A new geological map of the Lau Basin (southwestern Pacific Ocean) reveals crustal growth processes in arc-backarc systems

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ABSTRACT

A 1:1,000,000-scale lithostratigraphic assemblage map of the Lau Basin (southwestern Pacific Ocean) has been created using remote predictive mapping (RPM) techniques developed by geological surveys on land. Formation-level geological units were identified in training sets at scales of 1:100,000–1:200,000 in different parts of the basin and then extrapolated to the areas where geological data are sparse. The final compilation is presented together with a quantitative analysis of assemblage-level crustal growth based on area-age relationships of the assigned units. The data sets used to develop mapping criteria and an internally consistent legend for the compilation included high-resolution ship-based multibeam, satellite- and ship-based gravity, magnetics, seafloor imaging, and sampling data. The correlation of units was informed by published geochronological information and kinematic models of basin opening. The map covers >1,000,000 km² of the Lau-Tonga arc-backarc system, subdivided into nine assemblage types: forearc crust (9% by area), crust of the active volcanic arc (7%), backarc rifts and spreading centers (20%), transitional arc-backarc crust (13%), relict arc crust (38%), relict backarc crust (8%), and undivided arc-backarc assemblages (<5%), plus oceanic assemblages, intraplate volcanoes, and carbonate platforms. Major differences in the proportions of assemblage types compared to other intraoceanic subduction systems (e.g., Mariana backarc, North Fiji Basin) underscore the complex geological makeup of the Lau Basin. Backarc crust formed and is forming simultaneously at 12 different locations in the basin in response to widely distributed extension, and this is considered to be a dominant pattern of crustal accretion in large arc-backarc systems. Accelerated basin opening and a microplate breakout north of the Peggy Ridge has been accommodated by seven different spreading centers. The result is an intricate mosaic of small intact assemblages in the north of the basin, compared to fewer and larger assemblages in the south. Although the oldest rocks are Eocene (~40 m.y. old basement of the Lau and Tonga Ridges), half of the backarc crust in the map area formed within the last 3 m.y. and therefore represents some of the fastest growing crust on Earth, associated with prolific magmatic and hydrothermal activity. These observations provide important clues to the geological evolution and makeup of ancient backarc basins and to processes of crustal growth that ultimately lead to the emergence of continents.

INTRODUCTION

Geological maps are critical to our understanding of Earth evolution and processes, from plate tectonics and crustal growth to basin evolution and the formation of mineral and energy resources, including in the oceans. The geomorphology of the global oceans has been determined from satellite altimetry and derived gravity models (Sandwell et al., 2014), but <5% of the seafloor has been explored in detail, leaving the vast majority unmapped and its geological makeup poorly understood at a meaningful scale (Mayer et al., 2018). Large-scale geological compilations covering the oceans have so far been limited to the 1:35,000,000-scale publication of the Commission for the Geological Map of the World (Bouysse, 2014) and the 1:17,000,000-scale map sheets of the Circum-Pacific Council for Energy and Resources (Scheinbier et al., 2013). At these scales, the smallest features depicted are on the order of 100 km. Geological formations are mostly unclassified or limited to broad tectonic environments in the North Pacific (Bouysse, 2014) and the Circum-Pacific Council for Energy and Resources (Scheinbier et al., 2013). Detailed geological maps of the ocean floor have been created in areas where high-resolution multibeam bathymetry, acoustic backscatter data, and direct seafloor observations were acquired (e.g., Parson et al., 1994; Pelletier et al., 2001; Clague et al., 2013; McClintock et al., 2013; Anderson et al., 2016, 2017; Embley and Rubin, 2018; Klishchies et al., 2019). However, most of these maps are of limited areal extent (e.g., 1:100,000 scale) and rarely correlate units across a basin or regionally. To illustrate how lithostratigraphic correlations can be achieved for a larger area, we have prepared the first geological map of

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the Lau Basin at 1:1,000,000 scale on a single sheet (Item S1) and correlated assemblage- and formation-level geological units across the entire basin.

The Lau Basin (southwestern Pacific Ocean) is the type locality for intra-oceanic backarc basin formation, first recognized by Karig (1970). It was subsequently identified as the location of some of the fastest-growing crust on Earth (Hawkins, 1995; Taylor et al., 1996) and a region of prolific magmatic and hydrothermal activity (Lupton et al., 2012, 2015; Baker et al., 2019). After more than 50 research cruises since 1970, it is now one of the best-studied regions of the deep ocean. The available geophysical and sampling data provide the basis for recognition of discrete geological formations throughout the basin and for development of the first internally consistent geological legend. Using well-mapped areas as training sets, we assigned formation-level geological units to >1,000,000 km² of the Lau-Tonga arc-backarc system. The approach closely follows the techniques developed for remote predictive geological mapping (RPM) on land—and of other planets—in particular using well-established terrane classifications from terrestrial volcanic systems (e.g., Wilhelms and McCauley, 1971; Sabins, 1999; Schetselaar et al., 2007; Rogge et al., 2009; van der Meer et al., 2012; Tanaka et al., 2014). In many areas, the extrapolations are constrained by ship-based multibeam, magnetics, gravity, seismic reflection and refraction, and geological sampling data, including from drilling. In other areas where site-specific geological information is sparse, the extrapolation of formations was guided by remotely acquired geophysical data, including satellite altimetry and derived vertical gravity gradient (Smith and Sandwell, 1997; Sandwell et al., 2014).

The Lau Basin is part of the Tonga subduction zone, between the active Tofua volcanic arc in the east and the remnant arc of the Lau Ridge in the west (Fig. 1). Opening of the basin started ~6 m.y. ago, initiated by retreat of the Tonga Trench. The characteristic V shape reflects progressive splitting of the older arc crust toward the south and asymmetric opening toward the west. Bathymetric and magnetic data show that early crustal accretion behind the arc occurred along...
a major backarc spreading center, similar to a mid-ocean ridge (Hawkins, 1995; Taylor et al., 1996). Drilling by the Ocean Drilling Program (ODP) confirmed that the crust in the west of the basin formed through a combination of early-stage rifting followed by seafloor spreading (Hawkins, 1995). However, the sampled rocks have a range of ages spanning several millions of years that do not increase linearly with distance from the inferred spreading center as is typical at mid-ocean ridges. Instead, seafloor morphology and highly variable thickness and composition of sediment fill in numerous sub-basins throughout the backarc region indicate a more complex opening history. Chase (1971) was the first to postulate that several tectonic plates and triple junctions were needed to accommodate the rapid opening of the basin; however, many aspects of the structure and kinematics remained unresolved. Little was known about the more recent structure, particularly in the northern Lau Basin where a lack of high-resolution multibeam and high-quality magnetic data prevented a straightforward interpretation until recently (Zellmer and Taylor, 2001; Sleeper and Martinez, 2016). Seafloor mapping also provided particular insight into the crustal structure and composition as part of the Ridge2000 Integrated Studies Site in the central Lau Basin (e.g., Martinez et al., 2006) and more recently in the northeastern part of the basin (e.g., Embley and Rubin, 2018; Chadwick et al., 2019). One of the major results of the Ridge2000 research was the finding that arc proximity strongly influences morphology and thickness (Martinez and Taylor, 2002), chemistry (Pearce et al., 1995; Eason and Dunn, 2015), and seismic crustal structure (Dunn and Martinez, 2011; Araí and Dunn, 2014) in the near-ridge backarc. In addition, new refraction and multichannel reflection seismic data, ship-based gravity and magnetic data, multibeam bathymetry, and sediment echosounder data have been obtained in several long profiles crossing the northeastern Lau Basin (Hannington et al., 2019; Schmid et al., 2020), and an analysis of shallow seismicity has highlighted the kinematics of several emerging microplate boundaries in the area (Baxter et al., 2020). These data, together with compiled information from the past 50 years of research cruises, form the basis for the first comprehensive geological map of the Lau Basin, presented in this paper.

### REGIONAL GEOLOGICAL SETTING

Opening of the Lau Basin was triggered by the collision of the Ontong Java and Melanesian Borderland plateaus with the Australian plate in the Miocene (Ruellan et al., 2003; Ruellan and Lagabrielle, 2005). The Pacific plate has been converging with the Australian plate at as much as 80 mm/yr at the northern end of the Tonga Trench when measured with respect to the Lau Ridge, which is part of the Australian plate. Opening of the Lau Basin, which is partitioned among several spreading systems, reaches a total rate of ~160 mm/yr at the northern end of the basin, but this involves spreading on microplates that are not part of the Australian plate. The combination sums to a total subduction rate of ~240 mm/yr (Pacific-Tonga convergence; Bevis et al., 1995). Tomographic images show the Pacific plate subducting below the active Tofua volcanic arc with dips of 60°–70° (Zhao et al., 2007). Rollback of the Pacific slab induced upper-plate extension and separation of the former Vitiaz arc beginning at ca. 6 Ma. Because of the abrupt curvature of the trench at the northern edge of the Tonga platform, the slab is torn through the entire lithospheric thickness (Millien and Hamburger, 1998; Bonnardot et al., 2007). At the point of tearing, a STEP (subduction-transform edge propagator) fault (Govers and Wortel, 2005) developed along the northern Lau Basin after extinction of the Vitiaz subduction zone. The Vitiaz lineament is a relict feature of the extinct subduction zone and is presently inactive as shown by the lack of seismicity along it (e.g., Baxter et al., 2020). Transcurrent motion has stepped into the North Fiji Basin along the Fiji transform fault, and this deformation has left a trail of spreading centers, rift basins, and multiple microplates in the North Fiji Basin (Isacks et al., 1969; Millien and Hamburger, 1998).

Seafloor spreading started between 6 and 5.5 Ma in the north of the Lau Basin and has since propagated 700 km south following asymmetric rollback of the Pacific plate (Parson and Hawkins, 1994; Ruellan et al., 2003). The now-inactive Lau Ridge in the west (former Vitiaz arc) was separated from the Tonga Ridge in the east (Taylor et al., 1996). Because rifting of the Vitiaz crust initiated at the forearc, almost all of the original Eocene arc is now part of the Lau Ridge, which remained active even as the early backarc basin opened in front of it (Hawkins, 1995). Volcanism at the Lau Ridge continued for at least several million years after initial opening (until ca. 2.5 Ma; Parson et al., 1992a), and cores recovered during ODP Leg 135 confirm that volcaniclastic sediments in the local basins were derived first from the west and then from the east (Clift and Dixon, 1994). The active arc magmatism eventually stepped across the basin and reinitiated closer to its present position along the Tofua arc (Martinez and Taylor, 2006). Although it stabilized relatively recently, the Tofua arc has already begun to rift again at several locations in the northeastern part of the Lau Basin. A variety of geophysical data sets, including magnetization and GPS measurements, show that seafloor spreading is occurring in the south with a total opening rate of between 159 ± 10 and 91 ± 5 mm/yr and a maximum total opening of ~160 mm/yr between the northern Tonga Ridge and the Lau Ridge (Australian plate; Bevis et al., 1995). However, different models disagree on the precise locations where the strain is being taken up (Pelletier et al., 2001; Zellmer and Taylor, 2001; Conder and Wiens, 2011; Sleeper and Martinez, 2016).

Whereas only one major backarc spreading center was recognized in the 1980s, now at least 10 have been identified throughout the basin (Fig. 1). They include, in the south, the Eastern Lau Spreading Center (ELSC) and its southern extension, the Valu Fa Ridge, the Central Lau Spreading Center (CLSC), and the Lau extensional transform zone (LETZ), with a short relay zone (Intermediate Lau Spreading Center) between the ELSC and CLSC. This geometry was first described from GLORIA side-scan sonar surveys (Parson et al., 1990) and has since been refined by analysis of regional magnetics, gravity, and SeaMARC II side-scan sonar data (Zellmer and Taylor, 2001; Martinez and Taylor, 2006; Sleeper and Martinez, 2014, 2016; Sleeper et al., 2016). Based on spreading fabric and magnetic anomalies, the ELSC initially formed near 17°S and propagated south. Its northern segment has since been taken over by the CLSC near 18°S, which is now the main spreading center as far north as 19.5°S (Sleeper...
and Martinez, 2014). Spreading at the ELSC was abandoned north of 19°S, but the overlap with the CLSC is marked by numerous sub-basins and a zone of right-lateral shearing (Parson et al., 1990). The different spreading centers are generally very similar to mid-ocean ridges in degree of segmentation, volcanic architecture, composition, and axial depths (minimum ~1800 m and maximum ~3200 m; average 2200–2300 m). Both the ELSC and CLSC are propagating south at an estimated rate of 120 mm/yr (Parson et al., 1990). In the northeastern Lau Basin, there are at least three additional spreading centers of different ages: the Mangatolu triple junction (MTJ), which includes both active and inactive arms; the Northeast Lau Spreading Center (NELSC); and the Founalei Rift and Spreading Center (FRSC). Because there appears to be only one dominant spreading segment of the MTJ, we refer generally to this system as a single spreading center; however, the precise configuration remains to be determined. Farther west, the Northwest Lau Spreading Center (NWLSC), the Rochembeau rifts (RR), and the Futuna Spreading Center (FSC) have also been identified (Parson and Tiffin, 1993; Pelletier et al., 2001). Although the opening rate of the basin is comparable to that of ultrafast-spreading segments of the East Pacific Rise (Bevis et al., 1995), the individual spreading centers are much slower, with the extension distributed across many different structures. Sleeper and Martinez (2016) presented a revised kinematic model based on reinterpretation of the seafloor magnetization patterns and ridge morphology, which confirms the slow spreading in the east along the FRSC compensated by faster spreading in the west along the CLSC and LETZ. Focal mechanisms (centroid moment tensors) indicate a predominance of strike-slip motion, indicating significant rotation throughout the region (Parson et al., 1990; Wetzel et al., 1993; Sleeper and Martinez, 2014). Shallow seismicity shows that the main extensional faulting is occurring only at the northern and southern terminations of the spreading segments (Conder and Wiens, 2011; Baxter et al., 2020). Zellmer and Taylor (2001) first proposed a three-plate kinematic model involving the Australian plate to the west, the Niuafo’ou microplate between the CLSC and the FRSC, and the Tonga plate to the east (Fig. 1). They postulated a paleo-spreading axis located near the arc during magnetic anomaly 2, which moved away from the arc toward the currently dominant spreading system (CLSC-LETZ) as the basin opened. More recently, seafloor spreading has recoupled a position close to magnetic anomaly 2A in the FRSC (Sleeper et al., 2016). However, the ages of the magnetic anomalies are not well known in this region, and the seafloor features associated with those anomalies have only recently been mapped (Hannington et al., 2019). Among other complications, the region between the southern tip of the FRSC and the northern extension of the ELSC should be accommodating ~45 mm/yr of strain (Conder and Wiens, 2011), but it has been difficult to define a plate boundary at this location. Sleeper and Martinez (2016) predicted much slower opening rates (~8 mm/yr) at the southern tip of the FRSC, which is in better agreement with the lack of seismicity in the area, and Baxter et al. (2020) suggested a significant amount of non-rigid deformation throughout the northeastern Lau Basin region. North of the Niuafo’ou microplate, a complex pattern of small, poorly defined microplates has been recognized that formed in response to left-lateral shear related to the transition from subduction to transform faulting at the northern termination of the Tonga Trench (Conder and Wiens, 2011; Baxter et al., 2020). This is an area of intense deformation, left-lateral strike-slip faulting, plate rotation, and extension in the forearc crustal blocks, suggesting that the northern margin of the basin is highly unstable and actively breaking up (Baxter et al., 2020).

