Konrad, K., Jackson, M., Steinberger, B., Koppers, A., Balbas, A., Finlayson, V., Konter, J., Price, A. (2024): Toroidal flow around the Tonga slab moved the Samoan plume during the Pliocene. - Geology, 52, 3, 176-180.

https://doi.org/10.1130/G51588.1

Toroidal Flow Around the Tonga Slab Moved the Samoan Plume During the Pliocene

Kevin Konrad[1]; Matthew Jackson[2]; Bernhard Steinberger[3]; Anthony Koppers[4]; Andrea Balbas[5]; Valerie Finlayson[6]; Jasper Konter[7†]; Allison Price[8]

1. Department of Geoscience, University of Nevada Las Vegas, Las Vegas, Nevada 89154, USA
2. Department of Earth Science, University of California Santa Barbara, California 93106, USA
3. GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
4. College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331 USA
5. Department of Geological Sciences, California State University Long Beach, Long Beach, CA 90840, USA
6. Department of Geology, University of Maryland College Park, College Park, Maryland 20742
7. Department of Earth Sciences, School of Ocean and Earth Science and Technology, University of Hawai‘i Mānoa, Honolulu, Hawaii 96822 USA
8. Los Alamos National Laboratory, Los Alamos, New Mexico, USA, 87545, USA

1

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 require the plumes be fixed relative to the overriding lithosphere. When a plume interacts with a convergent or divergent boundary, it is often deflected within the strong local mantle flow fields associated with such regimes. Here we examine the age progressions and geometry of the Samoa hotspot track focusing on lava flow samples dredged from the deep flanks of the seamounts in order to best reconstruct when a given seamount was overlying the mantle plume (e.g., during the shield building stage). The Samoan seamounts display an apparent local plate velocity of 7.8 cm/a from 0 – 9 Ma, 11.1 cm/a from 9-14 Ma and 5.6 cm/a from 14-24 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, reconstructing the eruptive locations of the Samoa seamounts using APM models indicates that the surface expression of the plume migrated ~2° northward in the Pliocene. Large-scale mantle flow in the Pacific cannot explain the plume migration. Instead, the best fit 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 last 3-2 Ma. These observations provide novel constraints on how plume-trench interaction can alter hotspot track geometries.

INTRODUCTION

Age-progressive volcanic chains at hotspots are produced as Earth's lithosphere migrates over stationary or slowly moving (relative to plate motions) mantle plumes (Morgan et al., 1972; Wessel and Kroenke, 2008; Koppers et al., 2021). This phenomenon provides an ideal natural constraint 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 is 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 reproducing the geometry and age-progressions of numerous seamount chains on the same plate (Duncan and Clague, 1985; Wessel

2

and Kroenke, 2008; Konter et al., 2023). 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 precisely predicting 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 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-progressions, paleomagnetic reconstructions and numerical models) of rapid independent motion in the Pacific basin is the Hawaiian-Emperor plume in the 80-50 Ma timeframe (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 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 Pacific hotspot track age-progressions and geometry (Wang et al., 2019). Here we compile age determinations for lava flows sourced by the Samoan plume to provide evidence that the apparent surface expression of the hotspot has not been fixed, but instead has shifted northward by 2° during the Pliocene. Shallow mantle flow resulting from the approaching Tonga trench is likely responsible for the shift. This provides novel insights into the role plate-plume interaction plays in affecting apparent age-progressions and geometry of seamount chains.

THE SAMOAN SEAMOUNT PROVINCE

The Samoan plume has been sourcing islands and seamounts since at least 24 Ma (Duncan 1985; Hart et al., 2004; Koppers et al., 2011; **Fig. 1**). 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 extends westward to *ca.* 24 Ma volcanism on Alexa Bank on the westernmost end (Hart et al., 2004). Complicating the age-progressions 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 (Robbie Ridge; Chandler et al., 2012; **Fig. 1**), Eocene seamounts sourced from the

3

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 last ~5 Ma (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 define whether a recovered lava flow is Samoan in origin based on its (or same dredge) isotopic characteristics (e.g. elevated $^{87}Sr/^{86}Sr$ >0.7035 that 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). Furthermore, in order to best estimate when a seamount was directly above the plume, only lava flows dredged from the deep flanks of islands seamounts (i.e., subaerial lavas are excluded) are employed (Table S1). This is 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 towards heavily sampled structures. The lava flows used in this study are listed in the **Table S1** and shown in **Fig. 2**.

Age Progressions

Previous work on local plate velocity constraints using age progressions of Samoan volcanoes were complicated by significant rejuvenated volcanism on the islands (e.g. Workman et al., 2004) as well as sporadic reactivation of volcanism throughout the chain due to the advancement of the Tonga ± Vitiaz Trench (Strak and Schellart, 2018; Reinhard et al., 2019). **Fig. 2** shows the apparent plate velocity using currently available age constraints for the Samoa plume sourced seamounts. There are three clear changes in local plate velocity with slopes of 0.7 °/Ma (7.8 cm/a) for 0 – 9 Ma; 1.0°/Ma (11.1 cm/a) for 9-14 Ma and ~0.5°/Ma (5.6 cm/a) for 14-24 Ma. The mean local velocity for the 0-24 Ma Samoa chain is 0.71°/Ma (7.9 cm/a; **Fig. 2**), which is similar to previous estimates of ~7.6 cm/a (Koppers et al., 2011). The new local plate velocity is however slower than what is expected from Pacific APM models calculated without independent Samoa plume motion (Wessel and Kroenke, 2008: 9.3 cm/a; Doubrovine et al., 2012: 8.3 cm/a). This slower apparent plate velocity can be explained if the plume is migrating in a direction with a component of motion in the same direction as plate motion.

APPARENT MOTION OF THE SAMOA PLUME

Despite having a consistent age progression from 24 to 0 Ma, the Samoan hotspot track has been previously shown to contain a geometry that is similar to, but deviated from, Pacific APM-

4

derived model projections of the hotspot track (Brocher et al., 1985; Hart et al., 2004; Koppers et al., 2008, 2011) (**Fig. 3**). Hart et al. (2004) postulated that the misfit is related to a recent (e.g. last ~2 or 1 Ma) northward shift of the Samoa hotspot location. Here, we reexamine the evidence for plume motion using a larger seamount dataset to better constrain if and when the surface expression of the Samoa plume shifted.

