the most basaltic, are also the most comparable with modern ELSC/CLSC lithologies. Therefore, it seems that the derivation of the basement at Site 839 is from at least three parental magma types. A significant change in sedimentation and volcaniclastic input to the sequence occurs at around 1.6 Ma, the predicted time of closest approach of the tip. Thick successions of coarse volcanic conglomerates (e.g., Cores 135-839A-10H, -11H, and -17X) are dated around 1.6 Ma (Parson, Hawkins, Allan, et al., 1992), but this rapid sedimentation continued until 50 m from the top of the hole, allowing more than 160 m of sedimentary succession to be deposited into the basement. Within this thick succession, an angular unconformity can be clearly recognized (Parson, this volume); however, its precise age is difficult to determine without appropriate biostratigraphic/paleomagnetic control in this high sedimentation rate section. We can only speculate on the possible time relationship between the formation of the half-graben at Site 839 and the tectonism related to the propagation of the ELSC ridge tip.

DISCUSSION

We have summarized much of the above discussion of ages of basement and propagation in Table 1, which compares the youngest ages for basement recovered during Leg 135 with the time of the closest approach of the ELSC. One can readily recognize that at some sites (835, 837, and 839) similarities in the ages predicted by our model and those from the drilling results support suggestions that the sites are either located on crust generated at the ELSC or were close enough to be affected by intrusive/extrusive phases derived from the ELSC. In contrast, Sites 834 and 838 clearly show the most significant age difference and confirm that they are set in the attenuated, arc-derived, horst-and-graben terrain in the Western Lau Basin.

None of the sites, with the possible exception of Site 835, has a younger basement age than that predicted from our propagator model. Such a discrepancy would support our suspicions that off-axis volcanism locally persists after formation of the backarc spreading center. The observation of a highly reflective seafloor on GLORIA records from the western basin around 21°S, 177°15′W, some 120 km west of the ELSC, could be interpreted as off-axis volcanism (Parson et al., 1990). The GLORIA imagery across apparently fresh fault patterns in the western basin supports this suggestion of the continuing attenuation in the early rifted crust and the incomplete transfer of extension to the new backarc axis.

SUMMARY AND CONCLUSIONS

We have reinterpreted the detailed morphology and the magnetic anomaly pattern for the Lau Basin south of 16°30′ and conclude that the geologic history of the basin can be summarized as follows:

1. A protracted extensional phase beginning sometime after 10 Ma sundered the active Lau/Fiji/Tonga proto-arc, opening a basin floored with attenuated relict arc fragments and local arc-volcanic constructs.
2. The largely amagmatic basin floor developed an irregular horst-and-graben form through the period before 5.5 Ma, mainly through arc construction and local ephemeral rifting and spreading episodes.
3. At around 5.5 Ma, true backarc spreading was initiated in the north Central Lau Basin and propagated rapidly southward to form the ELSC. The southern limit of the Valu Fa Ridge marks the present position of the propagator tip. Insufficient data exists to the south or on flanks of the ridge tip to assess its rate of propagation at the present time.
4. Propagation of the ELSC appears to have taken place in an intermittent fashion, advancing in a stepwise, rather than smooth, mode. This has probably been controlled by the preexisting rifted fabric of the western basin.

5. We can confirm that, in terms of the geophysical data and their tectonic settings, Sites 835, 837, and 839, although lying close to the pseudofault separating ELSC-spread crust from the horst-and-graben terrain, probably have closer crustal affinities to the ELSC lithologies.

6. We have evaluated the history of backarc opening in terms of variations in spreading rate. A constant full-opening rate of 99 mm/yr is estimated between 3.4 Ma (beginning of Anomaly 2A) and after 1.66 Ma (the end of the Olduvai Subchron). Estimates for spreading rates between 1.66 Ma through the Jaramillo and to the Brunhes are uncertain, but they probably are on the order of 46 mm/yr. The spreading rate during the Brunhes is 42 mm/yr.

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* Abbreviations for names of organizations and publication titles in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

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