### METHODS AND DATA

The mapped formations were identified in training areas (e.g., MTJ; Item S2 [footnote 1]) using ship-based data sets, including multibeam bathymetry, acoustic backscatter (reflectivity), and side-scan sonar images of the seafloor integrated with gravity and magnetics. Additional data are from regional-scale side-scan sonar surveys (GLORIA and SeaMARC II) and airborne magnetics (Parson et al., 1990; Zellmer and Taylor, 2001; Martinez and Taylor, 2006). More than 650,000 km² of the map area is covered by ship-based multibeam and other geophysical data (Fig. 2), which were closely inspected to derive the mapped units. Digital enhancement techniques were used extensively (e.g., slope maps, terrain texture shading; see Lecours et al., 2016; Anderson et al., 2016, 2017). In the training areas, seafloor observations have been made from crewed submersibles (Alvin, Pisces, Nautile), remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs), including at the Ridge2000 Integrated Studies Site (Martinez and Taylor, 2006; Baker et al., 2006; German et al., 2006), as part of the U.S. National Oceanographic and Atmospheric Administration (NOAA) Submarine Ring of Fire Program (RVs Thompson, Kilo Moana, Roger Revelle, and Falkor; Baker et al., 2006, 2011; Embley et al., 2007; Merle et al., 2010, 2013; Resing et al., 2011) and during operations aboard RV Ka‘iimikai-O-Kanaloa (Stoffers et al., 2006). Extensive commercial surveys have also been carried out by Nautilus Minerals Inc. in partnership with the TELVE, NoToVE, and NoLauVE cruises led by Australian National University (RV Southern Surveyor; Arculus, 2003, 2004, 2008, 2009). Ten research cruises of RV Sonne (I and II) have been conducted in the area (cruise SO35; von Stackelberg et al., 1985; SO48: von Stackelberg et al., 1987; SO67: von Stackelberg et al., 1990; SO135: Stoffers et al., 1999; SO167: Stoffers et al., 2003; SO192: Schwarz-Schampera et al., 2007; SO195: Grevenmeyer and Fliß, 2008; SO215: Feirce et al., 2011; SO263: Haase et al., 2018; SO267: Hannington et al., 2019). ROVs and AUVs that were used to map the active arc and backarc spreading centers include Canadian ROV ROPOS (RV Sonne cruise SO192: Schwarz-Schampera et al., 2007; RV Falkor cruise FK160320: Kwasnitschka et al., 2016), RV Quest from the University of Bremen (RV Roger Revelle cruise RR1211: Merle et al., 2013; RV Sonne cruise SO263: Haase et al., 2018), ROV SuBastian from the Schmidt Ocean Institute (RV Falkor cruise FK171110: Rubin et al., 2018), ROV Jason and AUV Sentry from the Woods Hole Oceanographic Institution (RV Thompson cruise TN234: Merle et al., 2008; RV Falkor cruise FK171110: Rubin et al., 2018), AUV D. Allen B. from the Monterey Bay Aquarium Research Institute (RV Thompson cruise TN234: Merle et al.,...
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2009), and GEOMAR’s AUV Abyss (R/V Kilo Moana cruise KM1129A; Martinez et al., 2013; R/V Sonne cruise SO267: Hannington et al., 2019). Research cruises of Ifremer with the submersible Nautile were conducted in the French territorial waters of Futuna in 1999, 2000, 2010, and 2012 (R/V L’Atalante; Pelletier et al., 2000, 2001; Fouquet et al., 2015; Konn et al., 2016, 2018); more recent cruises have focused on the FRSC (Hannington et al., 2019) and the NELSC and Mata volcanoes (cruise RR1211: Merle et al., 2013; cruise FK160320: Kwasnitschka et al., 2016; cruise SO267: Haase et al., 2018; R/V Kilo Moana cruises KM1024 and KM1129A: Embley and Rubin, 2018; cruise FK171110: Rubin et al., 2018; Chadwick et al., 2019). Extensive dredging, sediment coring, and grab sampling has also been conducted. The distribution of geological sampling and seafloor observations is shown in Figure 3, and a complete listing of the data sources is provided in Items S3 and S4 (footnote 1).

These data were compiled from the literature and from cruise reports as georeferenced layers in ESRI ArcGIS software. Geological formations were then assigned on the basis of structure, crustal type (and thickness, where known), magnetic character, spreading fabric, composition, age, and sediment cover. Where multibeam data were available for reprocessing and gridding, detailed maps were prepared at 1:100,000–1:200,000 scale for training purposes and to establish an internally consistent classification system and legend. The interpreted formations and structures in the training areas were then digitized in ArcGIS and extrapolated to areas with fewer data to create the 1:1,000,000-scale map. The digitized map consists of 1159 polygons grouped into 49 different formations. Surface areas of the mapped features were calculated using the Calculate Geometry tool of ArcGIS using a Lambert cylindrical equal-area projection. At 1:1,000,000 scale, the average area of the mapped formations is 1014 km$^2$ per polygon (excluding individual volcanoes); for the backarc crust, it is 540 km$^2$ per polygon. The spatial resolution is comparable to that of regional (1:2,000,000 to 1:5,000,000 scale) quantitative bedrock maps on land, which ranges from 297 km$^2$ to 801 km$^2$ per polygon (Peucker-Ehrenbrink and Miller, 2002, 2003, 2004, 2007a, 2007b). The average number of polygons per formation type, approximately 35, provides a statistically meaningful basis for spatial analysis in a map of this scale, following the criteria of Peucker-Ehrenbrink and Miller (2003) and Peucker-Ehrenbrink and Miller (2004). By comparison, the ocean areas of the current Geological Map of the World (Bouysse, 2014) are represented by polygons with an average size of 74,700 km$^2$, based on 5215 polygons. The resolution of the 1:1,000,000-scale Lau Basin map is at least an order of magnitude higher than that of the Tectonic Map of the Circum-Pacific Region at 1:17,000,000 scale (Schelben et al., 2013) and 50 times higher than that of the offshore areas depicted in the Geological Map of the World.

Regional Bathymetric Data

Global bathymetric data for the study area were compiled from Shuttle Radar Topography Mission (SRTM) 30+ and SRTM 15+ data sets (Beker et al., 2008; Tozer et al., 2019), the General Bathymetric Chart of the Oceans (GEBCO Bathymetric Compilation Group, 2019), and the Global Multi-Resolution Topography data synthesis (GMRT version 3.6; Ryan et al., 2009). All four data sets use global marine gravity based on satellite altimetry, including the most recent data collected during the CryoSat-2 and Jason-1 missions, which have significantly improved the global gravity model (Sandwell et al., 2014); these data are

Figure 2. Locations of ship tracks where multibeam bathymetry and other geophysical data are available and were used in the creation of the 1:1,000,000-scale geological map. The total area covered by the ship-based multibeam is estimated to be ~650,000 km$^2$, based on 195,000 line km of ship tracks. Selected multibeam data sets were reprocessed with 35 m to 50 m grid spacing (listed in Item S1 [text footnote 1]). Primary data sets were obtained from publicly available national repositories, cruise reports, and chief scientists of the respective expeditions. Background is the slope-shaded GEBCO 2019 grid (GEBCO Bathymetric Compilation Group, 2019).
calibrated with depth soundings to predict the bathymetry of the global seafloor at 30 arc-second and 15 arc-second resolution (SRTM 30+ and 15+, respectively). The GEBCO 2019 grid uses SRTM 15+ as a base. The GMRT grid (version 3.6) also incorporates ship-based multibeam data processed and gridded at 100 m resolution. In areas with no ship-based multibeam coverage, GMRT uses the GEBCO 2014 compilation with 30 arc-second resolution. Version 3.7 of the GMRT grid was released in October 2019, after completion of our map, but there are no significant changes in the newer version in the Lau Basin region.

**Ship-Based Multibeam and Acoustic Backscatter Data**

Ship-based multibeam echo-sounder (MBES) data were also compiled from cruise data and public repositories (Fig. 2). Where available, raw data received as a point cloud were edited using Quality Positioning Services Fiedermaus or Qimera software to generate bathymetric grids. Approximately 195,000 line km of multibeam data, with an average swath of 4 km, have been compiled for the Lau Basin, including data not currently available in GMRT. In selected areas used for training at 1:100,000–1:200,000 scale, we reprocessed the data at 35 m to 50 m resolution. For the 1:1,000,000-scale map, the multibeam data were gridded at 100 m and integrated with GMRT version 3.6 to create the final bathymetric base. Data enhancements in ArcGIS, designed to capture the complex structure of the seafloor, were applied. These included the slope raster, implemented with the *Slope* tool, and the shaded-relief raster, implemented with the *Hillshade* function.

We incorporated GLORIA and SeaMARC II side-scan sonar data in the ArcGIS base layers where available to identify hard rock substrate or sediment cover. We used the compilation of GLORIA data from Zellmer and Taylor (2001) and combined it with higher-resolution backscatter data from MBES systems where they were recorded.
Satellite-Derived Gravity Gradient

The vertical gravity gradient (VGG) and gravity anomalies derived from the CryoSat-2 and Jason-1 satellite missions were used to investigate large-scale structures with an average pixel size >5 km². Seamounts between 1 and 2 km in height that were not visible in the older data sets are now visible in the CryoSat-2 and Jason-1 data, and buried structures (e.g., abyssal fabric with wavelengths of 2–12 km) can also be seen (Sandwell et al., 2014; MacLeod et al., 2017). The microplate boundaries typically appear as gravity lows, whereas volcanoes, seamounts, or other regions of focused crustal accretion typically appear as gravity highs. Mapping of these features based on VGG was greatly enhanced by merging the gravity gradient with bathymetric data, which was done using the GEBCO 2014 grid.

Magnetic Anomalies

Two types of magnetic data were used to guide the mapping: the 2–arc-minute–resolution Earth Magnetic Anomaly Grid (EMAG2: Maus et al., 2009) and the two-dimensional (2-D) magnetic inversions produced by Zellmer and Taylor (2001) and Sleeper and Martinez (2016). EMAG2 incorporates satellite, airborne, and marine magnetic measurements, compiled at a global scale. It was used to assist mapping of basin-scale structures; combined with VGG, the magnetic anomalies identify several of the assemblage boundaries in areas where multibeam or other data were limited. The 2-D magnetic inversions of Zellmer and Taylor (2001) and Sleeper and Martinez (2016) combine ship-based magnetic data with regional aeromagnetic data from the U.S. National Geophysical Data Center. The inversions identify regions of normal or reversed magnetic polarity (positive and negative magnetic anomalies) that can be correlated with spreading fabric. The compilation by Zellmer and Taylor (2001) covers most of the map area, whereas the study of Sleeper and Martinez (2016) is focused on the CLSC and FRSC. Both studies attempted to correlate anomalies with magnetic polarity chronos, which provided a means of assigning relative ages to formations, especially south of ~18°S.

Multichannel Seismic Reflection and Seismicity

Seismic reflection data were collected in the western half of the Lau Basin as part of the site survey data for ODP Leg 135 (Parson et al., 1994), and several attempts were made to image the magma chamber of the Valu Fa Ridge and ELSC (Collier and Sinha, 1992; Turner et al., 1999; Jacobs et al., 2007). Zhao et al. (1997) and Dunn et al. (2013) conducted active-source seismic tomography experiments on the ELSC, revealing persistent seismic low-velocity volumes beneath all segments. Prior to 2019, only two refraction lines crossed the arc-to-backarc transition. The first, completed in 1994, deployed 30 ocean-bottom seismometers (OBSs) in an 840 km line across the Tonga Ridge –220 km south of the FRSC (Crawford et al., 2003). The second, completed in 2008, deployed 40 OBSs in a 327 km line across the Tonga Ridge and Tonga Trench, ~100 km north of the intersection with the Louisville Ridge (Grevemeyer and Flüh, 2008; Contreras-Reyes et al., 2011). Six additional multichannel seismic lines, three with OBSs, were conducted during cruise SO267 in 2019 in the northern Lau Basin, highlighting the structure of the FRSC and the adjacent backarc basin as far west as the LETZ (Hannington et al., 2019; Schmid et al., 2020). Preliminary data from these surveys, together with Parasound (parametric sediment echosounder) data, identify a number of the backarc domains in our map, which are described below.

Global seismicity data (e.g., centroid moment tensors, CMTs) have also been used to identify major faults and their relative motions and to refine geological boundaries in the map area (Parson et al., 1990; Wezel et al., 1993; Conder and Wiens, 2011; Sleeper and Martinez, 2014). Baxter et al. (2020) compared the CMTs of nearly 700 shallow (<30 km), Mw >5 seismic events to the seafloor lineaments mapped in this study, helping to identify the active deformation zones.

Geological Sampling and Seafloor Observations

Volcanic sampling has been carried out during 42 different cruises, using dredges, TV grabs, ROVs, and crewed submersibles. The focus of sampling has been on the active spreading centers, including more than 1100 samples from the Valu Fa Ridge, ELSC, CLSC, FRSC, MTJ, NELSC, NWLSC, and FSC (Item S4 [footnote 1]). More than 700 additional samples have also been collected from the arc front and in off-axis and intraplate areas, including via extensive dredging away from the spreading ridges in the Niuafou’ou microplate during cruise SO267 in 2019 (Hannington et al., 2019). In 1973, at Site 203 of the Deep Sea Drilling Project (DSDP), one hole was drilled in the western Lau Basin area (Burns et al., 1973), and in 1990–1991, during Leg 135 of the Ocean Drilling Program (ODP), 18 holes were drilled at eight sites across the Lau Basin and Tonga Ridge (Parson et al., 1992a). Locations where direct seafloor observations and sampling have been recorded and used in this study are summarized in Figure 3 and listed in Item S4 (footnote 1).

GEOLOGICAL MAP OF THE LAU BASIN

To develop the geological legend for the Lau Basin map (Table 1), we used the standard lithostratigraphic classification scheme of the International Commission on Stratigraphy (Salvador, 1994; Murphy and Salvador, 1999). Geological units were first identified as formation types and then grouped into assemblages in increasing stratigraphic rank. The approach provides the basis for a comprehensive legend and correlation of units across the entire basin, although the names used are not formally accepted units. The assemblages were assigned to a newly defined province and subprovince: the Northwest
**TABLE 1. DESCRIPTION OF FORMATION TYPES IN THE LAU BASIN, WITH HEADERS INDICATING ASSEMBLAGE TYPES**

| CARBONATE PLATFORM |
|---------------------|
| **Cp** Carbonate platform |
| Carbonate rocks (reef complexes) built on active and extinct volcanoes and exposed arc basement |

| ACTIVE ARC |
|-----------|
| **Upper** |
| Arc-front volcano |
| Volcanic edifice at the arc front (typically active) |
| Inner-arc volcano |
| Volcanic edifice behind the arc front (may be active or inactive) |
| **Upper arc crust** |
| Undivided crust belonging to the active arc, including volcaniclastic material, flows, and dikes |
| **Lower** |
| Lower arc crust |
| Earliest exposed extrusive and intrusive rocks of the active arc (may include arc basement) |

| BACKARC VOLCANOES |
|-------------------|
| **Bav1** Conical volcano |
| Cone-shaped edifice composed of lava flows and volcaniclastic material erupted onto backarc crust, commonly with a summit crater or caldera and/or cut by dike complexes (>1 km diameter; width:height <5) |
| **Bav2** Shield volcano |
| Mound-shaped edifice composed of lava flows extruded onto backarc crust, commonly with a central caldera (>1 km diameter; width:height >5) |
| **Bav3** Dome volcano |
| Dome-shaped edifice composed of lava flows extruded onto backarc crust or onto an axial volcanic ridge (>1 km diameter; length:width ~1) |
| **Bav4** Fissure volcano |
| Elongate volcanic edifice composed mostly of lava flows extruded onto backarc crust, commonly with a central dike (>1 km length; length:width >3) |
| **Bavf** Volcanic field |
| A broad area of lava flows and volcaniclastic material surrounding a number of closely spaced volcanoes |

| BACKARC RIFTS AND SPREADING CENTERS |
|-------------------------------------|
| **Upper** |
| Axial backarc volcanic ridge |
| Volcanic ridge marking the active spreading center, commonly with discrete volcanic edifices (cones and domes), dike complexes, or calderas |
| **Middle** |
| Proximal volcanic or tectonic ridge |
| Elongate volcanic edifice or coalesced ridges in the outer rift valley or on the flank, adjacent to an active spreading center or axial volcanic ridge |
| **Lower** |
| Distal volcanic ridge |
| Elongate volcanic edifice or coalesced ridges on distal backarc crust (may include products of off-axis volcanism or earlier seafloor spreading from a distant ridge; commonly obscured by volcaniclastic cover) |
| **Relict backarc crust** |
| Undivided backarc crust beyond the outer rift valley and flank of an active spreading center (may include products of off-axis volcanism) |
| **Outer backarc crust** |
| Outermost backarc crust distal to an active spreading center |

| RELICT BACKARC |
|----------------|
| **Upper** |
| Relict ridge |
| Elongate volcanic edifice or coalesced ridges outside an identifiable area of active spreading (may be a product of intraplate volcanism, rifting of earlier backarc crust, or an unknown spreading center) |
| **Upper relict backarc crust** |
| Undivided backarc crust outside an identifiable area of active spreading (may be a product of intraplate volcanism, rifting of earlier backarc crust, or an unknown spreading center) |
| **Tectonized relict backarc crust** |
| Intensely deformed backarc crust outside an identifiable area of active spreading |
| **Lower** |
| Lower relict backarc crust |
| Earliest exposed extrusive and intrusive rocks in the backarc and outside an identifiable area of active spreading |

| ARC-BACKARC TRANSITION |
|-------------------------|
| **Upper** |
| Ridge at the arc-backarc transition |
| Elongate volcanic or tectonic ridge between an active or relict arc and a backarc basin (may be a product of rift volcanism or block faulting) |
| **Upper transitional arc-backarc crust** |
| Crust immediately surrounding volcanic or tectonic ridges at the arc-backarc transition (may include both arc and backarc crust) |
| **Lower** |
| Lower transitional arc-backarc crust |
| Undivided crust at the arc-backarc transition (may include both arc and backarc crust) |