To illustrate the apparent plume motion, here we take a set of seamount data (latitude, longitude, age) and rotate them based on APM models (both fixed and mobile hotspot) backwards 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 activity at a seamount will result in reconstructions further 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. **Figs. 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 non-systematically within a limited distance (yellow ellipse; **Fig. 3**), from 3 to 15 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 a ~2.3° (WK08-G) or 1.7° (D12) shift in the surface expression between 3 Ma and today. Note that D12 is smoothed to 10 Ma increments but provides the same first-order observations as the more detailed WK08-G model. To further illustrate this observation, **Figs. 4B** and **4D** show reconstructed hotspot tracks rooted relative to the current hotspot location (blue star) and the mean 3-15 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 >3 Ma Samoa seamounts – indicating the shift in hotspot location was relatively recent. The <3 Ma Samoa seamounts also display clear *en echelon* structures that step to the NE instead of a consistent seamount chain that progresses towards the southeast – like the Hawaiian Islands (Hart et al., 2004; Koppers et al., 2011; **Fig. 1**). This stepwise *en echelon* structure may be a function of the apparent rapid northward plume motion. What is certain is that the surface expression of the Samoa plume shifted northward during the Pliocene.

5

What is currently uncertain is whether the plume was located significantly further 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 3-15 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 24-15 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 post-erosional volcanism, then the apparent hotspot location — represented by hypothetical shield-stage lavas that would be even older — would move further south. In other words, an emplacement age of *ca.* 17-18 Ma is required for Alexa Bank to 'hotspot' to 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 Samoa plume should be migrating eastward over at least the last 24 Ma (Steinberger 2000; Hart et al., 2004; **Fig. S2, S3**). In these models, the plume conduit first becomes tilted, with its base moving eastward towards a large-scale upwelling beneath the central Pacific, 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, corresponding to E- to ESE-ward hotspot motion in "recent" times (e.g. since ~16.6 Ma in Fig. 10 of Hart et al., 2004; since ~30 Ma in **Fig. S2**) is predicted. The model used in Hart et al. (2004) can potentially explain the northwestward drift in hotspot location between Alexa (24 Ma) and ~17 Ma. However, in order for the 24-17 Ma time period to still be in the initial phase, before hotspot motion becomes east- to eastsoutheastward, that model requires the Samoa plume initiated around 40 Ma or even later, which is inconsistent with evidence for >100 Ma formation of the plume (Konter et al., 2023). Further sampling of presumed 24-15 Ma seamounts west of Bayonnaise (**Fig. 1**) is required to test if the plume has migrated

6

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 plume motion models (e.g. Steinberger, 2000) are resolved to spherical harmonic degree 63, which is likely not fine-scale enough to detect smaller, regional asthenosphere flow regimes related to the Tonga Trench. However, based on current model 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, consuming Pacific lithosphere, over the last 5 Ma (Ruellan et al., 2003). Importantly, the trench has advanced close to the Samoa plume over the last 2-3 Ma (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). This mantle flow field provides a geographic and temporal fit to the observed sudden Pliocene shift in the surface expression of the Samoan plume. **Fig. 4** shows a schematic illustration of how the progressing Tonga Trench and associated rollback can generate toroidal flow fields that deflect the Samoan plume northward. Prior to 3 Ma, the trench was located too far west of the plume 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.

ACKNOWLEDGEMENTS

This study was funded by NSF OCE# 1154070 to AAPK, NSF-OCE #1153894 and #1912931to MGJ. BS was supported by the innovation pool of the Helmholtz Association through the Advanced Earth System Modelling Capacity (ESM) activity. We thank R.G. Gordon, H.P. Bunge and an anonymous reviewer for their helpful suggestions.

7

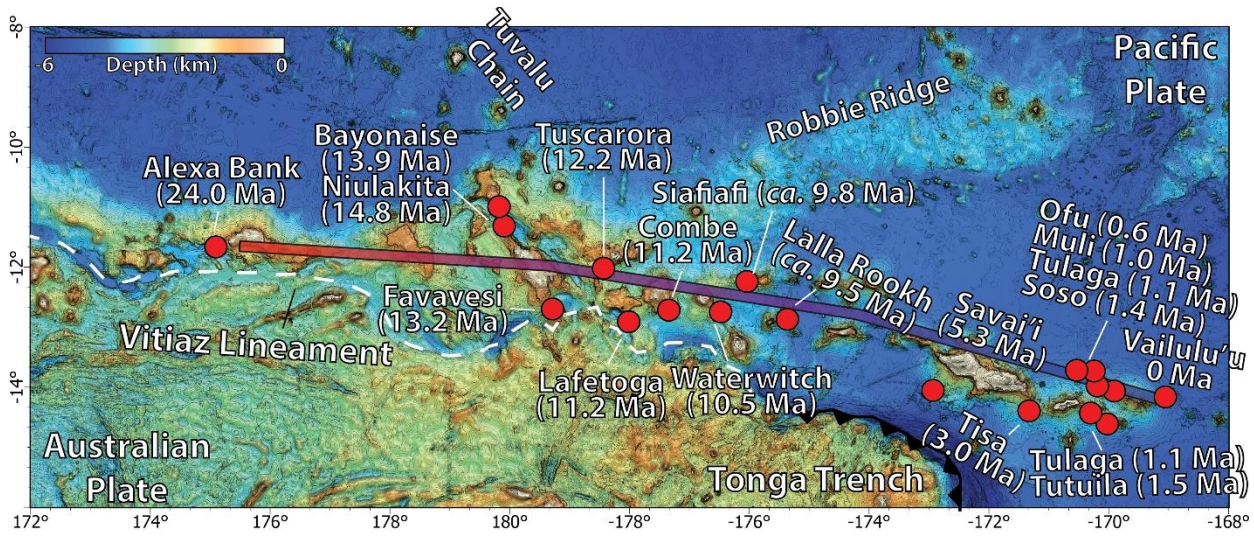
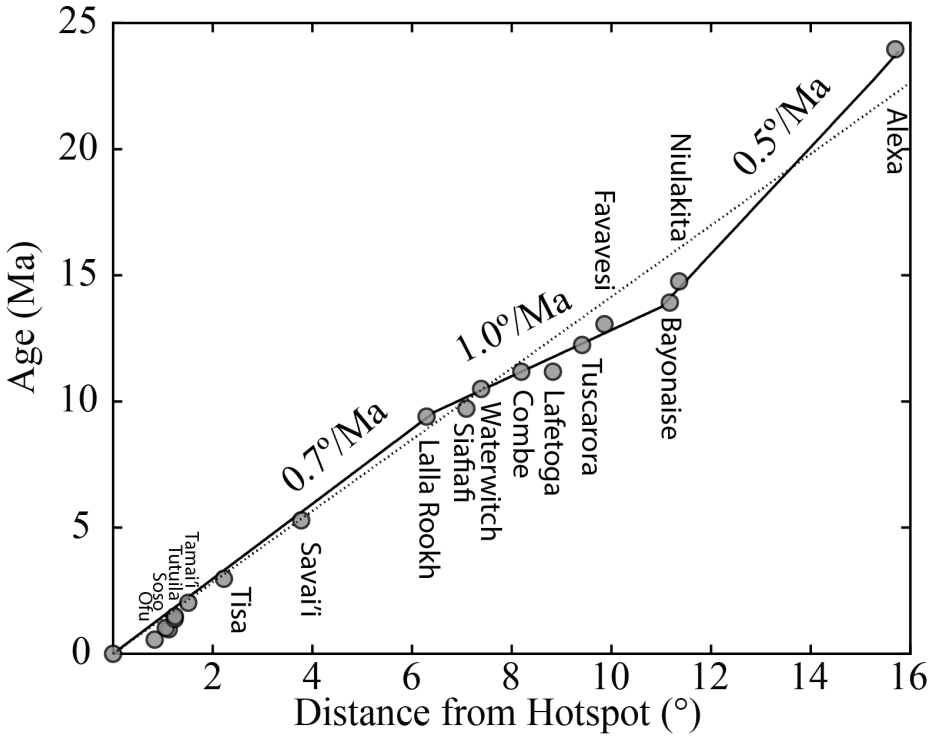


Figure 1: A bathymetric map of the Samoan Seamount Province. The seamounts, dredge locations (red dots) and oldest $^{40}Ar/^{39}Ar$ age determinations for each feature used in this study are shown. The color scaled bar (see **Fig 3** for ages) represents the mean hotspot track path and age progression, determined using a piecewise cubic hermite interpolating polynomial of seamount locations and calculated age progressions. The mean hotspot track does not match any fixed Pacific plate motion model. Bathymetry data is a merged multibeam and satellite altimetry dataset from GEBCO (Weatherall et al., 2015). The white dashed line represents the approximate paleo-Vitiaz boundary while the black line shows the region of active subduction.

8



209

210 **Figure 2:** Age versus distance from the hotspot for Samoan lava flow samples in **Table S1**.
211 Seamounts are labeled for clarity. The slopes of the lines are indicated and broken into three
212 distinct velocity trends. The dotted line represents the mean slope of all the points (0.71°/Ma or
213 7.9 cm/a)**.** Included in the calculation is a model age of 9.5 Ma for Lalla Rookh (**Fig. S1**), based
214 on the new $^{40}Ar/^{39}Ar$ experimental constraints as well as previous K/Ar age determinations (Hart
215 et al., 2004). A model age of 9.75 Ma is employed for Siafiafi Seamount based on the $^{40}Ar/^{39}Ar$
216 incremental heating results (**Fig. S1**).

9

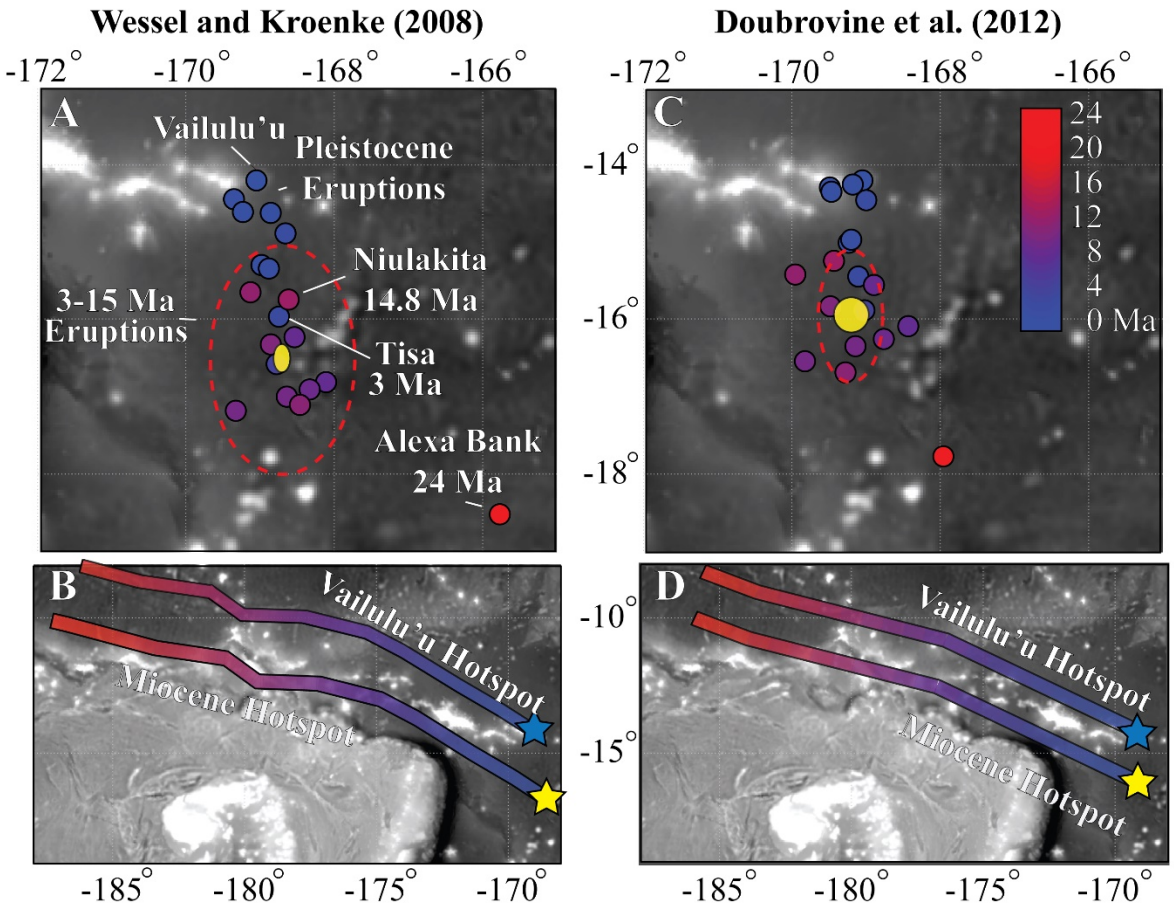


Figure 3: Absolute plate motion model indicators of plume motion. (A) Reconstructed eruptive latitude and longitudes for submarine lava flows with Samoa hotspot-like chemistry using the WK08-G fixed hotspot APM model of Wessel and Kroenke (2008). The dots represent the reconstructed coordinates with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

10

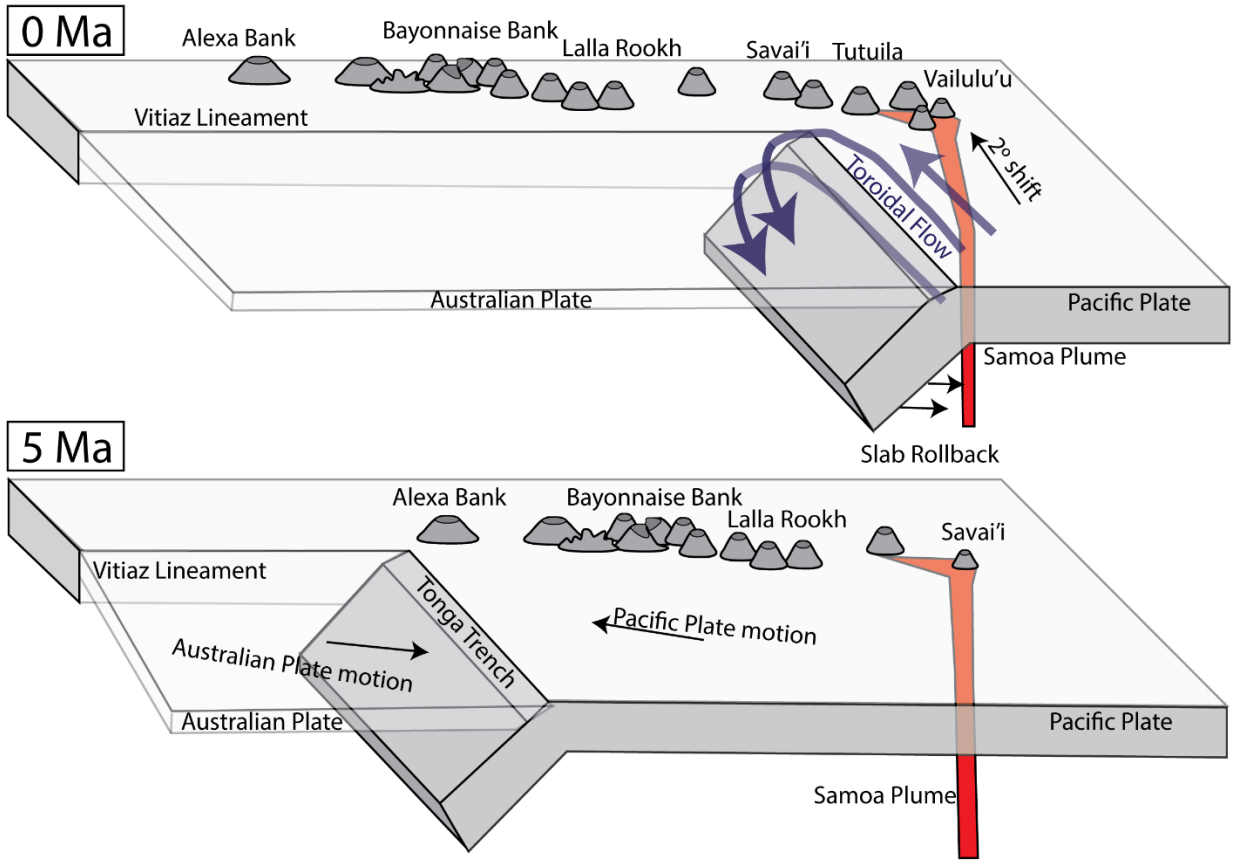


Figure 4: A schematic diagram explaining the observed ~2° N-NW shift of the surface expression of the Samoa plume. Shown is the position of the plume at 5 Ma and today. Figure influenced by Price et al. (2016). See text for details.

11

REFERENCES

Brocher, T.M., 1985. On the formation of the Vitiaz Trench lineament and North Fiji Basin. Circum-Pacific Council for Energy and Mineral Resources, Earth Science Series, Houston, Texas.

Chandler, M.T., Wessel, P., Taylor, B., Seton, M., Kim, S.-S., Hyeong, K., 2012. Reconstructing Ontong Java Nui: Implications for Pacific absolute plate motion, hotspot drift and true polar wander. Earth and Planetary Science Letters 331, 140-151.

Doubrovine, P.V., Steinberger, B., Torsvik, T.H., 2012. Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans. Journal of Geophysical Research: Solid Earth 117.

Duncan, R.A., 1985. Radiometric ages from volcanic rocks along the New Hebrides-Samoa lineament. Investigations of the Northern Melanesian Borderland, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, 3, 67–76.

Duncan, R.A., Clague, D.A., 1985. Pacific plate motion recorded by linear volcanic chains, The ocean basins and margins Vol.7A: The Pacific Ocean, Springer, pp. 89-121.

Finlayson, V., Konter, J., Konrad, K., Koppers, A., Jackson, M., Rooney, T., 2018. Sr–Pb–Nd–Hf isotopes and 40Ar/39Ar ages reveal a Hawaii–Emperor-style bend in the Rurutu hotspot. Earth and Planetary Science Letters 500, 168-179.

Gaastra, K.M., Gordon, R.G. and Woodworth, D.T., 2022. Quantification of Pacific Plate Hotspot Tracks Since 80 Ma. Tectonics, 41(7).

Hart, S.R., Coetzee, M., Workman, R.K., Blusztajn, J., Johnson, K.T.M., Sinton, J.M., Steinberger, B., Hawkins, J.W., 2004. Genesis of the Western Samoa seamount province: age, geochemical fingerprint and tectonics. Earth and Planetary Science Letters 227, 37-56.

Hart, S.R., Staudigel, H., Koppers, A.A., Blusztajn, J., Baker, E., Workman, R., Jackson, M., Hauri, E., Kurz, M., Sims, K., 2000. Vailulu'u undersea volcano: The new Samoa. Geochemistry, Geophysics, Geosystems 1(12).

Konrad, K., Koppers, A.A., Steinberger, B., Finlayson, V.A., Konter, J.G., Jackson, M.G., 2018. On the relative motions of long-lived Pacific mantle plumes. Nature communications 9, 854.

Konter, J.G., Finlayson, V.A., Konrad, K., Jackson M.G., Koppers, A.A.P., Wessel, P., Alverson, A., Kelley, C. (In revision) The longest-lived Pacific hotspots reveal a plume tail for the largest oceanic plateau. Nature. https://doi.org/10.31223/X5CQ2T

Koppers, A.A., Becker, T.W., Jackson, M.G., Konrad, K., Müller, R.D., Romanowicz, B., Steinberger, B., Whittaker, J.M., 2021. Mantle plumes and their role in Earth processes. Nature Reviews Earth & Environment 2, 382-401.

Koppers, A.A., Russell, J.A., Jackson, M.G., Konter, J., Staudigel, H., Hart, S.R., 2008. Samoa reinstated as a primary hotspot trail. Geology 36, 435-438.

Koppers, A.A., Russell, J.A., Roberts, J., Jackson, M.G., Konter, J.G., Wright, D.J., Staudigel, H., Hart, S.R., 2011. Age systematics of two young en echelon Samoan volcanic trails. Geochemistry, Geophysics, Geosystems 12(7).

Koppers, A.A.P., Yamazaki, T., Geldmacher, J., Gee, J.S., Pressling, N., Hoshi, H., Anderson, L., Beier, C., Buchs, D.M., Chen, L.H., 2012. Limited latitudinal mantle plume motion for the Louisville hotspot. Nature Geoscience 5, 911-917

Morgan, W.J., 1972. Deep mantle convection plumes and plate motions. AAPG Bulletin 56, 203-213

12

Price, A.A., Jackson, M.G., Blichert-Toft, J., Blusztajn, J., Conatser, C.S., Konter, J.G., Koppers, A.A. and Kurz, M.D., 2016. Geochemical evidence in the northeast Lau Basin for subduction of the Cook-Austral volcanic chain in the Tonga Trench. Geochemistry, Geophysics, Geosystems, 17(5), 1694-1724.

Price, A.A., Jackson, M.G., Blichert-Toft, J., Konrad, K., Bizimis, M., Koppers, A.A., Konter, J.G., Finlayson, V.A., Sinton, J.M., 2022. Distinguishing volcanic contributions to the overlapping Samoan and Cook-Austral hotspot tracks. Journal of Petrology 63(5), p.egac032.

Reinhard, A.A., Jackson, M.G., Blusztajn, J., Koppers, A.A., Simms, A.R., Konter, J.G., 2019. “Petit Spot” Rejuvenated Volcanism Superimposed on Plume-Derived Samoan Shield Volcanoes: Evidence From a 645-m Drill Core From Tutuila Island, American Samoa. Geochemistry, Geophysics, Geosystems. 20(3), pp.1485-1507.

Ruellan, E., Delteil, J., Wright, I. and Matsumoto, T., 2003. From rifting to active spreading in the Lau Basin–Havre Trough backarc system (SW Pacific): Locking/unlocking induced by seamount chain subduction. Geochemistry, Geophysics, Geosystems, 4(5).

Sims, K.W., Hart, S., Reagan, M., Blusztajn, J., Staudigel, H., Sohn, R., Layne, G., Ball, L., Andrews, J., 2008. 238U-230Th-226Ra-210Pb-210Po, 232Th-228Ra, and 235U-231Pa constraints on the ages and petrogenesis of Vailulu'u and Malumalu Lavas, Samoa. Geochemistry, Geophysics, Geosystems 9(4).

Sella, G. F., Dixon, T. H., & Mao, A. (2002). REVEL: A model for recent plate velocities from space geodesy. Journal of Geophysical Research: Solid Earth, 107(B4), ETG-11.

Steinberger, B., 2000. Plumes in a convecting mantle: Models and observations for individual hotspots. Journal of Geophysical Research: Solid Earth 105, 11127-11152.

Strak, V., Schellart, W.P., 2018. A subduction and mantle plume origin for Samoan volcanism. Scientific Reports 8, 10424.

Tarduno, J.A., Duncan, R.A., Scholl, D.W., Cottrell, R.D., Steinberger, B., Thordarson, T., Kerr, B.C., Neal, C.R., Frey, F.A., Torii, M., 2003. The Emperor Seamounts: Southward motion of the Hawaiian hotspot plume in Earth's mantle. Science 301, 1064-1069.

Weatherall, P., Marks, K.M., Jakobsson, M., Schmitt, T., Tani, S., Arndt, J.E., Rovere, M., Chayes, D., Ferrini, V., Wigley, R., 2015. A new digital bathymetric model of the world's oceans. Earth and space Science 2, 331-345.

Wessel, P., Kroenke, L., 1997. A geometric technique for relocating hotspots and refining absolute plate motions. Nature 387, 365-369.

Wessel, P., Kroenke, L.W., 2008. Pacific absolute plate motion since 145 Ma: An assessment of the fixed hot spot hypothesis. Journal of Geophysical Research: Solid Earth (1978–2012) 113.

Wessel, P., Kroenke, L.W., 2009. Observations of geometry and ages constrain relative motion of Hawaii and Louisville plumes. Earth and Planetary Science Letters 284, 467-472.

Workman, R.K., Hart, S.R., Jackson, M., Regelous, M., Farley, K.A., Blusztajn, J., Kurz, M. and Staudigel, H., 2004. Recycled metasomatized lithosphere as the origin of the Enriched Mantle II (EM2) end-member: Evidence from the Samoan Volcanic Chain. Geochemistry, Geophysics, Geosystems, 5(4).

13

Toroidal Flow Around the Tonga Slab Moved the Samoan Plume During the Pliocene

SUPPLEMENTAL MATERIAL

Kevin Konrad[1*]; Matthew Jackson[2]; Bernhard Steinberger[3]; Anthony Koppers[4]; Andrea Balbas[5]; Valerie Finlayson[6]; Jasper Konter[7†]; Allison Price[8]

1. Department of Geoscience, University of Nevada Las Vegas, Las Vegas, Nevada 89154, USA
2. Department of Earth Science, University of California Santa Barbara, California 93106, USA
3. GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany
4. College of Earth, Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331 USA
5. Department of Geological Sciences, California State University Long Beach, Long Beach, CA 90840, USA
6. Department of Geology, University of Maryland College Park, College Park, Maryland 20742
7. Department of Earth Sciences, School of Ocean and Earth Science and Technology, University of Hawai‘i Mānoa, Honolulu, Hawaii 96822 USA
8. Los Alamos National Laboratory, Los Alamos, New Mexico, USA, 87545, USA

*Corresponding author. Phone: (702) 895-3696; Email: Kevin.Konrad@unlv.edu

New $^{40}Ar/^{39}Ar$ Age Determination Methods and Results

Recovered dredge samples from expedition RR1310 were chosen for $^{40}Ar/^{39}Ar$ age determinations based on petrographic analyses. Rocks containing relatively unaltered phenocrysts (plagioclase, hornblende) or holocrystalline groundmass were chosen for analyses. All samples were prepared and analyzed using the standard methods described in Konrad et al. (2018). Age determinations from the heating experiments were calculated using ArArCalc v2.7.0 (Koppers, 2002). A fluence monitor age of 28.201 ± 0.046 Ma (Kuiper et al., 2008) was used for the J-curve calibration and a decay rate of 5.530 ± 0.097 x 10^{-10} yr^{-1} (Min et al., 2000) was used to calculate the ages. Uncertainties discussed here are 2σ internal errors (see Konrad et al., 2019 for description on how uncertainties are calibrated) with external errors provided on summary tables in the appendix. Qualifying plateaus required a probability of fit value (P) of > 5% with at least 50% the total ^{39}Ar released.

A dredge of Siafiafi Seamount (D39) recovered a trachytic lava flow (D39-02). A groundmass separate of that lava flow contained very high K/Ca (total fusion equivalent = 1.7) corresponding to individual steps with 0.1% uncertainty levels. The high precision coupled with a slight continuous recoil pattern (systematically decreasing apparent ages) resulted in a discordant age spectrum that is not usable by the statistical standards of the $^{40}Ar/^{39}Ar$ community (e.g. Schaen et al., 2020). However, despite the consistent recoil pattern the lava flow age is clearly *ca.* 10 – 9.5 Ma. A groundmass separate from lava flow D41-04, recovered from Lalla Rookh seamount, produced a discordant heating spectrum. There is a concordant mini-plateau (31%) that produced an age of *ca.* 9.4 Ma. Similarly, the groundmass separate was attempted from RR1310-D25-28a (West Niulakita) that did not produce a statistically robust heating spectrum. The sampled produced a ‘mini-plateau’ (40% ^{39}Ar released) at *ca.* 14.7 Ma, which is in line with the younger ages reported from East Niulakita (13.4-14.8; Finlayson et al., 2018).

First-order Samoa Plume Motion Calculation

The observation of a ~2° northward shift in the surface expression of the Samoan plume conduit provides an important physical constraint for refining models of mantle flow and plume migration. Here we provide a first-order assessment of whether the observation is consistent with previous constraints on plume conduit deflection. If a plume conduit rises through the horizontal flow of the asthenosphere, the deflection should be the depth integral of horizontal flow divided

2

by rising speed. Plume rising speed in the upper mantle should be of the order 7-10 cm a^{-1} (Steinberger and O'Connell, 2000; Steinberger and Antretter, 2006). Slab rollback in the northern Tonga trench is about 550 km in 7 Ma (reported by van de Lagemaat et al., 2018), i.e. about 8 cm a^{-1}. Strak and Schellart (2018) observe for similar amounts of rollback flow speeds of the order 5 cm a^{-1}. Assuming channel flow between 100 and 670 km, this would lead to deflections of: 570 km * $5x10^{-5}$ km a^{-1} * 2 / 3 / $10x10^{-5}$ km a^{-1} = 190 km (~1.7°) for a rise speed 10 cm a^{-1} and 270 km (~2.4°) for 7 cm a^{-1}, which fits very well with the ~2° northward migration since the effect of the toroidal flow around the slab edge began (observed in this study).

3

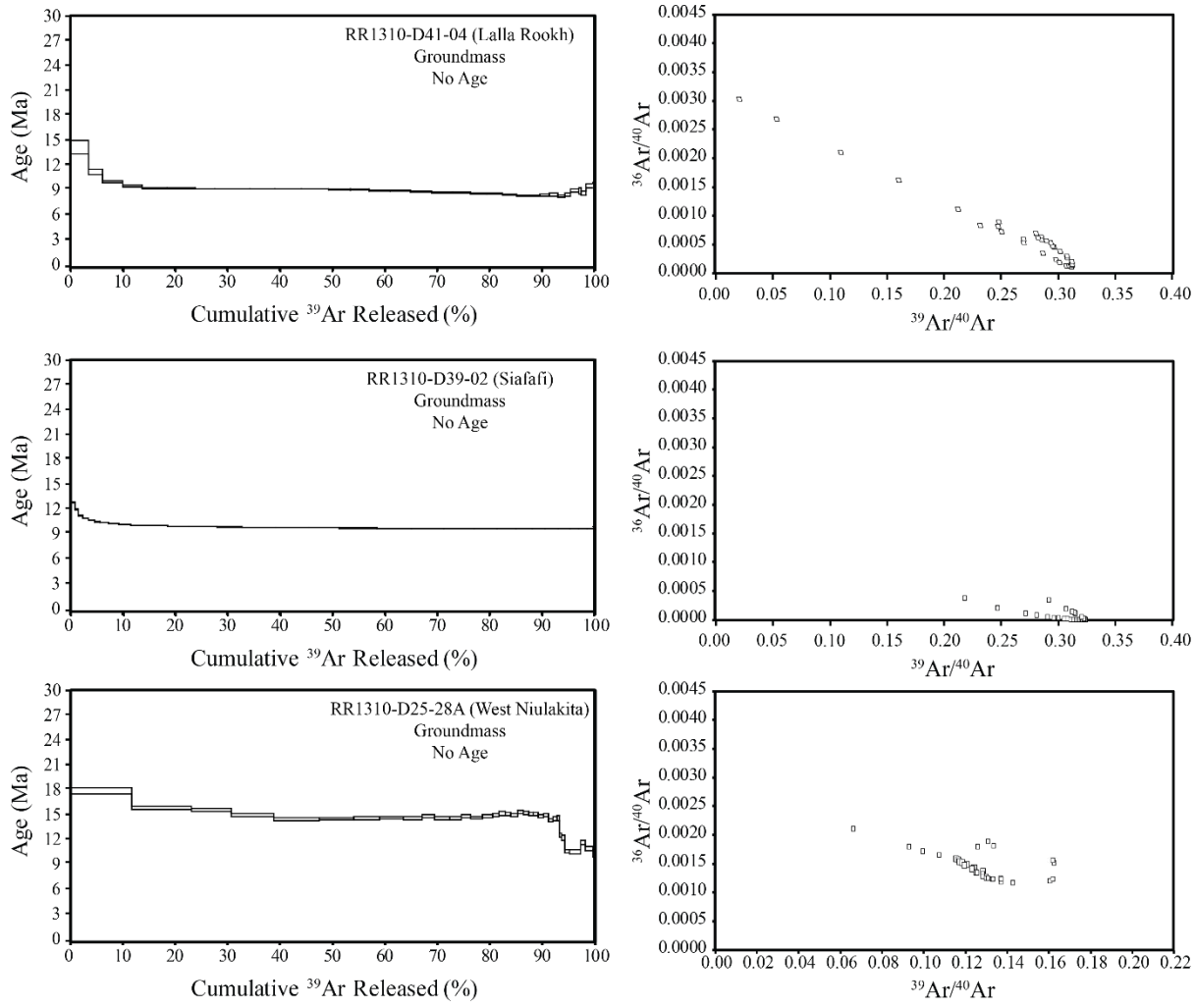


Figure S1: ^{40}Ar/^{39}Ar incremental heating results for lava flows from Lalla Rookh, Siafafi and West Niulakita. Note that none of the samples produced a statistically concordant plateau or isochron age. (Left) Incremental apparent age diagrams as a function of ^{39}Ar released. (Right) The inverse isochron diagrams.

4

Table S1: Lava Flows Used in Age Progression Calculations

Sample	Seamount	Lat	Long	Age (Ma)	2 σ (Ma)	Reference
Hotspot	Vailulu'u	-14.20	190.95	0	0	Hart et al., 2000
Alia 103-07	Ofu	-14.102	190.095	0.56	0.07	Koppers et al., 2011
Alia 104-09	Muli	-14.018	189.812	0.97	0.11	Koppers et al., 2011
Alia 109-20	Tulaga	-14.652	189.977	1.06	0.09	Koppers et al., 2011
Alia 110-23	Soso	-13.768	189.758	1.43	0.06	Koppers et al., 2011
Alia 108-04	Tutuila	-14.470	189.700	1.48	0.41	Koppers et al., 2011
Alia 111-05	Tamai'i	-13.755	189.465	2.07	0.06	Koppers et al., 2011
Alia 113-28	Tisa	-14.432	188.668	3.00	0.18	Koppers et al., 2011
Alia 115-18	Savai'i	-14.092	187.058	5.29	0.21	Koppers et al., 2011
RR1310-D41-04	Lalla Rookh	-12.902	184.618	9.50	0	This Paper
RR1310-D39-02	Siafiafi	-12.267	183.942	9.75	0	This Paper
RR1310-D38-41	Waterwitch Bank	-12.778	183.502	10.49	0.09	Price et al. 2022
Alia 123-03	Combe	-12.748	182.632	11.18	0.17	Koppers et al., 2011
RR1310-D32-01	Lafetoga	-12.943	181.962	11.18	0.06	Konrad et al., 2018
RR1310-D33-05	Tuscarora Bank	-12.044	181.541	12.24	0.13	Finlayson et al. 2018
Alia 125-04*	Favavesi	-12.696	181.186	13.16	0.16	Koppers et al., 2011
RR1310-28B-04	Bayonnaise	-11.333	179.875	13.92	0.1	Finlayson et al. 2018
RR1310-D27-42	Niulakita	-11.006	179.790	14.76	0.08	Finlayson et al. 2018
14-19	Alexa	-11.685	175.047	23.96	0.36	Hart et al., 2004

*All samples are (re)calculated against a fluence monitor age of 28.201 ± 0.046 Ma (Kuiper et al., 2008) and a decay rate of 5.530 ± 0.097 x 10^{-10} yr^{-1} (Min et al., 2000). *The dredge location reported in Koppers et al. (2011) was inacurate and the location from the cruise report is used here.*

5

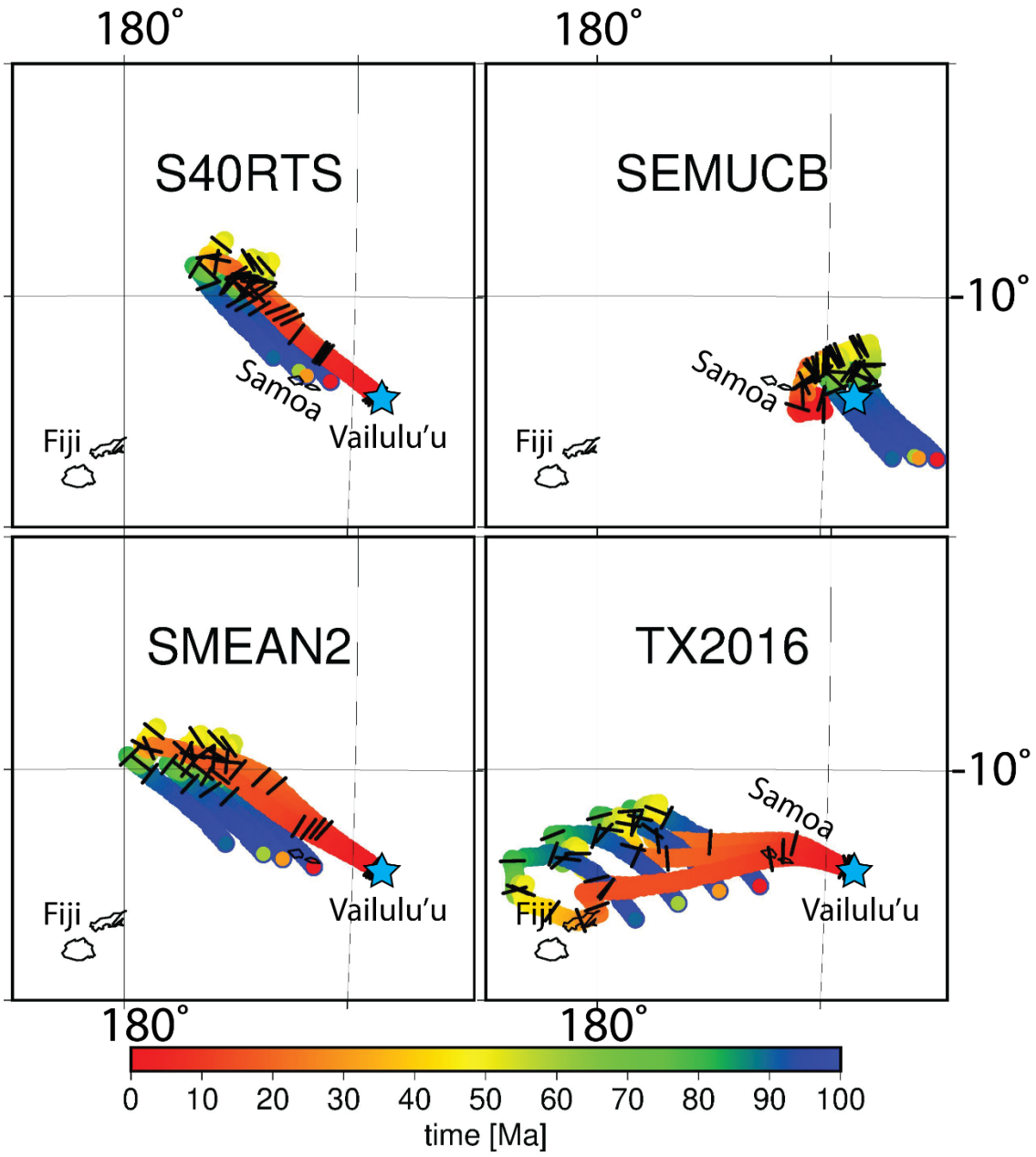


Figure S2: Reconstructed surface locations of the Samoan plume using different seismic tomography models and plume initiation constraints (e.g. Steinberger et al. 2019). The color of the circles drawn at the initial position where the plume head impacted corresponds to the plume head rise time (before that inital time). The age of the plume, when the head impacted, is 100 Ma in all cases. The color along the track (from blue=100 Ma to red=0 Ma) corresponds to the time when the plume was at that position. Black lines represent 10 Ma intervals. The model uses the APM model of Torsvik et al. (2010). S40RTS from Ritsema et al. (2011); SMEAN2 from Becker and Boschi 2002; SEMUCB from French and Romanowicz (2014); TX2016 from Lu and Grand (2016). Note that the SEMUCB model run failed to ultimately fit the Samoan plume to Vailulu'u at time 0.

6

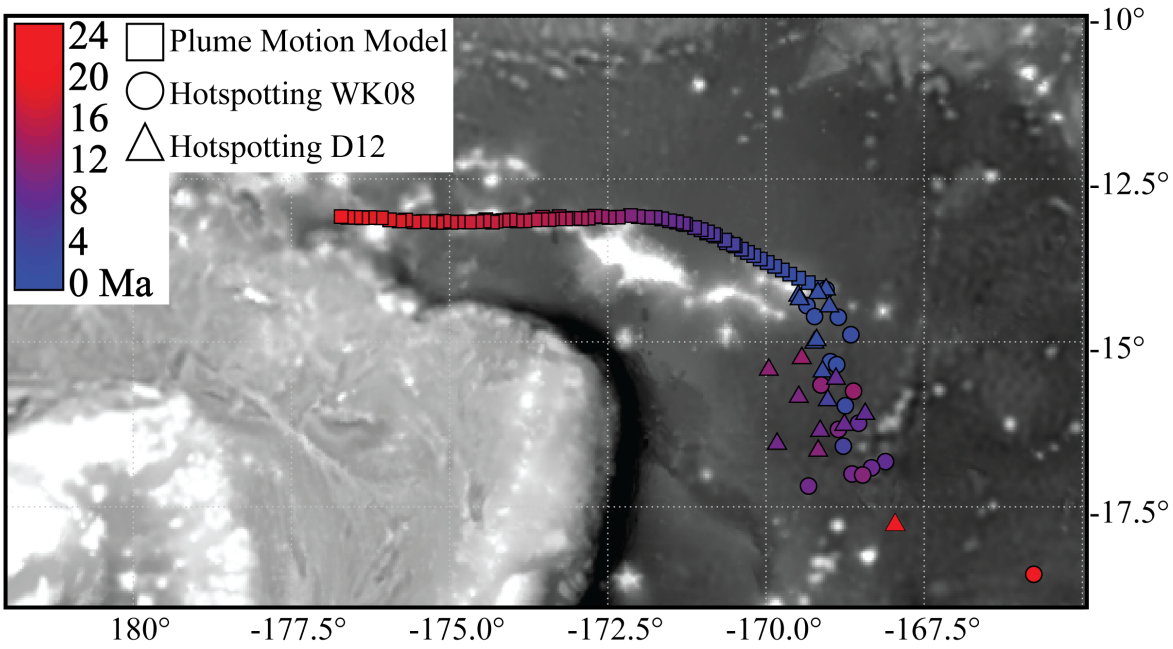


Figure S3: A bathymetric map showing the time-dependent modeled hotspot locations based on the eruptive location reconstructions using the APM models of Wessel and Kroenke (2008; circles), Doubrovine et al., (2012; triangles) and a mantle plume motion model using the seismic tomography model of TX2016 (Lu and Grand, 2016) and an instantaneous plume ascent and impact age of 100 Ma (bottom right panel in **Fig. S2**). The last 24 Myrs of hotspot locations in this model is fairly typically of the results shown in **Fig. S2**.

7

References:

Becker, T.W. and Boschi, L., 2002. A comparison of tomographic and geodynamic mantle models. *Geochemistry, Geophysics, Geosystems*, *3*(1).

Doubrovine, P.V., Steinberger, B., Torsvik, T.H., 2012. Absolute plate motions in a reference frame defined by moving hot spots in the Pacific, Atlantic, and Indian oceans. Journal of Geophysical Research: Solid Earth 117.

Finlayson, V.A., Konter, J.G., Konrad, K., Koppers, A.A.P., Jackson, M.G. and Rooney, T.O., 2018. Sr–Pb–Nd–Hf isotopes and 40Ar/39Ar ages reveal a Hawaii–Emperor-style bend in the Rurutu hotspot. *Earth and Planetary Science Letters*, *500*, pp.168-179.

French, S.W. and Romanowicz, B.A., 2014. Whole-mantle radially anisotropic shear velocity structure from spectral-element waveform tomography. *Geophysical Journal International*, *199*(3), pp.1303-1327.

Hart, S.R., Staudigel, H., Koppers, A.A., Blusztajn, J., Baker, E.T., Workman, R., Jackson, M., Hauri, E., Kurz, M., Sims, K. and Fornari, D., 2000. Vailulu'u undersea volcano: The new Samoa. *Geochemistry, Geophysics, Geosystems*, *1*(12).

Hart, S.R., Coetzee, M., Workman, R.K., Blusztajn, J., Johnson, K.T.M., Sinton, J.M., Steinberger, B. and Hawkins, J.W., 2004. Genesis of the Western Samoa seamount province: age, geochemical fingerprint and tectonics. *Earth and Planetary Science Letters*, *227*(1-2), pp.37-56.

Konrad, K., Koppers, A.A., Steinberger, B., Finlayson, V.A., Konter, J.G. and Jackson, M.G., 2018. On the relative motions of long-lived Pacific mantle plumes. *Nature Communications*, *9*(1), p.854.

Konrad, K., Koppers, A.A., Balbas, A.M., Miggins, D.P. and Heaton, D.E., 2019. Dating clinopyroxene phenocrysts in submarine basalts using 40Ar/39Ar geochronology. *Geochemistry, Geophysics, Geosystems*, *20*(2), pp.1041-1053.

Koppers, A.A., 2002. ArArCALC—software for 40Ar/39Ar age calculations. *Computers & Geosciences*, *28*(5), pp.605-619.

Koppers, A.A., Russell, J.A., Roberts, J., Jackson, M.G., Konter, J.G., Wright, D.J., Staudigel, H. and Hart, S.R., 2011. Age systematics of two young en echelon Samoan volcanic trails. *Geochemistry, Geophysics, Geosystems*, *12*(7).

Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R. and Wijbrans, A.J., 2008. Synchronizing rock clocks of Earth history. *science*, *320*(5875), pp.500-504.

van de Lagemaat, S.H., Van Hinsbergen, D.J., Boschman, L.M., Kamp, P.J. and Spakman, W., 2018. Southwest Pacific absolute plate kinematic reconstruction reveals major Cenozoic Tonga-Kermadec slab dragging. Tectonics, 37(8), pp.2647-2674.

Lu, C. and Grand, S.P., 2016. The effect of subducting slabs in global shear wave tomography. *Geophysical Journal International*, *205*(2), pp.1074-1085.

Min, K., Mundil, R., Renne, P.R. and Ludwig, K.R., 2000. A test for systematic errors in 40Ar/39Ar geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite. *Geochimica et Cosmochimica Acta*, *64*(1), pp.73-98.

Price, A.A., Jackson, M.G., Blichert-Toft, J., Konrad, K., Bizimis, M., Koppers, A.A., Konter, J.G., Finlayson, V.A. and Sinton, J.M., 2022. Distinguishing volcanic contributions to the overlapping Samoan and Cook-Austral hotspot tracks. *Journal of Petrology*, *63*(5), p.egac032.

Ritsema, J., Deuss, A., Van Heijst, H.J. and Woodhouse, J.H., 2011. S40RTS: a degree-40 shear-velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltime

8

and normal-mode splitting function measurements. *Geophysical Journal International*, *184*(3), pp.1223-1236.
Schaen, A.J., Jicha, B.R., Hodges, K.V., Vermeesch, P., Stelten, M.E., