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Toroidal flow around the Tonga slab moved the Samoan plume during the Pliocene

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ABSTRACT

Age-progressive seamount tracks generated by lithospheric motion over a stationary mantle plume have long been used to reconstruct absolute plate motion (APM) models. However, the basis of these models requires the plumes to move significantly slower than the overriding lithosphere. When a plume interacts with a convergent or divergent plate boundary, it is often deflected within the strong local mantle flow fields associated with such regimes. Here, we examined the age progression and geometry of the Samoa hotspot track, focusing on lava flow samples dredged from the deep flanks of seamounts in order to best reconstruct when a given seamount was overlying the mantle plume (i.e., during the shield-building stage). The Samoan seamounts display an apparent local plate velocity of 7.8 cm/yr from 0 to 9 Ma, 11.1 cm/yr from 9 to 14 Ma, and 5.6 cm/yr from 14 to 24 Ma. Current fixed and mobile hotspot Pacific APM models cannot reproduce the geometry of the Samoa seamount track if a long-term fixed hotspot location, currently beneath the active Vailulu'u Seamount, is assumed. Rather, reconstruction of the eruptive locations of the Samoan seamounts using APM models indicates that the surface expression of the plume migrated ∼2° northward in the Pliocene. Large-scale mantle flow beneath the Pacific Ocean Basin cannot explain this plume migration. Instead, the best explanation is that toroidal flow fields—generated by westward migration of the Tonga Trench and associated slab rollback—have deflected the conduit northward over the past 2–3 m.y. These observations provide novel constraints on the ways in which plume-trench interactions can alter hotspot track geometries.

INTRODUCTION

Age-progressive volcanic chains at hotspots are produced as Earth's lithosphere migrates over stationary or slowly moving (compared to plate motions) mantle plumes (Morgan, 1972; Wessel and Kroenke, 2008; Koppers et al., 2021). This phenomenon provides an ideal natural constraint with which to calibrate the motion of lithospheric plates through time relative to a fixed reference frame, known as an absolute plate motion (APM) model (e.g., Duncan and Clague, 1985; Wessel and Kroenke, 2008; Doubrovine et al., 2012). Utilizing hotspot tracks to produce APM models requires that any independent motion of the underlying mantle plume must be significantly slower relative to the motion of the overriding lithosphere (Wessel and Kroenke, 2008). To a first order, this assumption appears to be validated by APM models that reproduce the geometry and age progressions of numerous seamount chains on the same plate (Duncan and Clague, 1985; Wessel and Kroenke, 2008). Numerical models of plume ascent in mantle flow fields predict that plumes should move independently through time as a function of deflection in mantle convective fields; however, the precise prediction of these movements requires accurate knowledge of the plume's viscosity, buoyancy, and size relative to the ambient mantle (Steinberger, 2000; Doubrovine et al., 2012; Konrad et al., 2018). Thus, independent observations of potential plume movement are required to test and constrain these models (e.g., Tarduno et al., 2003; Koppers et al., 2012; Konrad et al., 2018).

To date, the only plume that has shown significant evidence (i.e., via age progression, paleomagnetic reconstructions, and numerical models) of rapid independent motion in the Pacific Ocean Basin is the Hawaiian-Emperor plume in the 80–50 Ma time frame (Tarduno et al., 2003; Wessel and Kroenke, 2009; Konrad et al., 2018). However, others have argued that motions between Pacific plumes are not required to fit the observed inter-hotspot distance trends, and that the age progressions are biased by minimal seamount sampling in the Emperor Seamount Chain and true polar wander occurring in the Eocene–Cretaceous, explaining the paleomagnetic observations (Gaastra et al., 2022). In addition, independent tests of mobile versus fixed hotspot APM models have indicated that the fixed hotspot model better fits young Pacific hotspot track age progressions and geometry (Wang et al., 2019). Here, we compiled age determinations from lava flows sourced by the Samoan plume to provide evidence that the apparent surface expression of the hotspot has not been fixed, but instead was shifted northward by 2° during the Plio-