(Continued)
### TABLE 1. DESCRIPTION OF FORMATION TYPES IN THE LAU BASIN, WITH HEADERS INDICATING ASSEMBLAGE TYPES (Continued)

#### RELICT ARC

| Layer  | Description                                                                 |
|--------|-----------------------------------------------------------------------------|
| Upper  | Cross-arc volcano Part of a volcanic chain crossing all or part of a relict arc |
| uRac   | Arc (or forearc) crust, including relict arc volcanoes, belonging to the latest episode of arc construction prior to or during backarc basin opening |
| Middle | Middle relict-arc crust Crust surrounding relict arc volcanic edifices and belonging to a stage of arc construction prior to backarc basin opening (comprises volcaniclastic rocks and flows associated with early arc magmatism) |
| Lower  | Lower relict-arc crust Earliest exposed extrusive and intrusive rocks in the relict arc (commonly obscured by volcaniclastic cover) |

#### FOREARC

| Symbol | Description                                                                 |
|--------|-----------------------------------------------------------------------------|
| Fv     | Forearc volcano Volcanic edifice composed of lava flows and volcaniclastic material erupted onto extended forearc crust |
| Fm     | Forearc mound Non-volcanic feature of the forearc crust that may include serpentinite mounds, mud volcanoes, or locally uplifted blocks |
| Fc1    | Undivided crust of the forearc, including sediment of the forearc slope |
| Fc2    | Tectonized forearc crust block Block of forearc crust affected by intense deformation |
| Fc3    | Forearc crust of the inner trench wall Crust at the leading edge of the forearc that is typically heavily tectonized and may include accretionary material |
| Fc4    | Extended forearc crust Forearc crust affected by extension and locally associated with rift volcanism |

#### OTHER ARC-BACKARC FORMATIONS

| Symbol | Description                                                                 |
|--------|-----------------------------------------------------------------------------|
| Us     | Seamount Volcanic or tectonic edifice of undetermined origin |
| Ur     | Ridge Elongate volcanic or tectonic feature of undetermined origin |
| Dz1    | Leaky transform zone Lava flows and deformed crust associated with a leaky (extensional) transform fault |
| Dz2    | Deformation zone High-strain zone commonly associated with transcurrent faults (likely of crustal scale) |
| Uc     | Unassigned crust Crust that is distinguishable from adjacent formations in terms of age (e.g., sediment cover) or texture but cannot be assigned to a particular origin |
| Ucr    | Unassigned crust with ridges Crust that cannot be assigned to a particular origin but with a distinct fabric comprising elongate volcanic or tectonic ridges |

#### OCEANIC FORMATIONS

| Symbol | Description                                                                 |
|--------|-----------------------------------------------------------------------------|
| uOs1   | Hot-spot volcano Intraplate volcano associated with a known hot spot |
| uOs2   | Intrplate volcano Intraplate volcano with no identifiable associated hot spot |
| uOs3   | Intrplate seamount Intraplate volcanic or tectonic edifice of undetermined origin |
| uOp    | Oceanic plateau Flat-topped, upper portion of intraplate volcanic edifice built on older oceanic crust |
| lOp1   | Hot-spot volcanic plateau rise Exposed lower portion of an oceanic plateau surrounding a known hot spot |
| lOp2   | Volcanic plateau rise Exposed lower portion of an oceanic plateau with no identifiable associated hot spot |
| lOc1   | Undivided oceanic crust Crust formed at a mid-ocean ridge |
| lOc2   | Oceanic crust of the outer trench slope Tectonized oceanic crust exposed in the outer trench wall |

#### SYMBOLS

- Caldera rim
- Lineament
- Major fault zone
- Spreading center
Indo-Australian Margin province and the Lau-Tonga Arc-Backarc (LTAB) subprovince (Fig. 4; Table 2). A province is defined as a tectonically bounded region with a protracted, multistage history that is distinct from adjacent regions in terms of its age, internal makeup, structure, and metamorphism. A subprovince is a discrete region therein with distinct lithological, stratigraphic, and structural characteristics belonging to a single tectonic system. Province boundaries are commonly major orogens, whereas subprovinces may be bounded only by large crustal-scale structures. A challenge in applying province and subprovince boundaries in the same manner as in ancient terranes is that the latter are already accreted into readily circumscribed regions bounded by major orogens and translithospheric structures, whereas the modern oceanic and continental margins are still accreting. Twenty-four (24) of the assemblages identified in Table 2 and Figure 5 are assigned to the LTAB. The number of mapped formations in the LTAB is comparable to the number of lithostratigraphic units.

### TABLE 2. ORGANIZATIONAL CHART OF MAPPED UNITS IN THE LAU BASIN ACCORDING TO STRATIGRAPHIC SUBDIVISIONS

| Province/subprovince | Assemblage type | Assemblage name(s) | Group | Formations |
|----------------------|----------------|-------------------|-------|------------|
| Active arc           | Tofua Arc      | —                 | Upper, lower | Arc-front volcano, inner-arc volcano, arc crust |
| Backarc volcanoes    | Niuato’ou, SE Futuna | — | Upper, lower | Conical volcano, shield volcano, dome volcano, fissure volcano, volcanic field |
| Backarc rifts and spreading centers | Central Lau Basin, Cikobia, East Lau Basin, Fonualeti, Futuna, Mangatolu, NE Lau Basin, NW Lau Basin, Rochambeau | Upper, middle, lower | Volcanic ridge (axial, proximal, distal), backarc crust (axial, proximal, distal, outer), backarc rift flank |
| Relict backarc       | North Fonualeti, North Futuna, Qeleleleu, South Futuna, Zephyr | Upper, lower | Relict ridge, relict backarc crust, tectonized relict backarc crust |
| Arc-backarc transition | West Lau Basin | Upper, lower | Ridge at the arc-backarc transition, transitional arc-backarc crust |
| Relict arc           | Lau Ridge, Tonga Ridge | Upper, middle, lower | Cross-arc volcano, relict-arc crust |
| Forearc              | North Lau Forearc, Tonga Forearc | — | Forearc volcano, forearc mound, forearc crust, tectonized forearc crustal block, forearc crust of the inner trench wall, extended forearc crust |
| Other arc-backarc formations | Peggy Ridge, South Vitiaz | — | Leaky transform zone, deformation zone, seamount, ridge, unassigned crust, unassigned crust with ridges |

Note: Em dash indicates assemblages for which the Group level subdivision is not applicable.
The mapped formations also take into account available geophysical and geochemical data (sampling, ocean drilling, seismic surveys, and seabed observations). Colors assigned to the assemblages are for illustration purposes only and approximate those in the lithostratigraphic correlation diagram of the Lau Basin (Fig. 8). See text for assemblage descriptions.

The assemblages of the LTAB subprovince include nine different types (Table 2), each consisting of one or more geological formations that are grouped in terms of their origin, lithology, inferred age, and tectonic and structural regime. They are defined by inspection of marine geophysical data (hydroacoustics, magnetics, gravity) integrated with the results of structural mapping, tectonic and structural regime. They are defined by inspection of marine geophysical data (sampling, ocean drilling, seismic surveys, and seabed observations). Colors assigned to the assemblages are for illustration purposes only and approximate those in the lithostratigraphic correlation diagram of the Lau Basin (Fig. 8). See text for assemblage descriptions. M—Mangatolu; Niua.—Niuafo’ou.
This classification facilitates correlation of units over larger areas of the basin, including formations that have been widely separated by seafloor spreading or other tectonic processes. Boundaries of the formations are drawn where a clear distinction from an adjacent formation can be made (e.g., between a ridge and volcanic flow field) and are interpolated between formations where a clear bathymetric or geophysical change is not observed. Unless they are defined by faults or clearly separated by an unconformity, the contacts between formations are interpreted to be conformable. The formations listed in Table 1 are the basis for the geological map shown in Figure 6, which was produced at 1:1,000,000 scale and has been scaled down for publication. This figure is reproduced as a full-map sheet with marginal notes in the Supplemental Material to this paper (Item S1 [footnote 1]).

Where high-resolution ship-based multibeam and/or acoustic backscatter data are available, formations may be further subdivided into members. These include, for example, individual flow sequences, talus fields (e.g., breccia deposits), or sedimentary units that are mappable at 1:100,000–1:200,000 scale. Member-level mapping has been done in the training areas, such as in the NELSC and the MTJ (e.g., McClinton et al., 2013; Anderson et al., 2016, 2017; Mensing, 2019; see Item S2 [footnote 1]), and was an important step in defining the formations in the 1:1,000,000-scale map. However, individual members are typically not mappable at the 1:1,000,000 scale, and so are not included in Table 1 or Figure 6. The smallest formal lithostratigraphic units (e.g., beds or individual flows) can only be mapped in small areas with direct seafloor observations from crewed submersibles, ROVs, or AUVs (e.g., Embley and Rubin, 2018).

**Mapped Formations**

By comparing the mapped formations in well-studied training areas to similar features in areas where they have not been sampled or directly observed, we have been able to make informed interpretations about formation types in most parts of the map. Sediments have not been mapped, except for carbonate platforms, in order to emphasize the bedrock geology. In general, sediments having a thickness of <500 m (equivalent to ~5% of the width of the smallest polygons, excluding individual volcanoes, at 1:1,000,000 scale) have been ignored. In general, the pelagic sediment thickness is much less than 500 m. In the most heavily sedimented portions of the western Lau Basin (e.g., at ODP Sites 834 and 835), the depth to basement is only 160 m (Parson et al., 1994). In areas where significant volcaniclastic material has been identified (e.g., on or adjacent to the active arc), these units are grouped with the associated coherent volcanic rocks.

More than 3000 discrete volcanoes are mapped at the 1:1,000,000 scale in the Lau Basin (Table 3). The volcano types are: (1) active arc volcanoes (Av in unit abbreviations); (2) backarc volcanoes (Bav); (3) relict arc volcanoes (Rav); (4) forearc volcanoes (Fv); and (5) oceanic volcanoes (Os). Only volcanoes >1 km in diameter were included in the 1:1,000,000-scale compilation (drawn at the steepest inflection point nearest the base of slope). Where flows and volcaniclastic rocks are identified beyond the base of the slope, these features are mapped as a separate formation (e.g., backarc volcanic field, unit Bavf). Volcanic fields typically occur only around the largest volcanoes (>10 km diameter) or clusters of more than five smaller volcanoes. Several different volcano morphologies are distinguished. Backarc volcanoes, in particular, are classified as cone (unit Bav1), shield (Bav2), dome (Bav3), or fissure volcanoes (Bav4; Table 1). Cones are steep sided, have a width-to-height ratio ≤5, and commonly have a summit crater or caldera; many are bisected by a rift or dike complex. Shield volcanoes have gentle slopes and a width-to-height ratio >5. They also commonly have a central caldera. Dome volcanoes are typically smaller than shield and conical volcanoes and have an aspect ratio of ~1. Fissure volcanoes are elongate edifices with length-to-width ratios >3. The arc volcanoes are classified according to their position relative to the volcanic front: along the active volcanic front (arc-front volcanoes, unit uAv1) or behind the volcanic front (inner-arc volcanoes, uAv2). Forearc volcanoes (unit Fv) and relict-arc volcanoes (uRav) include any volcanoes on forearc or relict-arc crust, respectively. The relict-arc volcanoes commonly occur as cross-arc volcanic chains. A number of volcanic or tectonic edifices are of undetermined origin and have been mapped as seamounts or “mounds”. These generic terms apply to isolated topographic features taller than 100 m that may be either volcanic or tectonic in origin (e.g., Staudigel et al., 2010; Buchs et al., 2016). They include forearc mounds (unit Fm), backarc seamounts (Us), hot spot volcanoes (uOs1), intraplate seamounts (uOs2), and intraplate seamounts (uOs3) identified according to their location with no particular genetic implications. Forearc mounds may include serpentinite mounds, mud volcanoes, or local uplifted blocks.

Below is a description of the different types of crust mapped as individual formations. Quantitative data on the different formation types and individual formations are summarized in Tables 4 and 5.

Arc crust is subdivided into upper and lower formations based on the inferred level of exposure (stratigraphic position). Upper arc crust (unit uAc) includes all flows, volcaniclastic rocks, and intrusions (exposed dike rocks) related to volcanism of the currently active arc. Lower arc crust (unit lAc) is the volcanic-dominated substrate upon which the active arc is built and mainly includes older arc crust formed at the same location. Lower arc crust is typically exposed only by crustal-scale faults in areas of arc rifting.

Backarc crust formations are classified according to their location relative to an active spreading center. Axial backarc crust (unit uBac) is located within the neovolcanic zone and typically forms the floor of an inner rift valley. Proximal backarc crust, designated “middle” (unit mBac), is located outside the neovolcanic zone but typically occupies a broader outer rift valley (Fig. 7). Backarc crust on the flank of the outer rift valley (unit mBaf) is broadly stratigraphically equivalent to middle backarc crust (mBac) but is located outside the rift. Distal backarc crust (units IBac1 and IBac2) is located outside the rift valley and generally beyond the rift flank. Where a rift valley is not clearly defined but a ridge morphology is still present, the backarc flanking crust (unit mBaf) or lower backarc crust (IBac) may occur adjacent to the axial spreading ridge.
Figure 6. Reduced version of the 1:1,000,000-scale geological map of the Lau Basin at the formation level. The corresponding legend is in Table 1. The complete map sheet with marginal notes is provided at the original scale in Item S1 of the Supplemental Material (text footnote 1). CLSC—Central Lau Spreading Center; ELSC—Eastern Lau Spreading Center; FRSC—Fonualei Rift and Spreading Center; FD—Fonualei Discontinuity; FSC—Futuna Spreading Center; FTF—Futuna Transform Fault; ILSC—Intermediate Lau Spreading Center; LETZ—Lau Extensional Transform Zone; MTJ—Mangatolu Triple Junction; NCSC—North Cikobia Spreading Center; NELSC—Northeast Lau Spreading Center; NL—Niutoputapu Lineament; NWLSC—Northwest Lau Spreading Center; OF—Gelelevu fault; RB—Rochambeau Bank; RR—Rochambeau Rifts; SEFVZ—Southeast Futuna Volcanic Zone; VFR—Valu Fa Ridge; WCVZ—West Cikobia Volcanic Zone.
Importantly, the proximal (units mBac and mBaf) and distal (lBac) backarc crust are not always present on both sides of the axial valley, indicative of asymmetric spreading (e.g., Fig. 7). The lower backarc crust is commonly obscured by volcaniclastic and/or sedimentary cover but can be further divided (units IBac1 and IBac2) on the basis of magnetic anomalies, major structural boundaries, degree of sedimentation, or obvious changes in crustal thickness established from published seismic sections or gravity anomalies. Relict backarc crust includes all crust that is interpreted to have formed at a backarc spreading ridge but is now located outside an identifiable region of active spreading. This crust is divided into upper (unit uRbc1) and lower (lRbc) formations where younger crust is clearly built on top of preexisting crust (e.g., where rifting fault blocks that have exposed older volcanic crust). Axial volcanic ridges that are associated with active spreading centers (cf. Yeo, 2016) are designated “active” backarc crust. Other ridges are simply tilted by backarc spreading, but different ridge formations are recognized in different settings. Ridges that are clearly volcanic in origin have centrally located eruptive fissures or volcanic cones. They may be related to dikes intruded into backarc crust during spreading, or they are products of off-axis volcanism associated with rifting of older backarc crust. Other ridges are simply tilted fault blocks that have exposed older volcanic crust. Axial volcanic ridges that are associated with active spreading centers (cf. Yeo, 2016) are designated “uplift” backarc ridges (unit uBar). They are elongated parallel to the spreading axis and typically occupy the center of the neovolcanic zone or inner rift valley. Proximal ridges, designated “middle” (unit mBar), are located outside the neovolcanic zone but within the outer rift valley (Fig. 7). Distal ridges, designated “lower” (unit lBar), are located beyond the rift valley on older backarc crust that was formed during an earlier episode of seafloor spreading or by off-axis volcanism. Relict ridges (uRr) occur outside identifiable areas of active spreading and may be products of intraplate volcanism, rifting of earlier backarc crust, or distal ridges related to an unknown spreading center. Other elongate volcanic or tectonic features that cannot be assigned to an identifiable spreading center or lack other data to confirm their origin are simply “undivided” ridges (unit Ur).

