

Multiple melt source origin of the Line Islands (Pacific Ocean)

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ABSTRACT

The Line Islands volcanic chain in the central Pacific Ocean exhibits many characteristics of a hotspot-generated seamount chain; however, the lack of a predictable age progression has stymied previous models for the origin of this feature. We combined plate-tectonic reconstructions with seamount age dates and available geochemistry to develop a new model that involves multiple melt regions and multiple melt delivery styles to explain the spatial and temporal history of the Line Islands system. Our model identifies a new melt source region (Larson melt region at ~17°S, ~125°W) that contributed to the formation of the Line Islands, as well as the Mid-Pacific Mountains and possibly the Pukapuka Ridge.

INTRODUCTION

The Line Islands chain is a collection of seamounts and volcanic ridges located in the central Pacific Ocean with a general north-west-southeast trend along its 4500 km length (Fig. 1; Fig. S1 in the Supplemental Material¹). The eruption age of the Line Islands generally falls between 88 and 50 Ma; however, there is no apparent age progression along the volcanic chain (Clague and Jarrard, 1973; Winterer, 1973; Jackson and Schlanger, 1976; Lanphere and Dalrymple, 1976a, 1976b; Schlanger et al., 1976; Saito and Ozima, 1977; Haggerty et al., 1982; Davis et al., 2002).

Previous attempts to explain the origin of the Line Islands with a single hotspot trace (e.g., Morgan, 1972) were unable to account for the complex age distribution, so models with multiple hotspots were proposed (e.g., Crough and Jarrard, 1981; Duncan and Clague, 1985). Alternative models included leaky transform faults (e.g., Orwig and Kroenke, 1980; Farrar and Dixon, 1981) or tensional cracks in the lithosphere related to cooling of the plate or differential far-field stresses that provided pathways for sublithospheric melt to erupt on the seafloor (e.g., Natland and Winterer, 2005). A more recent interpretation also suggested that neither single nor multiple hotspot models can explain the origin of the Line Islands (Davis et al., 2002). Instead, the melting of a

heterogeneous mantle in a region of diffuse lithospheric extension was thought to lead to the complex eruption history.

We revisited the question of the origin of the Line Islands by developing a tectonic reconstruction of the Pacific plate from 130 Ma to present. Our model uses updated plate motion models (Matthews et al., 2016) and a compilation of age-dated seamounts (Clouard and Bonnevillie, 2005; Seamount Catalog Home Page, <https://earthref.org/SC/> [accessed August 2019]) to constrain the spatial and temporal eruption history of the Line Islands system. We also reviewed isotope geochemistry data to verify that our interpretation is consistent with available information. Our study primarily represents a test of mantle plume models for the origin of the Line Islands system, but we acknowledge that some characteristics of this complex region are not readily explained solely by mantle plumes and may require alternative tectonic and magmatic processes.

REGIONAL MORPHOLOGY

The morphology of the Line Islands volcanic chain varies dramatically along its length (Fig. 1A; Fig. S1). The northernmost region, which we term the Northern Volcanic Province, is a collection of individual seamounts and east-west-trending seamount chains distributed over a 900 × 1500 km region located

immediately southeast of the Mid-Pacific Mountains, including Johnston Atoll. The central region of the chain is defined by the 1200-km-long and 200-km-wide volcanic Line Islands Ridge. The northern end of the Line Islands Ridge is a circular plateau that includes Kingman Reef and Palmyra Atoll, while the southern end includes Fanning and Christmas Islands. Continuing southward, the Boudeuse Ridge is a 1200-km-long linear chain of closely spaced seamounts that forms the southern segment of the Line Islands system. The age of volcanism along the length of the Line Islands system ranges from 91 to 24 Ma, with most of the dated seamounts (23 of 27) having ages between 86 and 55 Ma (Table S2) and no apparent age progression along the volcanic chain (Fig. 1B).