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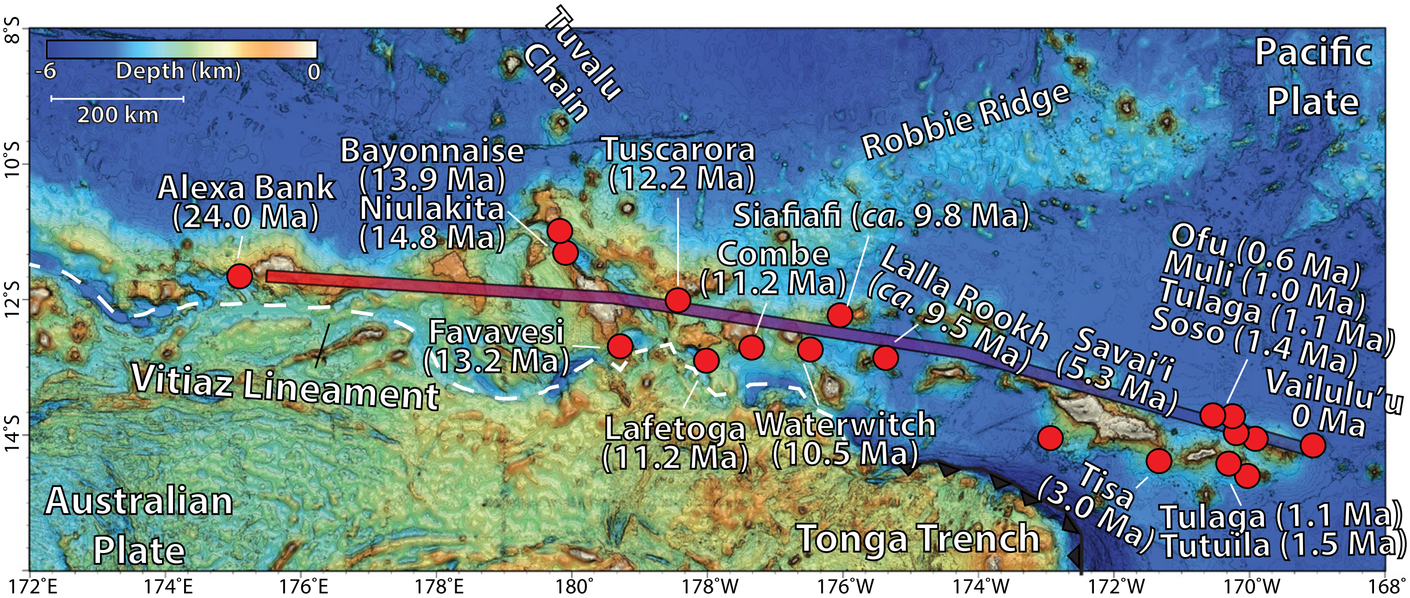

Figure 1. **Bathymetric map of Samoan Seamount Province. Seamounts, dredge locations (red dots), and oldest $^{40}Ar/^{39}Ar$ age determinations for each feature used in this study are shown. Color scale bar (see Fig. 3 for ages) represents mean hotspot track path and age progression, determined using piecewise cubic Hermite interpolating polynomial of seamount locations and calculated age progressions. Mean hotspot track does not match any fixed Pacific plate motion model. Bathymetry data are merged multibeam and satellite altimetry data set from General Bathymetric Chart of the Oceans (GEBCO; Weatherall et al., 2015). White dashed line represents approximate paleo-Vitiaz boundary; black line shows region of active subduction.**

cene. Shallow mantle flow resulting from the approaching Tonga Trench was likely responsible for the shift. This provides novel insights into the role that plate-plume interaction plays in affecting apparent age progressions and geometry of seamount chains.

SAMOAN SEAMOUNT PROVINCE

The Samoan plume has been sourcing islands and seamounts since at least 24 Ma (Fig. 1; Duncan, 1985; Hart et al., 2004; Koppers et al., 2011). The Samoan hotspot track consists of active and recent volcanism on the eastern end beneath Vailulu'u and Malumalu Seamounts (Hart et al., 2000; Sims et al., 2008; Koppers et al., 2011) and older volcanism extending westward to ca. 24 Ma volcanism on Alexa Bank (Hart et al., 2004). Factors complicating the age progression and geomorphology of the seamount chain are pulses of non-Samoan-plume–related volcanism, including ancient structures likely related to the Ontong-Java Nui large igneous province (Fig. 1; e.g., Robbie Ridge; Chandler et al., 2012), Eocene seamounts sourced from the Rurutu-Arago hotspot (Konrad et al., 2018; Finlayson et al., 2018), and recent small-scale, sporadic petite spot-like volcanism likely related to the advancement of the Tonga Trench over the past ~5 m.y. (Hart et al., 2004; Sims et al., 2008; Strak and Schellart, 2018; Reinhard et al., 2019; Price et al., 2022). To aid in filtering the noise from this complex region, we defined whether a recovered lava flow was Samoan in origin based on its (or same dredge) isotopic characteristics (where elevated $^{87}Sr/^{86}Sr > 0.7035$ is diagnostic of the Samoan plume; see compositional fields in Price et al., 2022) as well as following an age progression consistent with the Samoan plume (Hart et al., 2004; Koppers et al., 2011). To best estimate when a seamount was directly above the plume, only lava flows dredged from the deep flanks of islands seamounts were employed (i.e., subaerial lavas were excluded; see Table S1 in the Supplemental Material[1]). This was done to best represent the time of the shield-building stage (e.g., Koppers et al., 2008) as well as to avoid biasing the data toward heavily sampled structures. The lava flows used in this study are listed in the Table S1 and shown in Figure 2.

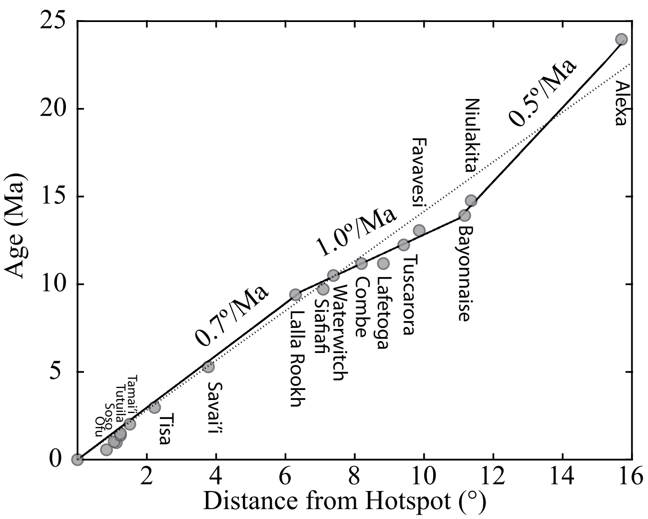

Figure 2. **Age vs. distance from hotspot for Samoan lava flow samples in Table S1 (see text footnote 1). Seamounts are labeled for clarity. Slopes of lines are indicated and broken into three distinct velocity trends. Dotted line represents mean slope of all points (0.71°/m.y. or 7.9 cm/yr). An age constraint of 9.5 Ma is employed for Lalla Rookh (Fig. S1; see text footnote 1), based on new $^{40}Ar/^{39}Ar$ experimental constraints as well as previous K/Ar age determinations (Hart et al., 2004). Model age of 9.75 Ma was used for Siafiafi Seamount based on $^{40}Ar/^{39}Ar$ incremental heating results (Fig. S1; see text footnote 1).**

APPARENT MOTION OF THE SAMOAN PLUME

Despite having a consistent age progression from 24 to 0 Ma (Fig. 2; also see the Supplemental Material), the Samoan hotspot track has

[1]Supplemental Material. File S1: Supplemental text, figures, and table. File S2: Computed Samoa Plume Motion Models. Please visit https://doi.org/10.1130/GEOL.S.24602448 to access the supplemental material; contact editing@geosociety.org with any questions.

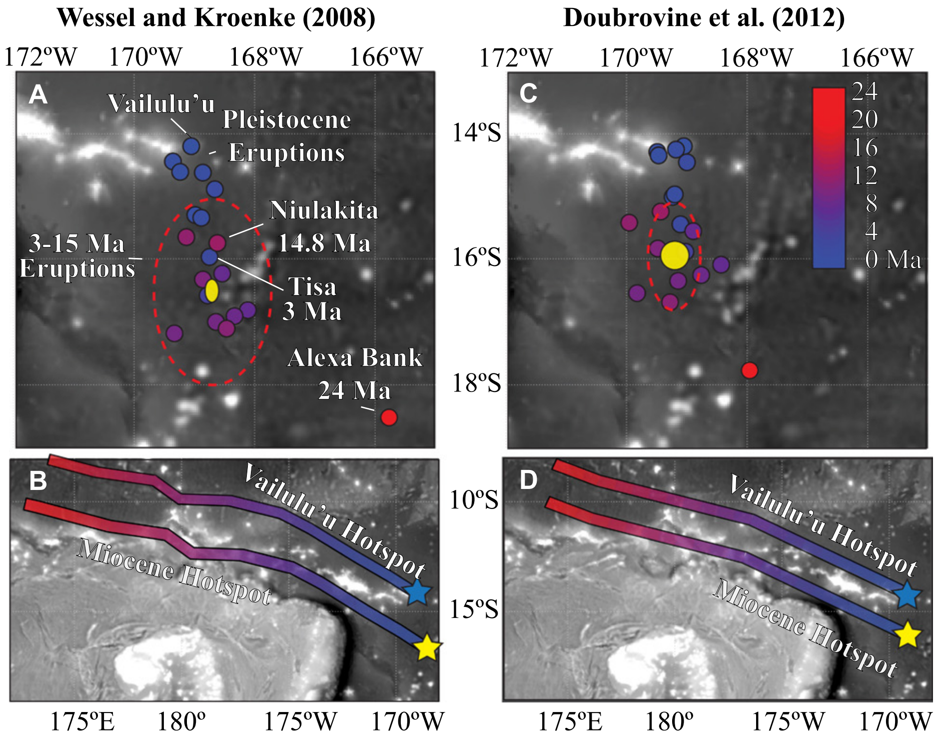

Figure 3. Absolute plate motion (APM) model indicators of plume motion. (A) Reconstructed eruptive latitudes and longitudes for submarine lava flows with Samoa hotspot-like chemistry using WK08-G fixed hotspot APM model of Wessel and Kroenke (2008). Dots represent reconstructed coordinates with key seamounts labeled. Dashed red line represents 2σ uncertainty ellipse for 15–3 Ma reconstructed eruptive locations. Yellow ellipse represents modeled mean hotspot location between 3 and 15 Ma. Size of yellow ellipse represents 2σ uncertainties on mean hotspot location using Monte Carlo simulation (n = 1000), wherein 40% of seamounts were randomly excluded during each iteration. (B) Modeled progressive hotspot tracks using Vailulu'u as current plume location (blue star) and average 15–3 Ma plume location from part A (yellow star). (C) Same as in part A but using mobile hotspot APM model of Doubrovine et al. (2012). (D) Same as in part B but with Doubrovine et al. (2012) APM model.

been previously shown to contain a geometry that is similar to, but deviated from, Pacific APM-derived model projections of the hotspot track (Fig. 3; Brocher, 1985; Hart et al., 2004; Koppers et al., 2008, 2011). Hart et al. (2004) postulated that the misfit is related to a recent (e.g., past ~2 or 1 m.y.) northward shift of the Samoa hotspot location. Here, we reexamined the evidence for plume motion using a larger seamount data set to better constrain if and when the surface expression of the Samoan plume shifted.