Transitional arc-backarc crust is the oldest crust in the basin, having formed where early arc rifting and basin opening was initiated. It is divided into upper (unit uTc) and lower (lTc) formations based on magnetic anomalies, degree of sedimentation, or obvious changes in crustal thickness, as for the backarc crust. The lower transitional crust surrounds obvious volcanic or tectonic ridges in heavily sedimented areas and includes the inferred basement in failed backarc sub-basins. The ridges may be volcanic, formed during the early opening of the basin, or fault blocks of old arc or backarc crust. In areas with limited ship-based bathymetry or other data, features of this type for which an origin is unknown are labeled “unassigned” (units Uc and Ucr; e.g., north and west of the FSC). Arc crust formed prior to backarc basin opening is designated relict arc crust, including any eroded early-arc volcanoes (e.g., on Lau Ridge and east of the currently active Tofoa arc). Relict arc crust is divided into upper (uRac), middle (mRac), and lower (lRac) formations based on level of exposure and contact.

### TABLE 3. SUMMARY STATISTICS OF VOLCANO TYPES, DISTRIBUTIONS, SURFACE AREAS, AND VOLUMES

| Formation                  | Legend abbreviation | Total area (km²) | Total volume (km³) | No. of polygons | Area/polygon (km²) | Volume/polygon (km³) |
|----------------------------|---------------------|------------------|-------------------|----------------|--------------------|---------------------|
| Forearc                    |                     |                  |                   |                |                    |                     |
| Forearc mound              | Fm                  | 3020             | 3508              | 4              | 378                | 439                 |
| Forearc volcano            | Fv                  | 93               | 66                | 10             | 9                  | 7                   |
| Active arc                 |                      | 12,143           | 7112              | 124            | 98                 | 57                  |
| Arc-front volcano          | uAv1                | 11,350           | 6781              | 109            | 104                | 62                  |
| Inner-arc volcano          | uAv2                | 793              | 331               | 15             | 53                 | 22                  |
| Backarc volcanoes          |                     | 13,987           | 4659              | 3018           | 5                  | 2                   |
| Backarc conical volcano    | Bav1                | 8200             | 2922              | 1343           | 6                  | 2                   |
| Backarc shield volcano     | Bav2                | 1508             | 781               | 7              | 215                | 112                 |
| Backarc dome volcano       | Bav3                | 2770             | 557               | 1408           | 2                  | 0.4                 |
| Backarc fissure ridge      | Bav4                | 1509             | 399               | 260            | 6                  | 2                   |
| Relict arc                 | Cross-arc volcano   | 3655             | 4332              | 27             | 135                | 160                 |
| Intraplate volcano         | uRav                | 3655             | 4332              | 27             | 135                | 160                 |
| Oceanic crust              |                     | 620              | 214               | 42             | 15                 | 5                   |
| Average                    |                     | 33,518           | 19,891            | 3229           | 10                 | 6                   |

Note: Bold indicates the tectonic setting in which the volcanoes are located.
**TABLE 4. SUMMARY STATISTICS AND QUANTITATIVE ANALYSIS OF MAPPED FORMATIONS IN THE LAU BASIN**

| Formation                        | Legend abbreviation | Area (km²) | Proportion of total area (%) | Proportion of total backarc area (501,877 km²) (%) | No. of polygons | Area/polygon (km²) |
|----------------------------------|---------------------|------------|------------------------------|-----------------------------------------------|----------------|---------------------|
| Upper arc crust*                 | uAc                 | 72,260     | 6.6                          | N/A*                                          | 1              | 72,260              |
| Lower arc crust*                 | lAc                 | 150        | 0.0                          | N/A*                                          | 1              | 150                 |
| Volcanic field                   | Bavf                | 5,739.0    | 5.2                          | 11.4%                                         | 18             | 318.8              |
| Axial backarc volcanic ridge     | uBar                | 10,696     | 1.0                          | 2.1%                                          | 33             | 324                |
| Axial backarc crust              | uBac                | 6,788      | 0.6                          | 1.4%                                          | 15             | 453                |
| Proximal backarc crust           | mBar                | 13,473     | 1.2                          | 2.7%                                          | 320            | 42                 |
| Proximal volcanic or tectonic ridge | mBac           | 11,682     | 1.1                          | 2.3%                                          | 11             | 1,063              |
| Backarc rift flank               | mBaf                | 21,400     | 2.0                          | 4.3%                                          | 12             | 1,783              |
| Distal volcanic ridge            | iBar                | 26,191     | 2.4                          | 5.2%                                          | 242            | 108                |
| Distal backarc crust             | iBac1               | 73,751     | 6.7                          | 14.7%                                         | 41             | 1,799              |
| Outer backarc crust              | iBac2               | 10,509     | 1.0                          | 2.1%                                          | 2              | 5,255              |
| Relict ridge                     | uRt                 | 3,387      | 0.3                          | 0.7%                                          | 25             | 135                |
| Upper relict backarc crust       | uRbc1               | 15,859     | 1.4                          | 3.2%                                          | 2              | 7,930              |
| Tectonized relict backarc crust  | uRbc2               | 7,072      | 0.6                          | 1.4%                                          | 33             | 214                |
| Lower relict backarc crust       | iRbc                | 41,990     | 3.8                          | 8.4%                                          | 14             | 2,999              |
| Ridge at the arc-backarc transition | uTr               | 17,882     | 1.6                          | 3.6%                                          | 73             | 245                |
| Upper transitional arc-backarc crust | iTc              | 11,039     | 1.0                          | 2.2%                                          | 3              | 3,680              |
| Lower transitional arc-backarc crust | iTc              | 70,559     | 6.4                          | 14.1%                                         | 9              | 7,840              |
| Upper relict-arc crust*          | uRac                | 123,510    | 11.3                         | N/A*                                          | 121            | 1,021              |
| Middle relict-arc crust*         | mRac                | 94,841     | 8.7                          | N/A*                                          | 8              | 11,855             |
| Lower relict-arc crust*          | iRac                | 203,789    | 18.6                         | N/A*                                          | 4              | 50,947             |
| Forearc crust*                   | fC1                 | 68,499     | 6.3                          | N/A*                                          | 2              | 34,250             |
| Tectonized forearc crustal block* | fC2              | 5320       | 0.5                          | N/A*                                          | 8              | 665                |
| Forearc crust of the inner trench wall* | fC3         | 25,291     | 2.3                          | N/A*                                          | 1              | 25,291             |
| Extended forearc crust*          | fC4                 | 1277       | 0.1                          | N/A*                                          | 2              | 638                |
| Seamount (undetermined origin)   | Us                  | 23,334     | 2.1                          | 4.7%                                          | 376            | 7,634              |
| Leaky transform zone             | Dz1                 | 6,341      | 0.6                          | 1.3%                                          | 1              | 6,341              |
| Deformation zone                 | Dz2                 | 2,423      | 0.2                          | 0.5%                                          | 11             | 220                |
| Unassigned crust with ridges     | Ucr                 | 37,444     | 3.4                          | 7.5%                                          | 4              | 9,361              |
| Unassigned crust                 | Uc                  | 30,879     | 2.8                          | 6.2%                                          | 4              | 7720               |
| **Totals**                       |                     | **1,095,036** | **1080**                  | **N/A**                                        | **1080**       | **N/A**            |

*Not included in backarc area calculations.*

**TABLE 5. SUMMARY STATISTICS AND QUANTITATIVE ANALYSIS OF FORMATION TYPES**

| Formation type                        | Total area (km²) | Proportion of total area (%) | No. of polygons | Area/polygon (km²) |
|--------------------------------------|------------------|-------------------------------|-----------------|---------------------|
| Ridges                               | 71,629           | 6.5                           | 693             | 103                 |
| Crust                                | 930,899          | 85.0                          | 295             | 3,156               |
| Arc crust                             | 494,549          | 45.2                          | 135             | 3,663               |
| Forearc crust                         | 97,367           | 8.9                           | 13              | 7,490               |
| Backarc crust                         | 338,983          | 31.0                          | 147             | 2,306               |
| Deformation zones                    | 8764             | 0.8                           | 12              | 730                 |
| Seamounts and mounds                 | 26,354           | 2.4                           | 70              | 376                 |
| Volcanic fields                      | 57,390           | 5.2                           | 18              | 3,188               |
| Volcanoes*                           | 33,517           | N/A*                          | 3229            | 10                  |
| Carbonate platforms*                 | 72,250           | N/A*                          | 197             | 367                 |

*Not included in total area calculations.*
relationships, similar to the crust of the active arc. Large areas between the trench and the active arc are designated forearc crust, including crust of the forearc slope (unit Fc1), tectonized forearc crustal blocks (Fc2), crust exposed on the inner trench wall (Fc3), and extended crust associated with active rifting of the forearc (Fc4). The crust exposed on the inner trench wall and the large uplifted blocks on the upper slope may include part of the arc basement (e.g., Meffre et al., 2012).

Several major deformation zones are mapped in the backarc, as in previous studies (e.g., Pelletier and Auzende, 1996; Pelletier et al., 2001). Although they are mainly structural elements of the map, they are identified here and in the legend as geological formations. In some cases, they include lava flows, for example, erupted from the leaky transform fault (unit Dz1) at the Peggy Ridge. Elsewhere, they are simply high-strain zones along one or more large-scale transcurrent faults (unit Dz2).

Oceanic formations include the Pacific plate, Samoan Plateau, and Melanesian Borderland, which comprise Cretaceous and younger oceanic crust formed at mid-ocean ridges and oceanic hot spots. A number of different types of volcanoes are mapped on this crust, including volcanoes that are associated with a hot spot (unit uOs1), intraplate volcanoes that are not clearly associated with a plume source (uOs2), and flat-topped, steep-sided volcanic edifices built on an oceanic plateau (uOp) and surrounded by a plateau rise (lOp2).

Carbonate formations of the Lau, Tonga, and Fiji platforms (unit Cp) are built on active and extinct volcanoes and exposed arc basement. A depth contour of 125 m, which is within the photic zone and encompasses all reefs in the Reefs at Risk database of the World Resources Institute (2011), was used to map the platforms.

**Mapped Structures**

Several major deformation zones are recognized in the north of the Lau Basin: the North Fiji fracture zone in the west, the Futuna transform fault between the FSC and RR, and the Peggy Ridge fault in the central Lau Basin. These structures are interpreted to be translithospheric and have accommodated much of the opening of the basin (Eguchi, 1984; Hamburger and Isacks, 1988; Clarke et al., 1993; Parson and Tiffin, 1993; Pelletier and Auzende, 1996; Pelletier et al., 2001). Several are marked by plate-boundary or intraplate volcanism that comprises discrete formation types (units Dz1 and Dz2) and, in one case (Peggy Ridge), an assemblage. Other structures mappable at the 1:1,000,000 scale include large numbers of lineaments that are distinct from volcanic ridges. Baxter et al. (2020) mapped 1100 major faults in the map area, defined as having individual strike lengths of >25 km and throws of >250 m, with a cumulative strike length of 19,160 km. It is reasonable to expect that many of the longest structures are also transcrustal, given that the depths of faults in extensional environments generally scale with their strike length at surface. The full lineament database is not included with the 1:1,000,000-scale map but is available in Baxter et al. (2020).

## LITHOSTRATIGRAPHIC ASSEMBLAGES

The mapped formations have been grouped into ten assemblage types:

1. active arc
2. backarc volcanoes
3. backarc rifts and spreading centers
4. relict backarc
5. arc-backarc transition
6. relict arc
7. forearc
8. other arc-backarc formations
9. oceanic formations
10. carbonate platforms

Each assemblage comprises a group of formations of similar age belonging to a common lithotectonic framework and crustal type. The locations of the assemblages with assigned names are indicated in Figure 5, and they are described in detail below and in Table 6. Quantitative data on the main assemblage types (excluding carbonate platforms) are given in Table 7, and data for the individual assemblages are listed in Table 8.

### Active Arc Assemblage

The Tofua volcanic arc is the only active arc assemblage in the map area, covering 72,295 km² (Fig. 5). The formations grouped in this assemblage comprise all volcanic edifices, volcanioclastic rocks, flows, and dikes associated with the active volcanic front of the subduction zone, including inner arc volcanoes behind the active arc front and any exposed arc basement. The assemblage contacts are depositional and marked by the limit of the volcanioclastic apron of the active arc; to the east is the Tonga Ridge, and to the west, the East Lau Basin assemblage. South of the Fonualei discontinuity, a major structure cutting across the Tofua arc, the boundary between the Tofua arc and Tonga Ridge is sharp and defined by major uplifted portions of the Tonga Ridge. Although volcanism in the Tofua arc began at ca. 3 Ma (Tappin et al., 1994),
The presently active volcanoes are all younger than 1 Ma (e.g., Stoffers et al., 2003; Arculus, 2008). Twenty-eight (28) of the larger stratovolcanoes are indicated in Figure 1, but as many as 100 smaller volcanoes were identified in this study. Most are built from effusive and explosive eruptive products, varying in composition from basaltic andesite to andesite with lesser dacite and rhyolite. Seventy-seven (77) volcanic eruptions have been recorded along the Tofua arc since 1774 CE (Global Volcanism Program, 2013), with the most recent occurring at volcano F (Fig. 1) in August 2019, which produced a large pumice raft (Brandl et al., 2020a; Jutzeler et al., 2020).

Samples from the Tafahi and Niuatoputapu volcanoes (Beier et al., 2017) and the adjacent forearc (Meffre et al., 2012) confirm that the active arc is built on a basement of old arc crust of the Tonga Ridge. Two seismic sections across the active arc indicate that these basement rocks are as much as 20 km thick (Crawford et al., 2003; Contreras-Reyes et al., 2011).

| Assemblage name       | Age                  | Assemblage type                               | Ship-based bathymetry coverage (%) |
|-----------------------|----------------------|-----------------------------------------------|-----------------------------------|
| Central Lau Basin     | 1.5 Ma–present       | Backarc rifts and spreading centers           | 95                                |
| Cikobia               | 5.5 Ma–present       | Backarc rifts and spreading centers           | 11                                |
| East Lau Basin        | 5.5 Ma–present       | Backarc rifts and spreading centers           | 81                                |
| Fonuaili              | 3.8 Ma–present       | Backarc rifts and spreading centers           | 78                                |
| Futuna                | 4.5 Ma–present       | Backarc rifts and spreading centers           | 69                                |
| Lau Ridge             | 46–31 Ma; 28–15 Ma; 14–0.3 Ma | Backarc rifts and spreading centers       | 99                                |
| Mangatolu             | 0.6 Ma–present       | Backarc rifts and spreading centers           | 78                                |
| Niuatofou             | 1 Ma–present         | Backarc volcanoes                             | 78                                |
| North Fonuaile        | 3.8–0.6 Ma           | Relict backarc                                | 68                                |
| North Futuna          | 5.5 Ma–present       | Relict backarc                                | 51                                |
| North Lau Forearc     | 35–28 Ma; 15–9 Ma    | Forearc                                       | 71                                |
| Northeast Lau Basin   | 2.5 Ma–present       | Backarc rifts and spreading centers           | 90                                |
| Northwest Lau Basin   | 1 Ma–present         | Backarc rifts and spreading centers           | 85                                |
| Peggy Ridge           | 5.5 Ma–present       | Backarc rifts and spreading centers           | 84                                |
| Qelelelevu            | 46–31 Ma; 28–15 Ma; 14–2.4 Ma | Relict backarc                                | 61                                |
| Rochambeau            | 0.5 Ma–present       | Backarc rifts and spreading centers           | 98                                |
| South Futuna          | 5.5 Ma–present       | Backarc volcanoes                             | 51                                |
| South Vitiia          | 1 Ma–present         | Other arc-backarc formations                 | 10                                |
| Southeast Futuna      | 1 Ma–present         | Backarc volcanoes                             | 83                                |
| Tofua Arc             | 3 Ma–present         | Active arc                                    | 29                                |
| Tonga Forearc         | 52–48 Ma; 44–35 Ma; 17 to present | Forearc                                 | 41                                |
| Tonga Ridge           | 46–40 Ma; 33–31 Ma; 19–17 Ma; 14–5.5 Ma | Relict arc                                   | 13                                |
| West Lau Basin        | 46–31 Ma; 28–15 Ma; 14–2.4 Ma | Arc-backarc transition                      | 43                                |
| Zephyr                | 5.5–1 Ma             | Relict backarc                                | 51                                |

| Table 7. Summary statistics and quantitative analysis of assemblage types | |
|---------------------------------------------------------------------|---|---|---|---|
| Assemblage type          | No. of assemblages | Area (km²) | Proportion of total area (%) | No. of polygons | Area/polygon (km²) |
|--------------------------|--------------------|------------|-------------------------------|-----------------|-------------------|
| Active arc               | 1                  | 72,295     | 6.60                          | 2               | 36,147            |
| Backarc volcanoes        | 2                  | 11,769     | 1.07                          | 4               | 2942              |
| Backarc rifts and spreading centers | 9 | 216,265   | 19.75                         | 696             | 311               |
| Relict backarc           | 5                  | 82,760     | 7.56                          | 111             | 746               |
| Arc-backarc transition   | 1                  | 143,775    | 13.13                         | 93              | 1546              |
| Relict arc               | 2                  | 419,992    | 38.35                         | 132             | 3182              |
| Forearc                  | 2                  | 100,872    | 9.21                          | 17              | 5934              |
| Other arc-backarc formations | 2 | 47,308 | 4.32                          | 25              | 1892              |
Backarc Rift and Spreading Center Assemblages

New backarc crust is forming throughout the Lau Basin in at least 12 distinct assemblages: East Lau Basin, Central Lau Basin, Fonualei, Mangatolu, Northeast Lau Basin, Niuafo’ou, Rochambeau, Northwest Lau Basin, Southeast Futuna, Futuna, Cikobia, and Peggy Ridge (Fig. 5; Table 6). Although the Niuafo’ou and Southeast Futuna assemblages are classified as the “backarc volcanoes” assemblage type and the Peggy Ridge assemblage is classified as a deformation zone under the “other arc-backarc formations” assemblage type, these assemblages are described here because they all represent regions of significant backarc crustal growth. The growth of these assemblages has kept pace with an integrated basin opening rate of 120–145 mm/yr (Bevis et al., 1995; Hawkins, 1995; Fig. 1) and locally >160 mm/yr north of the MTJ (Sleeper and Martinez, 2016).

Each assemblage encompasses an area of backarc crust with a spreading fabric that is demonstrably linked to a currently active spreading center. Although a distinction has been suggested between thick, felsic, arc-proximal crust and thinner, mid-ocean ridge basalt (MORB)-like arc-distal crust along the spreading centers (Martinez et al., 2006), we cannot identify that transition farther off axis and therefore have grouped all of the crust that originated at the spreading center into one assemblage (i.e., East Lau Basin and Fonualei assemblages). Further refinement based on the compositions of off-axis basalts, however, is an important objective for future mapping and sampling in the basin. The spreading axes are thought to have remained generally in their present location throughout the formation of the different assemblages, although several rift zones have propagated or jumped across overlapping spreading centers in response to basin opening. The assemblage boundaries are marked by sharp changes in spreading fabric and, in some cases, pseudofaults or transform zones (Parson et al., 1990; Martinez and Taylor, 2006).

The largest of the active backarc spreading center assemblages is the East Lau Basin assemblage, covering an area of 90,325 km² (Tables 6 and 8). It contains the ELSC, which is interpreted to be the oldest active spreading center in the Lau Basin, having initiated in the north at ca. 5.5–5 Ma during the transition

| Assemblage               | Area (km²) | Proportion of total area (%) | Proportion of backarc area (%) | No. of polygons | Area/polygon (km²) |
|--------------------------|------------|------------------------------|-------------------------------|----------------|-------------------|
| Central Lau Basin        | 11,030     | 1.0                          | 2.2                           | 72             | 153               |
| Cikobia                  | 47,275     | 4.3                          | 9.4                           | 36             | 2064              |
| East Lau Basin           | 90,325     | 8.2                          | 18.0                          | 316            | 286               |
| Fonualei                 | 16,145     | 1.5                          | 3.2                           | 61             | 265               |
| Futuna                   | 28,922     | 2.6                          | 5.8                           | 82             | 353               |
| Lau Ridge*               | 310,568    | 28.4                         | N/A*                          | 110            | 2823              |
| Mangatolu                | 1871       | 0.2                          | 0.4                           | 13             | 144               |
| Niuafo’ou                | 3509       | 0.3                          | 0.7                           | 1              | 3509              |
| North Fonualei           | 10,552     | 1.0                          | 2.1                           | 38             | 278               |
| North Futuna             | 17,529     | 1.6                          | 3.5                           | 18             | 974               |
| North Lau Forearc*       | 9384       | 0.9                          | N/A*                          | 9              | 1043              |
| Northeast Lau Basin      | 7916       | 0.7                          | 1.6                           | 76             | 104               |
| Northwest Lau Basin      | 4626       | 0.4                          | 0.9                           | 10             | 463               |
| Peggy Ridge              | 6341       | 0.6                          | 1.3                           | 1              | 6341              |
| Geleleveu                | 7417       | 0.7                          | 1.5                           | 11             | 674               |
| Rochambeau               | 8155       | 0.7                          | 1.6                           | 46             | 177               |
| South Futuna             | 15,682     | 1.4                          | 3.1                           | 21             | 747               |
| South Vitiaz             | 40,967     | 3.7                          | 8.2                           | 24             | 1707              |
| Southeast Futuna         | 8260       | 0.8                          | 1.6                           | 3              | 2753              |
| Tofua Arc*               | 72,295     | 6.6                          | N/A*                          | 2              | 36,148            |
| Tonga Forearc*           | 91,488     | 8.4                          | N/A*                          | 8              | 11,436            |
| Tonga Ridge*             | 109,424    | 10.0                         | N/A*                          | 22             | 4974              |
| West Lau Basin           | 143,775    | 13.1                         | 28.6                          | 93             | 1546              |
| Zephyr                   | 31,580     | 2.9                          | 6.3                           | 23             | 1373              |

*Not included in total backarc area calculations.

Total area (km²) 1,095,036  Total no. of polygons 1080
from early basin rifting to spreading (Parson et al., 1992b; Hawkins, 1995; Clift et al., 1998; Martinez and Taylor, 2006; Martinez et al., 2006). The associated assemblage contains the main volcanic formations of the neovolcanic zone and rift valley (units uBar, uBac, mBac) and of the adjacent backarc crust (mBar, mBaf, lBac1, lBac2). ODP drilling and other sampling indicates that these formations are dominantly tholeiitic basalt and basaltic andesite, with an arc signature where the spreading axis approaches the Tofua arc along the Valu Fa Ridge in the south (see Item S4 [footnote 1] and references therein). The arc signature decreases sharply north of 21°S and a few tens of kilometers west of the volcanic front, and the northern segment of the ELSC is entirely backarc-basin basalt. The eastern boundary of the East Lau Basin assemblage, adjacent to the active Tofua volcanic arc, is obscured by the volcaniclastic apron associated with the arc but corresponds generally to a gravity high and sharp discontinuity in the vertical gravity gradient. It is likely that some crust of the East Lau Basin assemblage (unit lBac1) underlies the Tofua volcanic arc assemblage (uAc). The western boundary of the East Lau Basin assemblage is an ~200-km-long pseudofault marked by dozens of en echelon sub-basins (Martinez and Taylor, 2006) and separating transitional arc-backarc crust of the West Lau Basin (units uTc and lTc) from the outermost backarc crust (lBac1 and lBac2) of the East Lau Basin (Fig. 6). This boundary coincides with the edge of the Gauss magnetic polarity chron (3.58–2.58 Ma) identified by Zellmer and Taylor (2001) and Sleeper and Martinez (2016).

At its widest point, in the north, the East Lau Basin assemblage is bordered by the southern boundary of the Zephyr assemblage. Here, the north-south fabric associated with spreading along the CLSC and LETZ, including units mBaf, lBac1, mBar, and lBar, terminates at a discontinuity that separates the East Lau and Zephyr basins. The boundary broadly coincides with the Matuyama magnetic polarity chron (2.58–0.78 Ma; Zellmer and Taylor, 2001; Sleeper and Martinez, 2016), but ship-based data also reveal a dramatic change in the magnetic fabric between the two assemblages (Barckhausen et al., 2019; Hannoning et al., 2019). The boundary is currently aseismic (Baxter et al., 2020) and therefore might be related to an older structure of the Niuafo’ou microplate. Three prominent northwest-trending ridges (unit uBar) at the northeastern corner of the East Lau Basin assemblage, which are notably oblique to the dominant north-south fabric, have been identified as mafic intrusions in seismic profiles and in one dredge (Hannahning et al., 2019; Schmid et al., 2020). These may be related to ongoing deformation of the Niuafo’ou microplate in this area.

The Central Lau Basin assemblage contains the CLSC and LETZ and associated neovolcanic formations (unit uBar) and is dominated by proximal volcanic ridges (mBar) and their flanks (mBaf). It is generally much younger than the East Lau Basin assemblage, and the area covered is much smaller (11,030 km²; Tables 6 and 8). It is distinguished from the adjacent East Lau Basin assemblage by higher acoustic backscatter in GLORIA side-scan sonar imagery (Hughes Clarke et al., 1993; Parson and Tiffin, 1993; Hilt and Tiffin, 1993; Zellmer and Taylor, 2001; Martinez and Taylor, 2006). Early workers interpreted the CLSC to have formed at 1.5 Ma (Parson and Hawkins, 1994); however, recent detailed magnetic studies suggest that it may be as young as 0.78 Ma (Sleeper and Martinez, 2016). It is interpreted to be propagating southward and is currently rifting older crust of the East Lau Basin assemblage. The northern part of the CLSC is entirely basalt, but andesite has been sampled just south of the maximum inflation of the main propagator (see Item S4 [footnote 1]). The western boundary of the assemblage is a pseudofault defined by truncation of spreading fabric of the East Lau Basin assemblage and coinciding approximately with the Brunhes magnetic polarity chron (Zellmer and Taylor, 2001; Martinez and Taylor, 2006; Sleeper and Martinez, 2016). To the east, the assemblage boundary is marked by several deep nodal basins that belong to the northern termination of the ELSC. This area is characterized by complex intersecting fabric with a number of backarc crustal blocks (unassigned seamounts, unit Us) stranded among the basins of the overlapping spreading center. In the north, the Central Lau Basin assemblage abuts the Peggy Ridge transform and associated formations. Here, the CLSC is connected to the Peggy Ridge via the LETZ and a series of axial volcanic ridges south of the transform (Sleeper and Martinez, 2016). The Peggy Ridge is a long-lived transcrustal boundary between the currently active and relict backarc spreading centers in the north of the Lau Basin and the LETZ, CLSC, and ELSC in the south. It appears to have accommodated significant differential opening of the Lau Basin (~600 km at latitude 15°S versus only 300 km at 18°S) and is included here as an assemblage in its own right (see below).

As many as 17 different assemblages are identified in the complex northern part of the Lau Basin, north of the Peggy Ridge. They contain seven distinct backarc rifts and spreading centers (FRSC, MTJ, NELSC, NWLSC, RR, FSC, and the enigmatic North Cikobia Spreading Center [NCSC] in the far west of the basins; Figs. 5 and 6). In the east, the Fonualei assemblage (16,145 km²) contains the FRSC, which is thought to be the youngest boundary of the Niuafo’ou microplate. The rift valley of the FRSC is located behind the active volcanic front of the Tofua arc. It was first mapped in 1996 and has been the subject of only a few studies since (German et al., 2006; Keller et al., 2008; Escrig et al., 2012). The valley, which is 200 km in length, is defined by a series of en echelon sub-basins, each ~25–50 km long and ~15–30 km wide, with the basin floors at depths of 2400 m below sea level in the north and deepening to 3000 m in the south. Originally, the opening rate was estimated to be 94 mm/yr at 16°S, decreasing to 47 mm/yr at 18°S where the rift impinges on the arc (Zellmer and Taylor, 2001). However, a reinterpretation by Sleeper et al. (2016) predicts FRSC opening rates of only ~32–8 mm/yr, decreasing from north to south. At least six rift segments can be recognized, marked by axial volcanic ridges (unit uBar); two in the north, three shorter overlapping segments in the central FRSC, and a deeper sub-basin which may contain new backarc crust (unit uBac) at the southernmost tip. The rift segments step progressively eastward toward the south, with the distance to the volcanic front decreasing from ~75 km at 16°S to <20 km at 18°S. The rift is thought to be propagating to the south, but the interpretation of magnetic data by Zellmer and Taylor (2001) suggests reversed magnetization at the rift tip, which is consistent with relatively little new crust being produced. Positive magnetization is highly localized in areas where there is clearly recent volcanic activity (cones and dikes), but there are few large earthquakes associated with the spreading (Conder and Wiens, 2011).
The shift in axial morphology of the FRSC from semicontinuous volcanic ridges north of 17°S to isolated volcanic cones and dike complexes south of 17°S may reflect along-axis variation in the focusing of melt as the opening rates decrease and the FRSC axis approaches the volcanic arc (Sleeper et al., 2016). Dredged lavas from the FRSC include mainly basaltic andesite and show strong arc signatures (Keller et al., 2008; Escrig et al., 2012). This is consistent with a model where the southern portion of the FRSC is “capturing” melt from the arc front. However, the location of the rift behind the volcanic front contrasts with that of the late Miocene rift that initiated at or near the arc front. Recent seismic tomography across the FRSC reveals a coincident gravity low and low-velocity anomaly in the arc crust between the rift and the active volcanic front, which has been interpreted as a region containing partial melts (Schmid et al., 2020). This might indicate an imminent rift jump that would strand additional blocks of arc crust in the backarc region. This appears to have happened already at the current location of the FRSC, given that dredging of the high-standing western flanks of the rift indicate that they are mainly arc crust (unit uAc; Hannington et al., 2019).

At its widest point, the Fonualei assemblage is nearly 110 km across, although it has formed relatively recently (<3.8 Ma). It is abruptly terminated in the north by the three arms of the MTJ, which have produced a small amount of new backarc crust composing the Mangatolu assemblage (1871 km²; Tables 6 and 8). Detailed mapping of the MTJ (see Item S2 [footnote 1]; Mensing, 2019) shows that crustal accretion is no longer occurring along the western arm, but this structure clearly truncates older backarc crust that originated from the southern arm or from earlier spreading associated with the northernmost segment of the FRSC. The dominant accretion is now occurring along the northern arm, where the rift valley is occupied by an inflated axial high. Dredged material from the northern arm is mostly basaltic andesite, whereas samples from the southern arm are entirely basaltic (Mensing, 2019).

The Northeast Lau Basin assemblage contains the NELSC as well as the Niutahi silicic volcanic calderas and its surrounding volcanic field, collectively 7916 km². This assemblage has been mapped in detail by Embley and Rubin (2018) and Norris-Julseth et al. (2020) who defined the region between the Tofua arc and the NELSC as “rear arc.” This assemblage is bounded by major faults that appear to have been inherited from the early stages of rifting in the north-eastern Lau Basin. The southern boundary crosses the Fonualei assemblage (unit IBac1) and the northern Tofua volcanic arc (uAc). The western boundary is interrupted by the northern arm of the MTJ, which appears to be propagating into the Northeast Lau Basin assemblage. The northern boundary is at the contact with forearc blocks belonging to the North Lau Forearc assemblage and rifted Tonga forearc (i.e., the Mata Basin; Embley and Rubin, 2018). The NELSC is propagating into old forearc crust in the north and also appears to be propagating south toward the northern tip of the FRSC. The two spreading centers may eventually connect in the area of rifted arc and backarc crust at the intersection of the N-FRSC, MTJ, and NELSC (Baxter et al., 2020). This area is heavily intruded by recent backarc volcanoes (e.g., Merle et al., 2013). Samples of the crust proximal to the NELSC are backarc-basin basalt and basaltic andesite, including the youngest lavas of the neovolcanic zone (Falloon et al., 2007; Michael et al., 2009), whereas the volcanic flow field (unit Bavf) surrounding the Niutahi volcano is mainly dacite (Embley and Rubin, 2018).

Recently formed backarc assemblages west of Fonualei and Mangatolu include Niuafo’ou, Rochambeau, Southeast Futuna, and Northwest Lau. The formations surrounding Niuafo’ou Island are grouped as an assemblage that comprises the large Niuafo’ou shield volcano (unit Bav2), several other large submarine volcanoes, and a large volcanic field (Bavf), covering 3509 km² (Tables 6 and 8). The volcanic field surrounding Niuafo’ou consists of lava flows and pyroclastic material (airfall and surge deposits; Taylor, 1991). Niuafo’ou Island is capped by the remnants of a composite cone, where the latest eruption occurred in March 1985 (Global Volcanism Program, 1985). The alignment of several large submarine volcanoes northwest and southeast of Niuafo’ou may mark an emerging microplate boundary between the western arm of the MTJ and the northern tip of the RR (cf. Baxter et al., 2020). Samples from the volcanoes include a wide range of rock types such as normal MORB, enriched MORB, oceanic island basalt, and dacite (Hawkins, 1995).

The western limit of the Niuafo’ou assemblage interfiners with, or is overprinted by, the formations of the Rochambeau assemblage. The Rochambeau assemblage comprises the proximal backarc crust and ridges of the Rochambeau spreading centers (Rochambeau rifts, RR), which together occupy an area of 8155 km². The main RR segment is interpreted to be spreading at 110 mm/yr (Lupton et al., 2012) and has a prominent axial volcanic high (unit uBar) and large summit caldera (Lobster caldera; Arculus, 2008). A smaller echelon rift to the northwest lacks an axial high but is floored by proximal backarc crust (unit uBac). Both of the rift valleys of the RR segments are only ~40 km wide, suggesting that they are not older than 350,000 yr. The northwestern segment terminates against the eastern extension of the Futuna transform fault and deformation zone (unit Dz2) in the north, which separates the young backarc region from the old forearc crust of the North Lau Forearc assemblage.

The Northwest Lau Basin assemblage (4626 km²) is dominated by the axial volcanic ridge of the NWLSC, which is surrounded by young backarc crust and volcanic ridges. The ridge is 97 km long and >500 m high, with two prominent summit calderas (Arculus, 2008). To the north, the assemblage is truncated by a large volcanic field belonging to the Southeast Futuna assemblage (Southeast Futuna volcanic zone). To the south, it is in contact with the Peggie Ridge. The western and eastern contacts are defined by the broad, 45-km-wide rift valley containing the NWLSC.

The large Southeast Futuna volcanic zone and Rochambeau Bank (Fouquet et al., 2015; Konn et al., 2016) are located within the Southeast Futuna assemblage at the intersection of the North Futuna, South Futuna, Northwest Lau Basin, and Rochambeau assemblages and may conceal the boundaries between these assemblages. The southern extent of the Southeast Futuna volcanic zone, in particular, represents a large volume of material possibly erupted along a crustal boundary between emerging microplates (Baxter et al., 2020). Like Niuafo’ou, the Southeast Futuna assemblage is dominated by a number of large shield volcanoes (unit Bav2; e.g., Kulo Lasi volcano, smaller...
volcanic cones, domes and ridges, and several broad volcanic fields (Bavf, collectively 8260 km$^2$). The northern boundary of the assemblage appears to be truncated by the Futuna transform fault. Several dredge samples from the perimeter of the field are all basaltic (Arculus, 2012). However, a distinctive feature of the volcanic rocks from the Southeast Futuna, Northwest Lau Basin, Rochambeau, and Niuafo’ou assemblages is a plume-like signature indicated by elevated $^{3}He/^{4}He$ (Lupton et al., 2015).

The Futuna assemblage, farther to the west, contains the FSC and all ridges and backarc crust thought to have formed at the spreading center (>28,922 km$^2$; Pelletier et al., 2001). A very broad but poorly defined outer rift valley (155–190 km wide) is interpreted to be the limit of the assemblage and is consistent with its presumed age (as old as 4.5 Ma, assuming a spreading rate of 40 mm/yr on the FSC; Pelletier et al., 2001). The FSC itself is nearly 215 km long and 800 m high with an axial ridge (unit uBar) at least 15 km wide. The entire ridge covers an area >2350 km$^2$, which is the largest of the currently active spreading centers in the Lau Basin. The spreading fabric of the Futuna assemblage is truncated by the Futuna transform fault in the north and the western extension of the Peggy Ridge in the south, where it is in contact with the Qelelevu assemblage. The southern end of the FSC may be propagating into the Fiji platform, although the connection to the North Fiji fracture zone is unclear.

Another enigmatic assemblage is centered on the North Cikobia Spreading Center (NCSC) and the West Cikobia volcanic zone (WCVZ), west of Futuna. The NCSC is an active spreading center with a spreading rate of 20 mm/yr (Pelletier et al., 2001); however, its relationship to the mapped Cikobia assemblage, which is dominated by unassigned crust (unit Ucr), is not clear. Based on the mapped area (47,275 km$^2$) and the spreading rate at the NCSC, this assemblage may have started forming as early as 12.5 Ma, assuming all of the crust was generated at the spreading center. Alternatively, the ridges and backarc crust outside the zones of active spreading may be much older, and the NCSC and WCVZ are relatively recent features. The northern boundary of the Cikobia assemblage is the Vitiaz lineament. The southern boundary is the contact with the Fiji platform. The eastern limit is drawn where volcanic ridges and backarc crust of the Futuna assemblage are clear.

Although their ages are not well constrained, the Fonualei, Futuna, and Cikobia assemblages cover the largest areas and are likely the oldest currently active backarc assemblages in the north of the Lau Basin. These older and larger assemblages likely represent an early phase of fast growth in the opening of the northern Lau Basin. The Mangatolu, Northeast Lau Basin, Northwest Lau Basin, and Rochambeau assemblages are much smaller and were probably not formed until after 1.5 Ma (Hawkins, 1995).

Relict Backarc Basin Assemblages

Five relict backarc basin assemblages have been identified in the north: Zephyr, North Fonualei, North Futuna, South Futuna, and Qelelevu (Fig. 5). They are interpreted to have formed by riftting and seafloor spreading but have less well-defined spreading fabric than the active assemblages, and the associated spreading centers are either no longer preserved or cannot be identified. The assemblage boundaries are drawn where a clear distinction from an adjacent assemblage can be made, including changes in the spreading fabric or the magnetic signature. Commonly, the relict backarc assemblages are in fault contact with other assemblages, marked by discontinuities in the gravity gradient.

The Zephyr assemblage (31,580 km$^2$) occupies a large region between the FRSC in the east and the NWLSC and RR in the west. It is composed of rifted arc and backarc crust (units uRbc1, uRbc2, and IRbc) that is overprinted by recent intraplate volcanism (Bavf1) in its eastern half. Zephyr shoshol was shown by Hawkins (1976) and found to be mostly dacite, similar to samples recently collected west of the FRSC (Hannington et al., 2019). These observations are consistent with characteristics of many of the deep depressions in the relict backarc basin assemblages representing failed rifts in earlier arc and backarc crust (e.g., the large Zephyr Deep) and some of the large seamounts (unit Us) representing rifted blocks of arc crust. These older formations (uRbc and IRbc) are interpreted to have originated in the early history of the opening of the basin (ca. 5.5 Ma), and so the large size of the assemblage reflects its age. The more recent intraplate volcanism in the southeast of the assemblage is basaltic (Hannington et al., 2019) and likely indicates widespread riftting and intrusion of the crust that is ongoing today.

The North Fonualei assemblage (10,552 km$^2$) consists of relict backarc crust (units uRbc1, uRbc2, and IRbc) and volcanic ridges (uRr), partly obscured by younger backarc crust (IBac1) from the Northeast Lau Basin and Mangatolu assemblages. Some of the tectonized crust in the east (depicted on the map as unit uRbc2) could be large blocks rifted from the Tofua arc by the MTJ and NELSC (Mensing, 2019; Norris-Julseth et al., 2020). In the north, the assemblage is structurally bounded by the Futuna transform fault, and in the south, it is bounded by the MTJ and the Niuafo’ou volcanic field. The western boundary is mapped along the contact with the younger backarc crust of the northern Rochambeau assemblage. Although the North Fonualei assemblage does not contain an active spreading center, the crust may be related to the Fonualei assemblage which was bisected by the formation of the MTJ. The age of North Fonualei is therefore likely bracketed by the maximum age of the Fonualei assemblage (between 3.8 Ma and 1.9 Ma).

The North Futuna assemblage is located west of the Rochambeau assemblage. It consists of a large area (17,529 km$^2$) of relict backarc crust (unit IRbc) and, in the far west, a series of ridges (uRr) interpreted to represent old spreading fabric (Pelletier et al., 2001). It is bounded to the north by an extension of the Futuna transform fault, separating backarc crust of the northern Lau Basin and forearc crust of the former Vitiaz arc, and to the south by the Southeast Futuna volcanic field.

The South Futuna assemblage is located between the younger backarc assemblages associated with the NWLSC in the east and the FSC in the west. It is in contact with the North Futuna assemblage along the Futuna transform fault and the Qelelevu assemblage in the south along the Peggy Ridge transform fault. Like the North Futuna assemblage, it consists of a large area (15,682 km$^2$) of
relict backarc crust (unit IRbc) and unassigned seamounts (Us); a clear spreading fabric is not evident, but dredge samples are all basalt (Item S4 [footnote 1]). A possible interpretation is that the South Futuna assemblage is a rifted portion of the Zephyr assemblage, separated by the NWLSC.

The Qelelevu assemblage (7417 km²) consists mainly of deformed backarc crust (units IRbc and uRbc) in a structurally bounded area trapped between the South Futuna assemblage, Peggy Ridge, the Qelelevu fault, and the North Fiji fracture zone. The origin of this assemblage is unclear, but it may be a relict of the West Lau Basin assemblage or Lau Ridge, separated from the West Lau by the Qelelevu fault.

Arc-Backarc Transition

The West Lau Basin assemblage is an areally extensive (143,775 km²) group of formations (units ITc, uTc, and uTr) at the boundary between the active backarc region, dominated by the East Lau Basin assemblage, and the Lau Ridge relict arc. It is interpreted to have formed during the initiation of backarc rifting and seafloor spreading during the earliest opening of the Lau Basin. It has a seismic velocity structure consistent with mainly rifted material and nearly identical to that of the crust from the ELSC rather than arc-type crust (Crawford et al., 2003). Thus, much of the West Lau Basin assemblage may have been magmatically accreted but in a less-organized way than at a focused spreading center. The dominant formations are similar to normal backarc and relict backarc crust but heavily deformed and sedimented, with sub-basins that are considered to be failed rifts floored by basalt (Parson et al., 1992b; Parson and Hawkins, 1994; Hawkins, 1995; Parson and Wright, 1996). Some parts may include remnants of old arc crust in addition to the basaltic crust formed during rifting (Hawkins, 1995; Martinez and Taylor, 2006). Thus, the overall assemblage is likely a mixture of rifted material from the early arc (i.e., Lau and Tonga Ridge age: 46–31 Ma, 28–15 Ma) and younger volcanic rocks formed during the transition from rifting to spreading (5.6–2.4 Ma; Table 6). We have drawn the assemblage boundaries in the east where the sediment cover decreases and the spreading fabric of younger backarc crust is visible, and in the west where elevated relict arc crust of the Lau Ridge dominates.

Three large volcanic fields (unit Bavf, individually 4411–27,010 km²) appear to overprint the West Lau Basin assemblage and partly overlap the boundary with the East Lau Basin assemblage, close to the southern ELSC and the Valu Fa Ridge. Although individual flows have not been identified, the associated formations are identified as unit Bavf, punctuated by numerous backarc volcanic cones (unit Bavf1) that indicate recent intraplate volcanism within the arc-backarc transition zone. These areas have been mapped previously as “ridges and knolls,” which were interpreted to be products of rifting and diapiric magma intrusion into the extended crust (Fujiiwara et al., 2001; Martinez and Taylor, 2006). The southernmost of the fields covers 27,010 km² and is associated with a significant regional-scale bulge or inflation of the arc and backarc region. This inflation has been described by Fujiiwara et al. (2001) as a precursor of basin opening produced by MORB-like magmatism in the uncertain, but those in the north are more heavily sedimented than in the south.

Relict Arc Assemblages

The Lau Ridge and Tonga Ridge are relict arc assemblages that formed prior to backarc basin opening. They comprise mainly flows and volcaniclastic rocks that were products of early arc magmatism, but they also include crust that may have formed as a result of rifting of the arc, forearc, or arc-backarc transition (e.g., Taylor and Karner, 1983; Stern et al., 1984; Hawkins and Allan, 1994; Martinez and Taylor, 2006). The majority of the Lau Ridge and Tonga Ridge assemblages belong to the former Vitiaz arc and forearc and are underlain by old arc basement along their entire length (Martinez and Taylor, 2006). This contrasts with rifting of the present-day Tofua arc by the FRSC and the Valu Fa Ridge, which is occurring behind the volcanic front and isolating relatively small reliefs of arc crust in the backarc basin.

The Tonga Ridge assemblage covers 109,424 km² and consists of mostly volcaniclastic and sedimentary material (units IRac and uRac; Hawkins and Allan, 1994; Meffre et al., 2012; Beier et al., 2017). Drilling at ODP Site 840 on the Tonga Ridge (Fig. 3) encountered >590 m of volcaniclastic and sedimentary rocks ranging from Holocene to late Miocene in age (Parson et al., 1992b). No crystalline rocks were encountered, but felsic igneous rocks of Eocene age were intersected on the Tonga forearc at ODP Site 841, which may suggest that similar material is present in the basement of the Tonga Ridge. In general, drilling on the Tonga Ridge at ODP Site 840 and in the forearc at ODP Site 841 recovered rocks belonging to similar formations.

The Lau Ridge assemblage (310,568 km²) is similar to the Tonga Ridge assemblage, consisting of volcanic and volcaniclastic rocks that range in age from Holocene to middle Eocene (Hawkins, 1976; Cole et al., 1990; Parson et al., 1992b; Hathway, 1994; Wharton et al., 1995; Taylor et al., 2000). Older volcanic rocks are present at the Lau Ridge, dating from 46 Ma to 31 Ma, when the ridge was part of the Vitiaz arc (Hathway, 1994; Wharton et al., 1995; Taylor et al., 2000). Volcanism continued as the crust was separated from the former Vitiaz forearc, and intermittent volcanic activity on the ridge has been dated to as young as ca. 0.3 Ma (Cole et al., 1990; Wharton et al., 1995). Cross-arc volcanic chains or coalesced volcanic ridges (unit uRav) have a west-southwest trend on the eastern side of the Lau Ridge and a west-northwest trend on the western side, implying a late-stage rotation in the direction of basin opening. Older eroded arc volcanoes are also present within the assemblage (unit uRac). To the east, the Lau Ridge is in contact with the West Lau Basin assemblage along the inferred boundary of early arc rifting, where deep, sediment-filled basins abut the Lau Ridge. To the west, the Lau Ridge descends into the South Fiji Basin, and its boundary is defined by a gravity high. The overlap with formations of the South Fiji Basin is likely conformable, marking the western limit of volcanism associated with the former Vitiaz arc.
Forearc Assemblages

The Tonga Forearc assemblage includes crust of the forearc slope (unit Fc1), tectonized forearc blocks (Fc2), crust of the inner trench wall (Fc3), forearc volcanoes (Fv), and different types of forearc mounds (Fm), including serpentinite mounds, mud volcanoes, and uplifted crustal blocks of uncertain origin. These formations, which cover 91,488 km², mostly belong to the former Vitiæa arc. The assemblage boundaries are drawn along the deepest part of the trench and at the inferred contact with the relict arc assemblage of the Tonga Ridge, described above. No accretionary material is assigned to this assemblage or anywhere in the Lau-Tonga region.

The Mata Basin, north of the Tonga Ridge, consists of extended forearc crust (unit Fc4) surrounding the active Niua arc volcano and the Mata rift volcanoes. The Mata rift volcanoes are boninitic in composition (Resing et al., 2021) and have erupted as recently as 2018 (Chadwick et al., 2019). The rifting of the forearc is thought to be related to significant left-lateral transcurrent motion and wrench tectonics associated with the STEP fault at the former Vitiæa trench (e.g., Embley et al., 2014; Baxter et al., 2020; Norris-Julseth et al., 2020). The anomalous magmatism may be related to an emerging ridge-trench-fault triple junction at this location (Escrig et al., 2012; Regelous et al., 2014). However, boninitic volcanism, like that at the Mata volcanoes, has had a protracted history in this region since at least 15.2 Ma (Meffre et al., 2012).

We separate the North Lau Forearc assemblage (9384 km²) from the Tonga forearc because of their very different structural settings. The North Lau forearc is bounded to the north by the regional Vitiæa lineament, which is a crustal-scale structure accommodating transcurrent motion between the Pacific and Australian plates and juxtaposing the arc, backarc, and oceanic assemblages (Govers and Wortel, 2005). Little or no forearc crust is preserved west of this location because most of the former Vitiæa arc was transported to the south with the rotation of the Fiji platform in the early stages of opening of the North Fiji Basin (Hawkins, 1995; Schellart et al., 2006).

Other Assemblages

The South Vitiæa assemblage in the north of the Lau Basin is difficult to classify because there are few ship-based data in the area, but it can be distinguished from adjacent assemblages on the basis of magnetic fabric and major bounding structures visible in the vertical gravity gradient. One of the seamounts, Manatu seamount, has been sampled, and the rocks recovered include basalt, dolerite, talus breccia, limestone, and marl (Sinton et al., 1985), but no additional information is available.

A number of the deformation zones (units Dz1 and Dz2) have also been mapped as assemblages where a significant amount of crust is involved. The Peggy Ridge assemblage, in particular, includes voluminous lava flows associated with leaky transform faulting along much of its length (Parson and Tiffin, 1993; Taylor et al., 1996). We consider the Peggy Ridge to be a distinct assemblage because of the extent of the erupted material (6341 km²) and the presence of several different formation types, including clearly visible dome volcanoes (unit Bav3). Eighty-four percent (84%) of the ridge is covered by ship-based bathymetry and GLORIA side-scan sonar imagery (Zellmer and Taylor, 2001; Martinez and Taylor, 2006). A strong magnetic anomaly, clear volcanic morphology, high acoustic backscatter, and fresh samples collected along the ridge are consistent with recent magmatism. The samples include tholeiitic basalt from thick flow units (Volpe et al., 1988; Falloon et al., 2007).

Taylor et al. (1996) interpreted the MORB-like magmatic rocks to be younger than magnetic polarity chron 2n (1.77 Ma) but older than the Brunhes chron (0.78 Ma). One sample of basalt from the northern end of the Peggy Ridge has elevated ³He/⁴He that is intermediate between MORB and the plume signature of the NWLCSR-RR basalts (Lupton et al., 2015).

All of the mapped formations on oceanic crust are grouped into a single oceanic assemblage because these were not the focus of the present study. However, we distinguish different types of volcanoes and seamounts (units uOs1–uOs3), oceanic plateaus (uOp, lOp1, lOp2), and undivided crust (units 1Oc1, 1Oc2) belonging to the Pacific and Australian plates.

Tectonic and Lithostratigraphic Correlations

Based on this compilation, we have assigned age ranges to each of the mapped assemblages and arranged them in approximate stratigraphic order in Figure 8, with major regional tectonic events also indicated. The tectonic and lithostratigraphic correlations are constrained by historical drill-hole data, geological sampling, and absolute age data summarized in Table 6. Where necessary, relative ages have been assigned based on crosscutting structural relationships or spreading fabrics (e.g., indicating crust that formed contemporaneously or at different times) and sediment cover. Following is a summary of the age constraints for the individual assemblages. These data provide a basis for the area-age calculations in our model of crustal growth.

The initiation of subduction and formation of the proto–Vitiæa arc began as early as 46 Ma and continued in three major intervals (Hatherton, 1994; Wharton et al., 1995; Taylor et al., 2000). The oldest arc crust now at the Lau Ridge formed during protracted arc volcanism in the middle Eocene (Yavuna Group at 46–31 Ma). Subsequent rifting of the proto–Vitiæa arc produced a significant unconformity at the top of the Yavuna Group, and a second stage of subduction formed the Vitiæa arc between ca. 28 and 15 Ma (Wainimala Group; Wharton et al., 1995). The latest episode of arc development started at ca. 14 Ma and continued through initial backarc basin opening. The Eocene to Miocene stratigraphy preserved on the Tonga Ridge differs slightly from that of the Lau Ridge, with volcanic episodes spanning 46–40 Ma, 33–31 Ma, and 19–17 Ma (Duncan et al., 1985). The thick sequence of volcanioclastic material at OD Site 840 on the Tonga Ridge is interpreted to have been deposited on the forearc of the Lau Ridge before it was separated from Tonga (Parson et al., 1992b; 1994; Hawkins, 1995). The shorter volcanic episodes recorded by rocks of the Tonga...
The crust associated with this early arc development is likely present beneath Groups; Cole et al., 1990). Volcanic activity on the Lau Ridge after 2.5 Ma is volcanism (Mago Volcanic Group; Cole et al., 1990). Volcanism continued on the Lau Ridge until ca. 0.3 Ma, but there is no correlation with units on the Tonga arc, which became part of the forearc assemblage of the Vitiaz arc following a change in principal stress during the early history of the arc. The volcanoes are related to the final stage of arc development (Lau and Korobasaga Volcanic Groups; Stewart et al., 2006). Hawkins (1995) proposed that the crust west of the ELSC and CLSC formed mainly through rifting rather than seafloor spreading, with numerous volcanic episodes and/or deposition of volcanioclastic material with published age constraints; lighter shades are of unknown stratigraphic extent. Assemblages outside the Lau Basin (South Fiji Basin, North Fiji Basin, Melanesian Borderland, Samoa) are included for regional context. See text for descriptions of regional events. CLSC—Central Lau Spreading Center; ELSC—Eastern Lau Spreading Center. Holo—Holocene, Ple.—Pleistocene, Pl.—Pliocene, E—Eocene, Q—Quaternary, L.—Late.

### Regional Events

- **South Fiji Basin opening**
- **North Fiji Basin opening**
- **Tonga-Kermadec subduction**
- **Fiji counterclockwise rotation**
- **Lau Basin opening**
- **ELSC rifting**
- **CLSC rifting**
- **Tofua arc volcanism**
- **Drilling of the Tonga forearc at ODP Site 841 (Parson et al., 1992b) intersected late Eocene rhyolite (44 ± 2 Ma) interpreted to be equivalent to Eocene formations on the Lau and Tonga Ridges. A major unconformity is present between late Eocene to early Oligocene sediments and volcanioclastics (44–35 Ma) and middle Miocene to middle Pleistocene sediments and volcanioclastics (17 to <1 Ma; Cunningham and Anscome, 1985; McDougall, 1994; Clift et al., 1998). The gap in deposition and development of the unconformity may have been the result of seamount collision, which is also suggested by a change in the dip of the sediments (Clift et al., 1998). The unconformity broadly coincides with the hiatus in volcanism on the Tonga Ridge between 31 and 19 Ma and a period of active volcanism at the Lau Ridge (Fig. 8). North of the Tongan island of ‘Eua, the forearc region was dominated by three episodes of crust development at 52–48 Ma, 35–28 Ma, and 15–9 Ma (Meffre et al., 2012). The North Lau Forearc assemblage has a somewhat different history more closely linked to the termination of subduction at the Vitiaz trench and lacking the more recent sediment and volcanioclastic rocks (Meffre et al., 2012). Crust formed during the initial rifting and opening of the Lau Basin is represented by the West Lau Basin assemblage (Parson et al., 1992b; Parson and Hawkins, 1994; Hawkins, 1995; Parson and Wright, 1996; Martinez and Taylor, 2006). Hawkins (1995) proposed that the crust west of the ELSC and CLSC formed mainly through rifting rather than seafloor spreading, with numerous
sediment-filled basins characteristic for this early opening phase. Basaltic flows and sediments in the sub-basins have a broad range of ages, generally decreasing from 5.6 Ma at ODP Site 834 in the west to 0.8–0.64 Ma at ODP Site 836 in the east (Fig. 3) (Hawkins and Allan, 1994). The intervening crust is thought to be a combination of rifted arc crust from the early opening phase and basalts from the advanced stages of opening, with seafloor spreading occurring mainly distant from the volcanic arc (Hawkins, 1995; Martinez and Taylor, 2006). We interpret the Qelelevu assemblage to be a remnant of the West Lau Basin assemblage with a similar stratigraphy (Fig. 8).

The assemblages formed during recent backarc rifting and spreading have well-established ages based on magnetic data (Zellmer and Taylor, 2001; Sleeper and Martinez, 2016). The East Lau Basin assemblage began forming early in the opening history at ca. 5.5–5 Ma (Parson and Hawkins, 1994; Hawkins, 1995; Taylor et al., 1996; Sleeper and Martinez, 2016). The Central Lau Basin assemblage is considerably younger, having formed since the CLSC initiated and began propagating south from the Peggy Ridge at ca. 1.5–1.2 Ma (Parson and Hawkins, 1994; Hawkins, 1995).

Ages of the other backarc assemblages are assigned according to the oldest (most distant) crust that originated from the present-day spreading center. The Futuna assemblage, which is ~180 km wide, is interpreted to have started forming at 4.5 Ma, assuming a constant spreading rate of 40 mm/yr (Pelletier et al., 2001), and it is still growing today. In contrast, the North–West Lau Basin assemblage is only 50 km wide and is spreading at a rate of 48 mm/yr (Taylor et al., 1996), suggesting that it is <1 m.y. old. This is consistent with the positive magnetization, corresponding to the Brunhes–Matuyama magnetic polarity reversal at 0.78 Ma (Zellmer and Taylor, 2001). The age of the Rochambeau assemblage is poorly constrained. The global plate-boundary model suggests a spreading rate as high as 110 mm/yr (Lupton et al., 2012, citing Bird, 2003), which is probably too high considering that the entire basin is widening at 159 mm/yr (Pelletier et al., 1998) to 174 mm/yr (Zellmer and Taylor, 2001). Even if crustal accretion were occurring at half the rate cited above, the Rochambeau assemblage, which is only 22 km wide, would still be considerably younger than 1 Ma.

Different estimates for the rate of extension of the FRSC result in a range of ages for the Fonualei assemblage. At a width of ~106 km in the north and an opening rate of 28 mm/yr at this location (Sleeper and Martinez, 2016), the maximum age of the Fonualei assemblage is 3.8 Ma, whereas in the south, where the rift valley is 15 km wide and the opening rate is 8 mm/yr (Sleeper and Martinez, 2016), the crust is younger than 1.9 Ma. This discrepancy in age between the northern and southern regions of the Fonualei assemblage is consistent with southward propagation of the FRSC (Sleeper and Martinez, 2016), similar to what has been documented for the ELSC and CLSC (Parson et al., 1990). At the rift tip where the FRSC is propagating into the Tofua arc, the magnetic polarity is reversed (Zellmer and Taylor, 2001), indicating that significant new crust has not yet formed there. Spreading on the MTJ is occurring at an average rate of 30 mm/yr (Sleeper and Martinez, 2016) and, based on the width of the rift valley (18 km), is younger than 600,000 yr. This crust has formed contemporaneously with the Rochambeau and Northwest Lau Basin assemblages.

Spreading rates for the NELSC are poorly constrained but estimated to be ~42 mm/yr (Baker et al., 2019). We estimate the age of the Northeast Lau Basin assemblage to be 2.5 Ma, assuming a full width of 105 km. Our mapping suggests that the border of the Northeast Lau Basin assemblage truncates the northern portion of the Tofua arc, and the NELSC appears to propagate into arc crust, which would indicate that the backarc assemblage is younger than 3 Ma, the maximum age of the Tofua arc. Thus, we consider the Northeast Lau Basin assemblage to be the same age as the Fonualei assemblage. The North Fonualei assemblage does not contain an active spreading center, but it may be the northern extension of the Fonualei assemblage, bracketed by the maximum age of Fonualei crust (3.8 Ma) and the maximum age of the Mangatolou assemblage (<1 Ma).

The Niuafo’ou assemblage cross-cuts the Fonualei assemblage and therefore has a maximum age between 3.8 and 1.9 Ma. However, we suggest that it may be significantly younger, given that it contains the active Niuafo’ou volcano. The Southeast Futuna assemblage is similarly an active volcanic center (Souquet et al., 2011; conn et al., 2016). The relationship to the NWLSC and southern RR strongly suggests that the Southeast Futuna, Northwest Lau Basin, and Rochambeau assemblages are of similar age and mostly younger than 1 Ma.

The age of the Peggy Ridge assemblage is uncertain, but Parson and Hawkins (1994) proposed that basin opening was initiated on the trace of this structure, and therefore it must have been present as early as 5.5 Ma. It is still an important locus of deformation in the northern Lau Basin, connecting the northern spreading centers (notably the FSC and NWLSC) to the LETZ and CLSC in the south. Fresh volcanic rocks have been recovered from the ridge (Hawkins, 1995; Falloon et al., 2007), and most of the Peggy Ridge assemblage is characterized by high acoustic backscatter, indicating little sedimentation (Zellmer and Taylor, 2001). The fact that the Peggy Ridge transform cuts some of the oldest crust in the basin (e.g., the Qelelevu assemblage) and also the youngest in the Central Lau Basin assemblage confirms that it is one of the longest-lived structures in the region and has been key to basin opening. The northern edge of the Fiji platform might have been an important crustal boundary along which the Peggy Ridge was initiated. For example, Martin (2013), citing data in Malahoff et al. (1982), Inokuchi et al. (1992), and Taylor et al. (2000), suggested that rotation of the Fiji platform started at or before 10 Ma and ceased after collision with the Lau Ridge between 2.7 Ma and 1.56 Ma, with the pole of rotation close to the north end of the Peggy Ridge.

The Cikobia assemblage straddles the boundary between the Lau and North Fiji Basins and therefore might have begun forming during the opening of the North Fiji Basin and prior to the formation of the Lau Basin. If the entire assemblage formed by spreading at ~20 mm/yr (Pelletier et al., 2001), the maximum age of the assemblage would be 12.5 Ma, which approximately coincides with the end of subduction at the Vitiq trench at ca. 12 Ma and the beginning of opening of the North Fiji Basin (Malahoff et al., 1982; Taylor et al., 2000; Martin, 2013). The ages of the Zephyr, North Futuna, and South Futuna
assemblages are also poorly constrained due to limited sampling and the lack of identifiable spreading. The Zephyr assemblage is interpreted to be older than the Northwest Lau Basin and Fonualei assemblages and may date from the beginning of basin opening (ca. 5.5 Ma). However, small volcanic cones and ridges in the eastern half of the Zephyr assemblage have high acoustic backscatter, suggesting that some younger intraplate volcanism continued after 1 Ma. The South Futuna assemblage is interpreted here to be the extension of the Zephyr assemblage and therefore the same age. It also shows signs of widespread, late-stage intraplate volcanism. The North Futuna assemblage has an uncertain tectonic history but is considered to be similar in age to the South Futuna assemblage. There are no constraints on the age of the South Vitiaz assemblage; however, some of the unassigned seamounts in the South Vitiaz assemblage may have been accreted from the Melanesian Borderland during subduction at the Vitiaz trench. Therefore, we interpret the maximum age of the South Vitiaz assemblage as the termination of subduction at the Vitiaz trench (12 Ma).

The South Fiji Basin, North Fiji Basin, Melanesian Borderland, and Samoa are included in the correlation diagram (Fig. 8) to provide a larger tectonic context. The South Fiji Basin crust west of the Lau Ridge is early Oligocene to early Miocene in age, based on magnetic anomalies 13–8 (Meffre et al., 2012; van de Lagemaat et al., 2018). The North Fiji Basin crust has been produced during the opening of the North Fiji Basin since 12 Ma and is still forming (Yan and Kroenke, 1993; Taylor et al., 2000; Meffre et al., 2012; van de Lagemaat et al., 2018). The Samoa assemblage has a maximum age of 14.8 Ma in the area surrounding the Samoan Islands (Finlayson et al., 2018) but also includes crust associated with the active Samoan hot spot. In the vicinity of the Melanesian Borderland assemblage, the Samoa and Rarotongan hot-spot tracks span 20–40 Ma (Finlayson et al., 2018). One of the volcanic features in the Melanesian Borderland assemblage (Alexa Bank) has been dated at 37 Ma (Duncan, 1985), and all of the crust in the area has a thick sedimentary cover, suggesting that it is old (Pelletier and Auzende, 1996).

### Quantitative Analysis

Early models of the Lau Basin focused on the rate of basin opening as the complete picture of crustal accretion, but new research has shown that crustal growth has been highly episodic and, in the last 1.5 m.y., dominated by extension distributed across many active spreading segments and deformation zones (e.g., Martinez and Taylor, 2006). In the southern Lau Basin, >100,000 km² of backarc crust has been created at the ELSC and CLSC in the last 5 m.y. In the same time period, 202,000 km² of backarc crust was created among the different assemblages of the northern Lau Basin, including 33,450 km² in the last 1.5 m.y. Our mapping also suggests that important episodes of crustal growth and basin opening were not the result of simple backarc spreading but included significant non-volcanic rifting, magmatism at leaky transform faults and deformation zones, and intraplate volcanism.

The greatest part of the map area is occupied by relict arc crust (310,568 km² and 109,424 km² in the Lau and Tonga Ridges, respectively), reflecting the long history of construction of the Vitiaz arc prior to opening of the Lau Basin. The Lau Ridge covers 28% of the map area, and the Tonga Ridge 10%. Assemblages that can be confidently identified as originating from a backarc spreading center account for only ~28% of the map area (Table 7). The earliest backarc crust (143,775 km² of transitional arc-backarc crust of the West Lau Basin assemblage) covers 13% of the map area and accounts for 29% of the total backarc crust. This large area of crust formed over a period of steady crustal growth from at least 5.5 Ma to ca. 2.5 Ma. Subsequent episodes of crustal accretion between 2.5 and 1.5 Ma were dominated by the East Lau Basin assemblage (90,325 km²) in the south and the Cikobia (47,275 km²) and Futuna (28,922 km²) assemblages in the north, corresponding to a period of rapid growth. The young backarc assemblages that appeared in the northern Lau Basin within the last 1.5 m.y. are far more numerous but also much smaller. The Fonualei assemblage is the largest, covering 16,145 km²; the Mangatolu, Northeast Lau Basin, Northwest Lau Basin, and Rochambeau assemblages are the smallest, from 1871 to 8155 km². Based on the total width (~222 km) and inferred ages of these assemblages, the average spreading rate in the last 1.5 m.y. was 148 mm/yr, consistent with published values. However, because opening of the basin has been partitioned across five different spreading centers (FSC, RR, FRSC, NWLSC, NELSC), the individual spreading rates were much slower (8–110 mm/yr; Pelletier et al., 1998; Zellmer and Taylor, 2001; Bird, 2003; Lupton et al., 2012; Sleeper and Martinez, 2016). Large areas of relict backarc crust older than 1.5 Ma (North Futuna, South Futuna, Oelelevu, and Zephyr assemblages) cover 72,208 km² and account for almost 15% of the total backarc crust. They belong to an episode of protracted crustal growth in the early history of opening before the emergence of the presently active arc-backarc spreading centers.

The mapped areas of different assemblage types confirm that crustal accretion has occurred simultaneously at widely spaced zones of extension and at major centers of intraplate volcanism. More than 10% (66,154 km²) of the backarc comprises formations associated with intraplate volcanism, non-volcanic rifting, leaky transforms, and deformation zones. The large volcanic fields of the Niuaofo’ou and Southeast Futuna assemblages cover 11,769 km². This does not include >3200 individual volcanoes that have a total area of 29,877 km² (Table 3) and 60 other seamounts that cover an area of 23,334 km², equivalent to some of the largest mapped assemblages. Unassigned, relict backarc, and transitional arc-backarc crust cover 64,921–81,598 km², and a significant area consists of foundered blocks of old arc crust stranded in the backarc region (e.g., Sleeper and Martinez, 2016; Schmid et al., 2020). However, these crust types cannot be confidently related to specific episodes of basin opening. The undivided crust of the South Vitiaz assemblage alone covers 40,967 km², highlighting the need for additional surveys in these areas.

The rates of crustal growth can be quantified in terms of area-age relationships (e.g., Peucker-Ehrenbrink and Miller, 2002; Dürre et al., 2005; Wilkinson et al., 2009). Crustal growth during the evolution of the Lau Basin is tracked by
This approach is useful for identifying changes in far-field tectonic stresses that are commonly correlated with pulses of growth. An early stage of rapid crustal growth in the early Eocene produced the Lau Ridge, Tonga Ridge, Tonga Forearc, and North Lau Forearc assemblages (Fig. 8). After 12 Ma, at the end of subduction along the Vitiaz trench and in the earliest stages of opening to form the Lau Basin, a protracted episode of slow crustal growth produced the South Vitiaz, West Lau Basin, Zephyr, and Qelelevu assemblages (Fig. 9). At ca. 5 Ma, a rapid transition from rifting to spreading formed the East Lau Basin assemblage, followed by initiation of the Tofua arc at ca. 3 Ma. Spreading at the FSC and possibly the NCSC also occurred at this time to produce the large Futuna and Cikobia assemblages. The significant expansion of the basin between 5 Ma and 3 Ma correlated with the appearance of the Peggy Ridge as a major structure accommodating basin opening. During the last 3 m.y., the rate of crustal growth has been ~115,600 km²/m.y. (Fig. 9), with many small assemblages emerging as a result of the microplate breakout in the north (Figs. 10 and 11).

The predominance of a few large assemblages in the initial period of rapid crustal growth in the Lau Basin is consistent with the inferred long ridge lengths at that time (e.g., Taylor et al., 1996; Martinez and Taylor, 2006). The more abundant and smaller assemblages in the last few million years agrees well with the models of microplate formation as basin opening progressed (Conder and Wiens, 2011; Sleeper and Martinez, 2016). The Peggy Ridge marks the boundary between the two domains of relatively fast early crustal growth in the south and the more recent breakup and apparent slower growth in the north. The strong deformation in the north is partly decoupled from the more organized basin opening in the south by rotation of non-rigid domains of the crust (Wetzel et al., 1993; Baxter et al., 2020). This style of crustal accretion has been difficult to model based on magnetic inversions because of the lack of obvious reversals in the available data (e.g., Sleeper and Martinez, 2016). A number of studies suggest that changes in the rate and distribution of crustal growth have a direct link to mantle flow, such as the sudden release of enriched mantle material that resulted in the switch from mainly arc rifting to backarc spreading along the ELSC (Dunn and Martinez, 2011; Sleeper et al., 2016). Significant along- and across-strike changes in upper crustal seismic velocity and gravity imply discontinuities in the mantle supplying the melts (Dunn and Martinez, 2011; Schmid et al., 2020), and in the north, the complex organization of crustal assemblages may reflect a lack of a stable zone of upwelling.

**FIGURE 9. Model of crustal growth within the Lau backarc basin based on area-age relationships of the mapped assemblages. The area-age plot shows rates of crustal growth, which can be quantified by comparing the cumulative areas of the assemblages with their inferred ages. The plot shows a significant increase in the rate of crustal growth coinciding with the formation of the Peggy Ridge and the emergence of the large East Lau Basin, Futuna, and Cikobia assemblages during the initial opening of the Lau Basin. Current rates of crustal growth are lower, with accretion distributed across many active spreading centers. The Tofua Arc assemblage is shown for reference, but it is not part of the crustal growth of the backarc assemblages. Note: To improve diagram clarity, inferred ages are averages of the minimum and maximum age for each assemblage; actual ages are referenced in the text. MTJ—Mangatolu triple junction; Niua.—Niuafo’ou; RR—Rochambeau.**

**DISCUSSION AND CONCLUSIONS**

The Lau Basin is arguably one of the most important settings for understanding crustal growth in the oceans today (Martinez and Taylor, 2006). Early pictures of the crustal accretion focused on a simple two-stage model of arc rifting and seafloor spreading, first producing the West Lau Basin and then the East Lau Basin assemblages. However, it is clear that more complex growth soon emerged, with early rift segments taken over by multiple spreading centers and highly distributed extension in the north. Basin opening was diachronous and neither symmetric nor unidirectional. Major structures along which new crust was accreting jumped repeatedly both to the west (e.g., from the ELSC to the CLSC and LETZ) and to the east (e.g., toward the arc along the Valu Fa Ridge and FRSC). Identical units have formed in different assemblages at the same time (e.g., at multiple spreading centers simultaneously) and even at different times in the same location (e.g., rifting of preexisting backarc crust at the MTJ). The result is a mix of active and relict arc and backarc crust with extensive overprinting and inheritance, as indicated by low-velocity andesitic material dominating some backarc crustal blocks (Schmid et al., 2020). Rates of deformation associated with the different phases of opening of the basin have been deduced from studies of magnetic data (Sleeper and Martinez, 2016) and teleseismic data (Conder and Wiens, 2011; Baxter et al., 2020). In...
the last 2–3 m.y., failed rifts, ridge jumps, and deformation zones linked to distributed extension have resulted in mainly slow rates of accretion at the individual spreading centers. The large number of spreading centers led to high rates of basin opening observed in the north, despite the slow spreading. The incremental opening has been accommodated in part by the Peggy Ridge, which separated the northern Lau Basin from the southern Lau Basin following acute rotation of the Fiji platform. Ruellan et al. (2003) previously suggested that subduction of the Louisville seamount chain (LSC) has temporarily locked backarc spreading in the south, where the arc experiences the most compression today, whereas farther north, the LSC has already passed, unlocking the backarc rift and allowing basin opening to accelerate. The LSC would have migrated past the Peggy Ridge at ca. 3.5 Ma, when maximum basin opening commenced in the north.

The formation-level geological map of the Lau Basin provides new insight into the nature of crustal growth in this iconic arc-backarc system. At 1:1,000,000 scale, the spatial and temporal resolution of the map is sufficient for performing quantitative analysis of the area-age relationships and identifying lithostratigraphic correlations that track where, when, and how the backarc crust was created. The makeup of the crust (38% relict arc, 9% forearc, 7% active arc, 20% active backarc rift and spreading centers, 13% transitional arc-backarc, and 8% relict backarc; Table 7) differs markedly from that of other intraoceanic subduction systems such as the Mariana backarc and the North Fiji Basin, which are dominated by crust of relatively uniform
structure and composition originating at long-lived spreading centers. The mapped assemblages of the Lau Basin are a product of microplate tectonics, as originally defined in this area by Conder and Wiens (2011) and Sleeper and Martinez (2016). Early workers initially identified four microplates, but Baxter et al. (2020) suggested there may be as many as six microplates actively developing in the northern part of the basin alone (Fig. 1).

Microplates are structural rather than lithostratigraphic domains, and so they typically contain elements of several different assemblages. For example, the Futuna microplate (Fig. 1), bounded by the FSC in the west and the NWLSC in the east, contains parts of four different assemblages: the eastern half of the Futuna assemblage, all of the South Futuna assemblage, and portions of both the Southeast Futuna and Northwest Lau Basin assemblages. Where new microplates are forming, such as in the area between the CLSC and the northern termination of the ELSC (identified by Conder and Wiens [2011] as an emerging “nanoplate”), crust from both the Central Lau Basin assemblage and the East Lau Basin assemblage is being transferred to the new microplate.

Thus, the proliferation of microplates in the north of the Lau Basin is the main control on the large number of assemblages in the map area (Figs. 10 and 11). Several seismic studies of the backarc crust in the Lau Basin have identified unexpected high-velocity zones (7.3–76 km/s; Dunn and Martinez, 2011; Arai and Dunn, 2014; Schmid et al., 2020), which are interpreted to indicate magmatic underplating (Handy and Streit, 1999; Mjelde et al., 2002). This has been observed in other backarc regions, including the Izu-Bonin-Mariana arc-backarc system in the western Pacific Ocean (Takahashi et al., 2008) and the Yamato Basin in the southern Japan Sea (Sato et al., 2014), and several authors have suggested it is a consequence of elevated upper-mantle temperatures (Fujisawa et al., 2001; Ruellan et al., 2003). Thus, the complex pattern of crustal growth and microplate formation may reflect structurally controlled mantle domains that in turn influence the distribution of magmatic and hydrothermal activity.

The rate of crustal accretion across the basin is on the order of 0.3 km/kyr, or nearly 2% of the amount of new oceanic crust formed globally at mid-ocean ridges (~18 km/yr; Cogné and Humler, 2006; Deligne and Sigurdsson, 2015). The cumulative length of active spreading centers in the basin (~1500 km) exceeds the entire length of the adjacent Tofua arc by nearly 500 km, and the length of new and emerging microplate boundaries, combining results of Conder and Wiens (2011) and Baxter et al. (2020), is now >860 km longer than the entire north of the Lau Basin, including the Rochambeau, Northwest Lau Basin, Southeast Futuna, Niuafo’ou, and Peggy Ridge assemblages and rivals the helium plume of the East Pacific Rise (Lupton et al., 2012, 2015). Large new hydrothermal fields have now been discovered at plume-related backarc volcanoes in the South Futuna assemblage at Kulo Lasi (Fouquet et al., 2015; Konn et al., 2018), providing further support for this model.

In addition to the proof of concept that geological mapping of the seafloor can be done at 1:1,000,000 scale using RPM techniques, the new geological map of the Lau Basin shows the benefits of regional seafloor mapping for understanding crustal growth and composition at a scale that is appropriate for tectonic interpretations, emphasizing the lack of such maps in the published record. Although it is hard to assess limitations in terms of identifying formation types from the remote-sensing data, with the different data sets now available for the Lau Basin, we believe that the uncertainties are not large enough to challenge the geological model. Geological maps at this scale are of fundamental importance for quantitative assessment of crustal makeup and evolution and can be analyzed directly in terms of area-age relationships. The 1:1,000,000-scale map of the Lau Basin provides a further useful reference and legend for future geologic studies in the region.

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