Two additional volcanic features located at either end of the Line Islands are the Mid-Pacific Mountains to the northwest and the Pukapuka Ridge to the southeast (Fig. 1A; Fig. S1). The Mid-Pacific Mountains are a broad volcanic plateau extending over 2000 km, with a roughly east-west trend, southwest of the Hawaiian Ridge. The western half of the Mid-Pacific Mountains is roughly equidimensional in plan view (1200 × 1200 km) with age dates ranging from 128 to 88 Ma, while the eastern half is more elongate (800 × 150 km) and oriented in a southwest-northeast direction with a single eruption age date of ca. 73 Ma. At the easternmost end, there is a series of narrow ridges trending southwest-northeast that includes Necker Ridge with eruption ages ranging from 88 to 82 Ma. Pukapuka Ridge, at the southern end, is a series of discontinuous volcanic ridges with an east-west trend spanning a distance of 2500 km between the Tuamotu Islands (to the west) and the Rano Rahi seamounts (to the east). The volcanism along Pukapuka Ridge exhibits a general age-progressive trend from ca. 11 Ma at the

¹Supplemental Material. Supplemental information, Figures S1 and S2, Tables S1–S3, and Videos S1–S4. Please visit <https://doi.org/10.1130/G49306.1> to access the supplemental material, and contact editing@geosociety.org with any questions.

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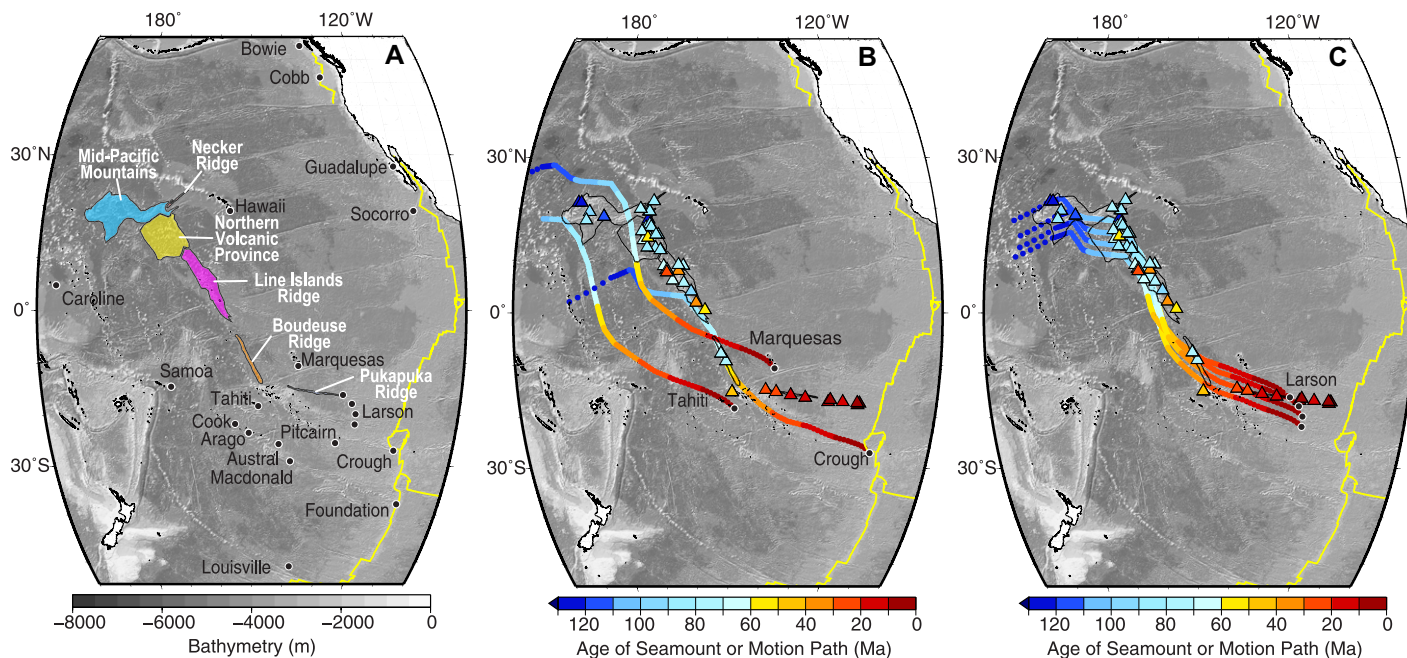


Figure 1. Series of maps of the central Pacific Basin illustrating (A) features related to the Line Islands system (white text), hotspots (black dots with white outlines), and zero-age plate boundaries (yellow lines); (B) previously identified hotspots that potentially contributed to Line Islands system; and (C) “hotspot” tracks for the proposed Larson melt region. Triangles denote locations of dated seamounts. Colors of seamounts and hotspot tracks indicate age of feature.

western end to ca. 6 Ma at the eastern end near the East Pacific Rise (Sandwell et al., 1995).

RECONSTRUCTION MODELS

We used GPlates tectonic reconstruction software (Müller et al., 2016; <https://www.gplates.org/>) and included rotation poles (Matthews et al., 2016), hotspot locations on the Pacific plate (Table S1; Courtillot et al., 2003; Morgan and Morgan, 2007), and a compilation of dated seamounts in the central Pacific (Table S2; Clouard and Bonneville, 2005; Seamount Catalog Home Page) to model the volcanic evolution of the Line Islands (Figs. 1 and 2). We used a qualitative forward modeling approach with a series of trial-and-error hotspot locations to obtain a visual best-fit model.

Our initial models displayed good temporal and spatial correlation of the Crough hotspot track with the Boudeuse Ridge, the Tuamotu Islands, and possibly the southern end of the Line Islands (Fig. 1B). However, the Northern Volcanic Province and northern half of the Line Islands Ridge were not well predicted by the Crough hotspot track, and while they are closest to the Marquesas hotspot track, they are still far away (~500 km). Furthermore, this initial reconstruction did not account for the mixture of seamount ages along the Line Islands Ridge and the Northern Volcanic Province.

Our preferred reconstruction requires an additional melt source region currently located along an arc between 16°S, 129°W and 22°S, 124°W (Fig. 1C), which we call the Larson melt region, in memory of Roger Larson’s

significant contributions toward unraveling the complex tectonic history of the Pacific Basin (Pockalny et al., 2015; Fletcher et al., 2020). This new hotspot is located between the Crough and Marquesas hotspots near the eastern limit of the Pukapuka Ridge. The tectonic reconstruction traces a path along the Line Islands Ridge, through the heart of the Northern Volcanic Province, and along the Mid-Pacific Mountains (see Videos S1–S4 in the Supplemental Material).

RESULTS

The spatial and temporal history of the Larson melt region is coincident with much of the volcanism along the Line Islands system, and also the adjacent Mid-Pacific Mountains and Pukapuka Ridge (Figs. 1C, 2, and 3). The Crough hotspot appears to coincide with the southern end of the Line Islands, while the Marquesas and Tahiti hotspots potentially may coincide with portions of the northern end of the Line Islands but to a much-reduced extent (Fig. 1B).

In our proposed scenario (Figs. 2 and 3), the western Mid-Pacific Mountains were formed 130–110 Ma through a plume-ridge interaction with the Larson melt region. The melt region at this time was likely a robust melt event (i.e., plume head) located within 500 km of the Pacific-Farallon spreading axis (e.g., Thiede et al., 1981; Fletcher et al., 2020). The eastern portion of the Mid-Pacific Mountains appears to be younger than the western portion and overlays an inferred trace of a precursor of the Molokai Fracture Zone. A later stage of distributed volcanism on the Mid-Pacific Mountains may have

been due to the passage of the Tahiti hotspot from 110 to 85 Ma.

Necker Ridge and related northeast-trending narrow volcanic ridges at the eastern end of the Mid-Pacific Mountains (Figs. 1–3; Fig. S1) may be the result of an off-axis extensional eruption event that coincided with the Larson melt region at ca. 95 Ma or with the Marquesas hotspot at 85–75 Ma.

According to our model, the Line Islands proper are likely the combined result of the Larson, Crough, and Marquesas hotspots (Figs. 2 and 3). The Northern Volcanic Province appears to have been caused by distributed volcanism associated with the Larson melt region from 100 to 75 Ma and possibly the Marquesas hotspot from 75 to 65 Ma. The northern half of the Line Islands Ridge coincides with the passage of the Larson melt region from 80 to 65 Ma, while the southern half coincides with the Crough hotspot from 100 to 85 Ma and the Larson melt region from 70 to 50 Ma. The cross-grain ridges emanating from the eastern side of the Line Islands Ridge suggest an extensional environment (Davis et al., 2002), but we interpret the similar trends of the hotspot tracks and the Line Islands as a melt conduit hotspot track (e.g., Morgan, 1972). The track of the Crough hotspot coincides with the Boudeuse Ridge from 75 to 45 Ma and also suggests a melt conduit melt delivery style.