To illustrate the apparent plume motion, we took a set of seamount data (latitude, longitude, age) and rotated them based on APM models (both fixed and mobile hotspot) backward in time to the latitude and longitude where the lava flow initially erupted (e.g., Wessel and Kroenke, 1997). If the hotspot has remained largely stationary over time, seamounts comprising a hotspot track will cluster around the active hotspot location. By contrast, plume motion and/or prolonged late-stage volcanism at a seamount will result in reconstructions farther away from the modern hotspot. This technique is thus valuable for studies on mantle plume dynamics to evaluate how plumes have moved relative to the overriding plate. Figures 3A and 3C show the reconstructed eruptive locations using the stationary hotspot APM model of Wessel and Kroenke (2008) (WK08-G) and the mobile hotspot APM model of Doubrovine et al. (2012) (D12). Both results indicate that the plume was either relatively stationary or moved nonsystematically within a limited distance (yellow ellipse, Fig. 3) from 15 to 3 Ma (mean apparent hotspot location: WK08 = 16.5°S, 168.7°W; D12 = 15.9°S, 169.2°W). Assuming the main melt production zone of the plume is currently underlying the active Vailulu'u Seamount (14.2°S, 169.05°W; Hart et al., 2000), this result yields an ~2.3° (WK08-G) or 1.7° (D12) shift in the surface expression between 3 Ma and today. Note that D12 was smoothed to 10 m.y. increments but provided the same first-order observations as the more detailed WK08-G model. To further illustrate this observation, Figures 3B and 3D show reconstructed hotspot tracks rooted relative to the current hotspot location (blue star) and the mean 15–3 Ma hotspot location (yellow star). In both APM models, WK08-G and D12, the adjusted hotspot locations produce a much better fit to the positions and ages of the Samoa seamounts older than 3 Ma, indicating the shift in hotspot location was relatively recent. The Samoa seamounts younger than 3 Ma also display clear en echelon structures that step to the NE instead of a consistent seamount chain that progresses toward the southeast, like the Hawaiian Islands (Fig. 1; Hart et al., 2004; Koppers et al., 2011). This stepwise en echelon structure may be a function of the apparent rapid northward plume motion. The data certainly show that the surface expression of the Samoan plume shifted northward during the Pliocene.

A currently uncertain factor is whether the plume was located significantly farther south during the emplacement of Alexa Bank at 24 Ma, which has an apparent reconstructed eruptive location of 18.5°S, 165.8°W (WK08-G). This apparent location is 5.3° SE of Vailulu'u Seamount and ~3.4° SE of the mean 15–3 Ma hotspot location, indicating there was significant northwestward motion of the plume between 24 Ma and 15 Ma. Unlike the Tonga slab's approach to the Samoan plume during the Pliocene (discussed below), there are no clear tectonic drivers for a 3.4° northwestward shift in the plume location between 24 and 15 Ma apparent at this time. The eruptive location offset between Alexa and other Samoa seamounts is likely not due to sampling bias. For instance, if the lava flows dated in Hart et al. (2004) represented late-stage or posterosional volcanism, then the apparent hotspot location—represented by hypothetical shield-stage lavas that would be even older—would have moved farther southeast. In other words, an emplacement age of ca. 18–17 Ma is required for Alexa Bank to record the hotspot at the same location as the other 3–15 Ma volcanoes. Therefore, either a plume motion or tectonic model is required to explain the apparent migration of the Samoa hotspot.

Could Large-Scale Mantle Flow Be Responsible?

A plume conduit ascending in convecting mantle flow fields should naturally be laterally advected, assuming a reasonable buoyancy flux. Models of mantle flow fields inferred from seismic tomography–derived density differences indicate that the Samoan plume should have been migrating eastward over at least the past 24 m.y. (Steinberger, 2000; Hart et al., 2004; Figs. S2 and S3). In these models, the plume conduit first becomes tilted, with its base moving eastward toward a large-scale upwelling area beneath the central Pacific plate, whereas its top part moves W to NW-ward, with the flow in the upper part of the mantle driven by Pacific plate motion and subducted slabs. However, for most plume models using a current hotspot location at Vailulu'u, a straightening up of the conduit is predicted, corresponding to E- to ESE-ward hotspot motion in "recent" times (e.g., since ca. 16.6 Ma in fig. 10 of Hart et al., 2004; since ca. 30 Ma in Fig. S2). The model used in Hart et al. (2004)

