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Sea-floor spreading in the Lau back-arc basin

Brian Taylor *, Kirsten Zellmer, Fernando Martinez, Andrew Goodliffe

School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, HI 96822, USA

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Abstract

We report the first 3-D magnetization inversion of bathymetry and magnetics data for the entire Lau Basin and confirm a history of southward-propagating sea-floor spreading during the past 4 Myr. Magnetic lineations, seafloor fabric and ridge segmentation patterns indicate that lithospheric accretion on discrete spreading centers in this back-arc basin is fundamentally similar to that occurring on mid-ocean ridges. The Brunhes Chron spreading rates (65–100 mm/yr) are < 75% of the opening rates determined geodetically. In the absence of earthquake evidence for significant off-axis deformation between 18–21°S, we infer that opening rates have recently increased on the central and east Lau spreading centers.

Keywords: Lau Basin; sea-floor spreading; magnetization; bathymetry

1. Introduction

Although the Lau Basin was the first marginal basin shown to have formed by extension between a volcanically active island arc and an inactive remnant arc [1], the nature of that extension has been debated ever since [2–9]. At issue is whether back-arc basin opening is fundamentally different from that of mid-ocean basins, being dominated by diffuse deformation and magmatism [2–4] versus localized sea-floor spreading following arc rifting [5–7].

Shallow sea-floor morphology, thin sediment cover, young tholeiitic basalts, crustal earthquakes, geodetic surveys and vigorous hydrothermal systems provide ample evidence for active extension in the Lau Basin [1–14]. Recent drilling and geophysical survey results have been used to derive a two-stage model of basin opening in which distributed arc rifting has been replaced progressively southwards by sea-floor spreading [8,9].

Despite this wealth of information, and the known location of the spreading centers in most of the basin [11,15–19], the magnetic lineation pattern is not well defined. Many different identifications of magnetic lineations have been proposed and sea-floor spreading rates derived from them vary from 42 to 99 mm/yr [5,8,20–23]. The short lengths of correlatable magnetic anomalies, together with the apparently diffuse loci of shallow earthquakes, have prompted some [2–4] to question the hypothesis that lithospheric accretion in back-arc basins occurs along discrete spreading centers similar to those observed in the major ocean basins [5–7]. They argue that extension in the Lau Basin is more diffuse than on mid-ocean ridges, characterized by short-lived spreading ridges, point-source volcanism, and shear-dominated deformation. Others suggest that off-axis deformation and sea-floor spreading may both occur