Beyond the southern end of the Line Islands, the Crough hotspot coincides with the Tuamotu Islands from 50 to 20 Ma and parallels the series of seamounts connecting the Tuamotu Islands

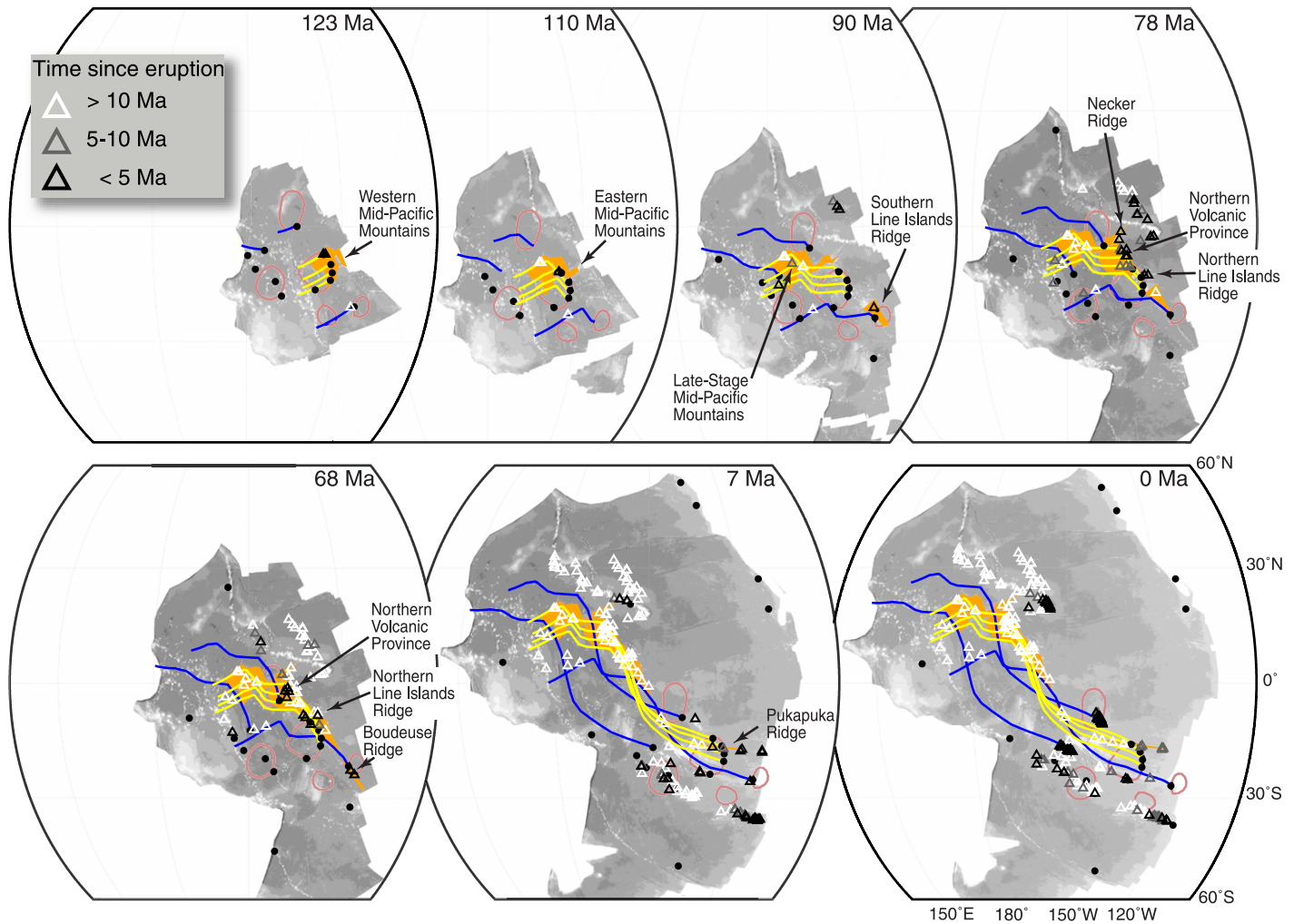


Figure 2. Series of tectonic reconstructions of the Pacific plate illustrating the melt source and timing of various eruptive events related to the Line Islands system. Motion paths of the Larson melt region (yellow lines) and previously identified hotspots potentially contributing to the Line Islands system (blue lines) are shown. Dated seamounts are color-coded according to time since eruptions (black <5 m.y., gray 5–10 m.y., white >10 m.y.). Pink circles are locations of selected upward-projected shear-wave anomaly isosurfaces (French and Romanowicz, 2015) shown in Figure 4. Changing portions of the Line Islands system are shown in orange to indicate approximate timing of their formation and appearance on the seafloor. See Videos S1–S4 in the Supplemental Material (see footnote 1) for animated reconstructions.

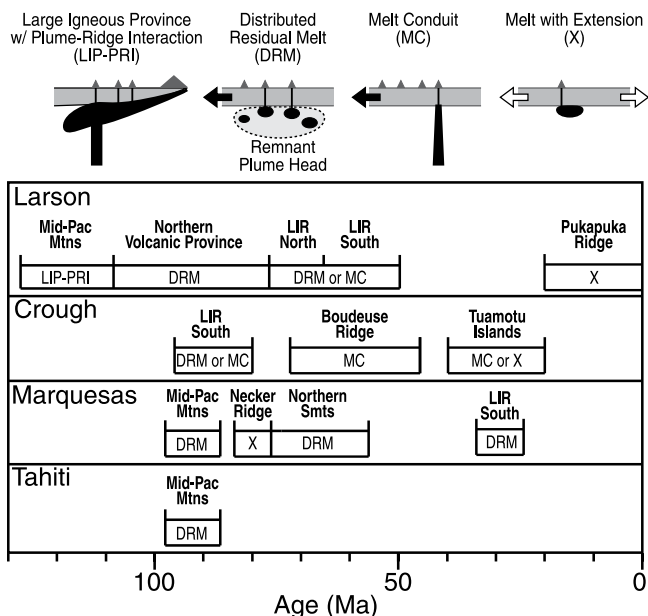


Figure 3. (Top) Simplified diagrams of four melt delivery styles (e.g., Morgan, 1972; Kincaid et al., 1995; McNutt et al., 1997; Lynch, 1999) proposed to contribute to the formation of the Line Islands system (LIR). (Bottom) Time lines of eruption timing and melt delivery style for each of four contributing melt sources.

with the Easter microplate (Figs. 2 and 3). Limited seamount age information does not provide enough information to assess the melt delivery style, so these features may be due to either melt conduits or lithosphere extension. The Pukapuka Ridge, however, is likely the result of lithosphere extension, with the Larson melt region as a possible melt source (Sandwell et al., 1995; Lynch, 1999; Janney et al., 2000).

DISCUSSION

We propose four different melt sources (e.g., Crough, Marquesas, Tahiti, and Larson hotspots) to explain the formation of the Line Islands and adjacent Mid-Pacific Mountains and Pukapuka Ridge (Figs. 2 and 3; Fig. S2). The Larson and Crough hotspots were the predominant contributors to the volcanism, but neither of these melt sources is consistently listed in catalogs of deep mantle plumes or hotspots (e.g., Courtillot et al., 2003; Montelli et al.,

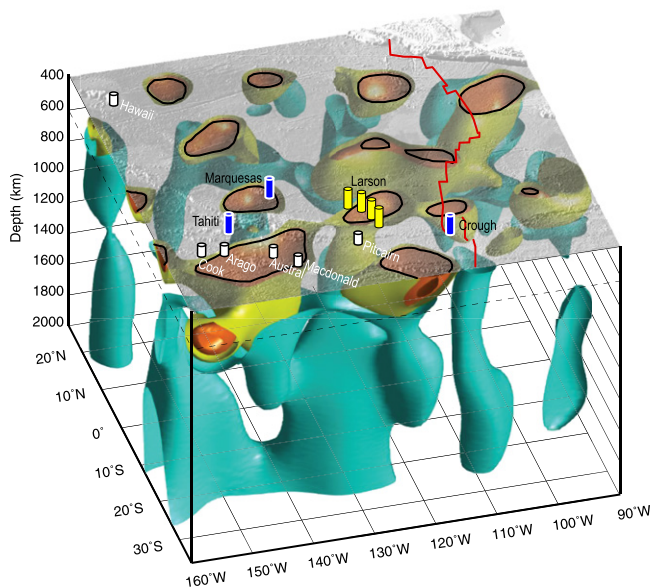


Figure 4. Three-dimensional rendering of shear-wave velocity anomalies ($\delta V_s/V_s$) (French and Romanowicz, 2015) overlain with shaded bathymetry. Here, -0.75 velocity-anomaly isosurface (cyan) is shown from 2000 km to 660 km depth, and -1.2 velocity-anomaly isosurface (yellow) and -1.5 velocity-anomaly isosurface (red) are shown up to 410 km depth, with -1.5 velocity-anomaly isosurface (black line) projected upward onto bathymetry. Locations of hotspots (white cylinders), hotspots contributing to the Line Islands system (blue cylinders), and the Larson melt region (yellow cylinders) are shown.

2006). Shear-wave velocity models (French and Romanowicz, 2015), however, suggest that both of these hotspots may have been associated with mantle plume sources (Fig. 4). The Larson and nearby Pitcairn hotspots are linked to a deep-mantle plume source in the broad South Pacific superswell region. The Crough and possibly the Easter hotspots are associated with a midmantle plume source near the Easter microplate. The Marquesas hotspot also appears to be connected to a midmantle plume source, while the Tahiti hotspot appears to have a shallow mantle source, based on the shear-wave velocity models.

Several melt delivery processes are proposed to explain the various volcanic morphologies observed along the Line Islands system (Fig. 3). Our proposed plume-ridge origin of the Mid-Pacific Mountains, the melt conduit origin of the Boudeuse Ridge, and the lithosphere extension origin of the Pukapuka Ridge are consistent with previous explanations (Winterer and Metzler, 1984; Lynch, 1999; Davis et al., 2002). The melt delivery style of the Line Islands Ridge was most recently attributed to diffuse lithospheric extension and subsequent volcanism (Davis et al., 2002); however, the large erupted volumes and the orthogonal orientation of the volcanic chain relative to the intersecting fracture zones are significantly different from other proposed extensional volcanic ridges (e.g., Pukapuka Ridge). We believe the spatial and temporal history of the Line Islands Ridge is better explained by overlapping conventional hotspot tracks of the Crough hotspot and Larson melt region. The Northern Volcanic Province was also previously attributed to lithosphere extension to explain the cross-grain seamount chains (e.g., Keli Ridge) in the region (Natland, 1976). We believe this mechanism is still a viable origin, but we also suggest a distributed volcanism

origin to explain the dispersed seamounts. In our interpretation, the melt source for the distributed volcanism of cross-grain seamounts would be small, residual mantle heterogeneities related to the passage of the Larson melt region and/or Marquesas hotspots.

Limited geochemical data from seamounts and ridges along the Line Islands system and related volcanic features provide additional constraints and clues for their possible origins (Fig. S2; Table S3). This is best shown in the plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$, where the majority of samples from the Northern Volcanic Province and northern section of the Line Islands Ridge (yellow triangles) (Garcia et al., 1993; Konter et al., 2008) cluster together and are coincident with the samples from the Boudeuse Ridge (blue inverted triangles) (Garcia et al., 1993), one sample from Necker Ridge (yellow diamond) (Garcia et al., 1993), and a sample at the western end of the Pukapuka Ridge (yellow star) (Janney et al., 2000). This clustering and the observed trends in all of the isotopic ratio plots are consistent with a similar mantle source, although the overlap with several regional data arrays may not require a truly unique source.

A second, smaller cluster of samples from the southern end of the Line Islands (purple squares) and another Necker Ridge sample (yellow diamond) exhibit elevated $^{87}\text{Sr}/^{86}\text{Sr}$ at a given $^{206}\text{Pb}/^{204}\text{Pb}$ ratio. These samples fall within the Marquesas compositional cloud, which trends toward higher $^{87}\text{Sr}/^{86}\text{Sr}$. This signature is consistent with our tectonic/volcanic reconstruction model for the southern end of the Line Islands Ridge, which suggests influence of the Marquesas hotspot in this region at ca. 30–10 Ma. The cause of the offset of the Necker Ridge sample is uncertain but may be related to the Marquesas hotspot passing Necker Ridge at ca. 80 Ma.

The isotope ratios of the samples along the Pukapuka Ridge suggest possible mixing between the Larson melt region (yellow star) and depleted mid-oceanic ridge basalt (MORB) mantle (DMM), with samples reflecting a greater contribution from DMM toward the east (white stars). This is consistent with our location of the Larson melt region in the vicinity and a lithosphere extension origin.

CONCLUSIONS

We propose a new multiple-hotspots model to explain the complex Line Islands system. Our model includes three previously suggested hotspots (Crough, Marquesas, Tahiti), as well as the new proposed Larson melt region in the area of 125°W – 129°W and 16°S – 22°S . This new model not only addresses the eruption history of the Line Islands system, but it also may account for portions of the Mid-Pacific Mountains and the Pukapuka Ridge. Not all characteristics of this complex region are readily explained by mantle plumes alone, and alternative tectonic and magmatic processes may also be required. Overall, our study demonstrates the merits of a mantle plume model to explain the origins of the Line Islands system. Perhaps most importantly, our model provides predictive consequences for future tests with additional age dating and geochemical analyses along poorly constrained sections of the Line Islands system.

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