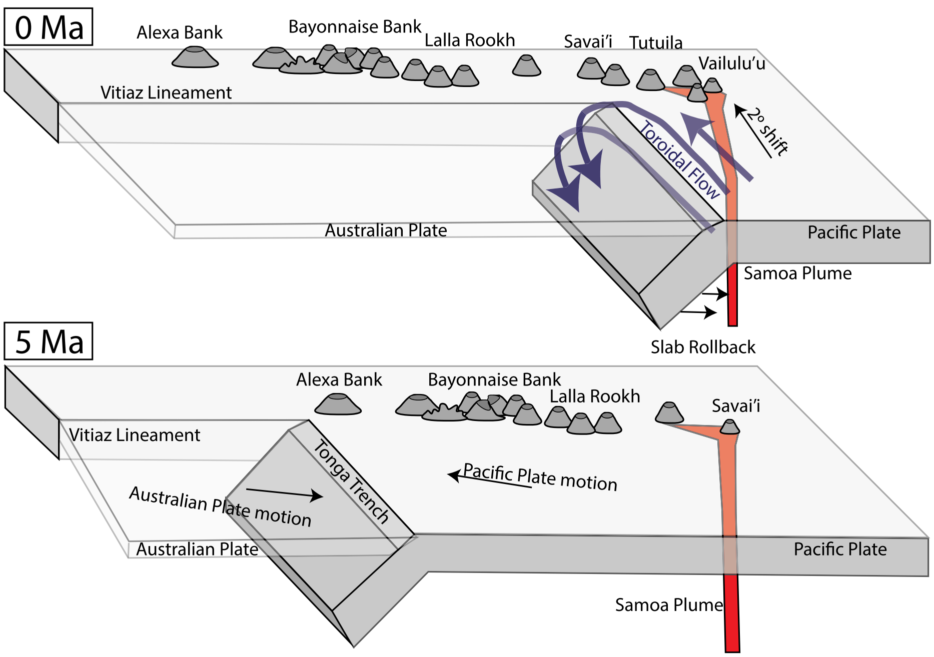

Figure 4. Schematic diagram explaining observed ~2° N-NW shift of surface expression of Samoa plume. Position of plume is shown at 5 Ma and today. Figure is influenced by Price et al. (2016). See text for details.

can potentially explain the northwestward drift in hotspot location between Alexa (24 Ma) and ca. 17 Ma. However, in order for the 24–17 Ma time period to still be in the initial phase, before hotspot motion becomes E- to ESE-ward, that model requires that the Samoan plume initiated around 40 Ma or even more recently, which is inconsistent with evidence for >100 Ma formation of the plume (Koppers et al., 2003). Further sampling of presumed 24–15 Ma seamounts west of Bayonnaise (Fig. 1) is required to test if the plume migrated northwestward during the early Miocene or if the ages from Alexa Bank are anomalous. Importantly, none of the seismic tomography–based plume motion models can match the observed rapid northward migration of the plume over the Pliocene. It is important to note that the tomography-based mantle flow models (e.g., Steinberger, 2000) are resolved to spherical harmonic degree 63 or less, which is a resolution that is likely too coarse to include smaller, regional asthenospheric flow regimes related to the Tonga Trench. Based on a comparison of current models and observations, large-scale mantle flow regimes are likely not responsible for the observed drift.

Could Advancement of the Tonga Trench Be Responsible?

The Tonga Trench has been advancing eastward at ~16 cm yr^{-1}, consuming Pacific lithosphere, over the past 5 m.y. (Bevis et al., 1995; Ruellan et al., 2003). Importantly, the trench has advanced close to the Samoan plume over the past 2–3 m.y. (Hart et al., 2004; Koppers et al., 2008). The rollback of the subducted Pacific slab is modeled to generate a counterclockwise toroidal mantle flow field in the region of the Samoan plume today (Strak and Schellart, 2018). The controls on the toroidal component of the subduction-induced mantle flow were investigated by Király et al. (2017) by means of numerical modeling. This mantle flow field provided a geographic and temporal fit to the observed sudden Pliocene shift in the surface expression of the Samoan plume. Figure 4 shows a schematic illustration of the way in which the progressing Tonga Trench and associated rollback could have generated toroidal flow fields that deflected the Samoan plume northward. Prior to 3 Ma, the trench was located too far west of the plume for rollback-induced toroidal flow to impact the plume conduit (Fig. 4). By 3–2 Ma, the trench and associated local mantle flow fields around the Tonga slab were proximal enough to deflect the Samoan plume northward, generating an apparent migration of the plume. Thus, plume-proximal trench interaction can alter the apparent surface expression of the plume and generate track geometries that are inconsistent with APM models.

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