* Corresponding author. E-mail: taylor@soest.hawaii.edu

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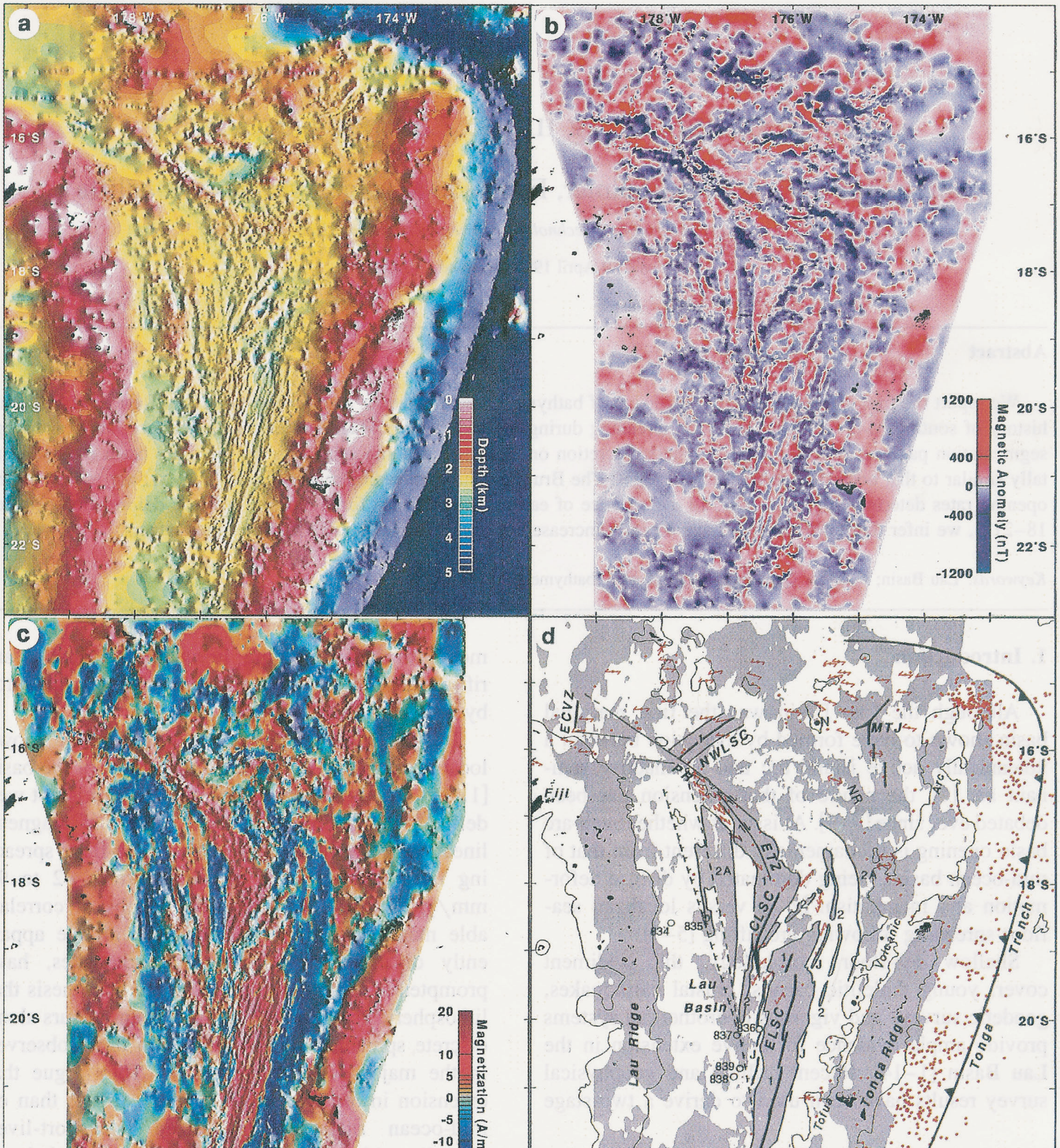
a
178°W
176°W
174°W
16°S
18°S
20°S
22°S
Depth (km)
0
1
2
3
4
5
b
1200
400
0
-400
-1200
Magnetic Anomaly (nT)
c
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20
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-5
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d
ECVZ
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834
835
Lau Basin
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838
ELSC
Lau Ridge
VF
Tofua
Volcanic Arc
Tonga Ridge
Tonga Trench

within the basin [8], especially given that no spreading rate estimates are as high as the northward-increasing opening rates (91–159 mm/y) determined by repeat Global Positioning System (GPS) measurements across the basin in 1990 and 1992 [10].

From an analysis of magnetic lineations, seafloor fabric and ridge segmentation, we will show that the pattern of lithospheric accretion on discrete spreading centers in the Lau back-arc basin is fundamentally similar to that occurring on mid-ocean ridges. We infer, from the disparity between the opening rates derived from magnetic anomalies versus GPS, that opening rates have recently increased on the central and east Lau spreading centers.

2. Sea-floor magnetization pattern

All previous interpretations of magnetic lineations in the Lau Basin have used magnetic anomalies uncorrected for variations in the bathymetry and skewness of the magnetic source layer (with the exception of a local study of Valu Fa Ridge [24]). We recompiled the digital marine and aeromagnetic data for the basin available from the U.S. National Geophysical Data Center (see [8] for data distribution). Using GMT software [25] and methods described more fully in [26], we combined these data and a shoreline database to produce 1 arc minute grids of bathymetry and magnetic anomaly data (Fig. 1a,b). Poorly located data were removed and small navigation errors in 3 days of the 1978 aeromagnetic survey were corrected by cross-over analysis with GPS-navigated ship data. Using these grids and a 3-D Fourier domain magnetization inversion we derived a magnetization distribution (Fig. 1c) that assumes a source layer 1 km in thickness whose top is the seafloor — a reasonable assumption given the generally thin sediments in the basin. In the Fourier domain, regional wavelengths (> 400 km) and potential noise spikes (wavelengths < 2 km) were filtered out of the data.

Our magnetization map (Fig. 1c) clearly reveals the sea-floor spreading magnetic pattern in the central Lau Basin for the first time (Fig. 1d). In contrast, amplitude variations and even apparent reversals occur within individual lineations on the magnetic anomaly map (Fig. 1b). In the center of the basin south of Peggy Ridge there is a V-shaped wedge of crust with sea-floor spreading magnetic lineations and abyssal hill bathymetric fabric (Fig. 1). Volcanoes of the Tofua arc line the eastern edge of the crust formed by spreading. East of the Lau Ridge and west of the spread crust there is a region of mainly negative magnetizations with a north-trending sea-floor fabric. Drilling and other geophysical data have been interpreted as inferring that this province formed by progressive stretching of the Lau arc and fore-arc, accompanied by widespread intrusion and extrusion of magmas, with chemistries varying between island arc tholeiites and mid-ocean ridge basalts (MORB) [8,9,27]. Weak north-trending magnetic lineations within this province appear to be structurally controlled (Fig. 1) and may be caused by magmas emplaced along faults, as has been proposed for the rifted arc crust of the northern Mariana Trough [26]. Drilling into the western edge of this province at Ocean Drilling Program (ODP) Site 834 (Fig. 1d) recovered MORB-like basalts erupted from 5.6 to 3.8 Ma [27].

The boundary between the stretched and spread crust is a propagation boundary, trending 343° between 17° and 20°S, marked by shallow crust on the west and a valley on the east (Fig. 1a,d). Several of

Fig. 1. Geophysical data for the Lau Basin and surrounding regions. (a) Bathymetry, with relief shading from the east and islands black. (b) Magnetic anomaly. (c) Sea-floor magnetization, highlighted with bathymetric texture. (d) Tectonic interpretation, shallow earthquakes (1964–1987, < 50 km depth, magnitude > 5.0, located by > 15 stations) from the International Seismological Center catalogue (red dots), and slip vectors of earthquake focal mechanisms [33]. Divergent arrows = normal faults; split arrows = strike-slip faults; convergent arrows = thrust faults; bold lines = spreading segments; lines with double arrows = strike-slip faults; ticked lines = propagation boundaries; dashed lines = pseudofaults and lines with teeth = trench axis. Islands are irregular shapes, filled black, and surrounded by the 1500 m contour (thin line). Positive magnetic anomalies are shaded and sea-floor spreading magnetic lineations are outlined and labeled. *1* = Brunhes; *J*, *2* = Jaramillo; *2A* = Gauss. ○ = numbered drill site. *CLSC* = central Lau spreading center; *ECVZ* = east Cikobia volcanic zone; *ELSC* = east Lau spreading center; *ETZ* = extensional transform zone; *MTJ* = Mangatolo Triple Junction; *N* = Niuafo'ou; *NR* = Natsushima Ridge; *NWLSC* = northwest Lau spreading center; *PR* = Peggy Ridge; *VF* = Valu Fa.

the ODP holes were sited on or near this boundary (Fig. 1d). Initial interpretations were that these holes penetrated syn-rift lavas presumed to mantle rifted arc crust [27]. Our magnetization inversion and identification of the rifting-to-spreading boundary corroborates this interpretation for the arc-like basalts and basaltic andesites drilled at Sites 837–839. We locate the propagation boundary west of Site 835, however, and infer that the MORB-like basalts recovered there form the carapace of oceanic crust. The magnetostratigraphy and biostratigraphy of the sediments at Site 835 indicate that the underlying lavas were extruded at 3.5 Ma during the earliest phase of the Gauss Chron (2An.3n) [27]. This agrees with our identification that Site 835 is located on the oldest part of magnetic anomaly 2A (Fig. 1d).

3. Tectonic evolution

From the pattern of sea-floor spreading magnetic anomalies that we identify (Fig. 1) and existing geological data, we infer the following tectonic evolution for the region south of Peggy Ridge [28]. Crustal stretching between the Lau and Tonga Ridges began ~ 6 Ma accompanied by intrusion of arc- and MORB-like magmas [9,27]. While this distributed extension, and intrusion continued in the south, it was progressively replaced from the north by focused accretion on the east Lau spreading center (ELSC) which propagated south from 16.5° to 20°S between ~ 4 Ma and ~ 2 Ma. The initial ELSC was oriented north–south and spread at ~ 100 mm/yr. It comprised two segments; the northeastern one propagated south faster than the other to produce the pseudofault oriented 170° (Fig. 1d). When the pseudofault joined the propagation boundary ~ 2 Ma (just before magnetic anomaly 2), (1) the ELSC rotated 15–25° clockwise, subdivided into left-stepping overlapping segments, and continued to propagate south; and (2) the Peggy Ridge transform fault was initiated, as was the central Lau spreading center (CLSC) and an extensional transform zone (ETZ) linking the two [29] (Fig. 1d). Subsequently, the CLSC propagated south, replacing the ELSC and transferring magnetic anomaly 2 and younger crust eastwards.

With its present rift tip at 19°20′S, the CLSC overlaps all the northern segment and one quarter of the next segment of the ELSC [15,19]. The region of overlap is characterized by strike-slip earthquakes (Fig. 1d), compatible with bookshelf faulting along rotating ridge-parallel crustal slivers [30]. The southern segment of the ELSC, Valu Fa Ridge, extends to 22°45′S and is characterized by a deep axial magma lens reflector [18,31,32]. Clusters of normal fault earthquakes south of 23°S are associated with continued back-arc rifting [33]. Brunhes Chron spreading rates increase northwards, from 65 mm/yr along 110° on the ELSC at 21°S, to 90 mm/yr along 115° on the ELSC at 18°S, to perhaps 100 mm/yr along the ETZ where normal polarity volcanism has overprinted anomaly-2-reversed crust south of Peggy Ridge (Fig. 1c).

The present tectonics and the tectonic evolution of the region north and east of Peggy Ridge are not understood in detail. Earthquake foci and focal mechanisms indicate that a broad sinistral shear zone extends west from the northern termination of the Tonga trench to the transform relay zone along the northern margin of the Lau Ridge and Fiji platform [33–35] (Fig. 1d). There are three neovolcanic zones just south of this seismic zone, but the structures connecting their northern limits to each other or to the shear zone are unsurveyed. The east Cikobia volcanic zone [16] is not associated with a positive magnetic lineation (Fig. 1c,d), suggesting that it formed very recently. The northwest Lau spreading center (NWLSC) [16,19] extends 100 km northeast from Peggy Ridge and has a Brunhes Chron spreading rate of 48 mm/yr. The Mangatolo triple junction [11] joins three spreading limbs within, but at high angles to, a positive (Brunhes or Gauss?) magnetic lineation that trends SSE between 15° and 17°S near 175°W (Fig. 1c,d). There is insufficient data to map the extensions of the west and northeast axial grabens of this triple junction. The southern limb is divided into three left-stepping segments each about 20 km long. Sidescan [17] and seismicity [33] data indicate that this structure continues south to 17°45′S as a zone of tectonic rifting. Although the axial segments may have recently reoriented, it appears that a rifting–spreading center nucleated along the northern shear zone and propagated south, forming the V-shaped wedge of crust that separates the Natsushima Ridge (including Niuafo'ou Island) from the Tofua volcanic arc [29] (Fig. 1d). This process of arc crust being rifted close to the volcanic front, followed by propagation into the rift basin of a sea-floor spreading system initiated at a basin margin strike-slip zone, has occurred twice within the Lau Basin and is common to other back-arc basins [36].

4. Recent increase in spreading rates

Repeat measurements in 1990 and 1992 across the Tonga–Fiji GPS network reveal significantly faster crustal motion [10] than recorded by the sea-floor magnetic anomalies identified here. In an Australia- and Lau Ridge-fixed frame of reference, the GPS data show that the Tonga Ridge is moving on azimuths of ~ 115° at rates increasing from ~ 90 mm/yr at 21°S to ~ 130 mm/yr at 18.5°S and ~ 160 mm/yr at 16°S. Although our magnetic anomaly identifications do not constrain the total opening rates northeast of Peggy Ridge, the Brunhes Chron sea-floor spreading rates at 21°S and 18°S are only 65 and 90 mm/yr, respectively (Fig. 1). Either the spreading rates are < 75% of the short-term geodetic rates, implying a recent increase in opening rates or, in addition to spreading, significant off-axis extension is occurring.

There is sidescan evidence for minor faulting and volcanism in some of the western rift basins after spreading is established [8]. However, unlike the western Woodlark Basin where earthquake seismicity and other evidence demonstrate that continental rifting continues for up to 1 m.y. after spreading initiation [37], and unlike the Lau Basin south of 23°S and along the eastern margin north of 18°S, where numerous normal fault earthquakes indicate active extension [33], there is a dearth of magnitude > 5 off-axis crustal earthquakes in the western rifted province of the Lau Basin (Fig. 1d). Apparently, therefore, opening rates have recently increased on the major spreading centers (ELSC and CLSC) in the Lau Basin.

5. Summary

Following initial rifting of arc crust close to the volcanic front, the Lau back-arc basin has opened over the last 4 Ma by the successive southward propagation of discrete seafloor spreading centers. The sea-floor bathymetric and magnetization fabric is similar to that of mid-ocean ridges, as is the pattern of ridge segmentation (propagating rifts, overlapping spreading centers, extensional transform zone and transform fault). Present rifting is occurring in the basin south of 23°S and along the eastern margin north of 18°S, but there is no teleseismic earthquake evidence for off-axis extension between these latitudes. We infer that opening rates have recently increased on the central and east Lau spreading centers, given that Brunhes Chron spreading rates (65–100 mm/yr) are < 75% of the opening rates determined geodetically.

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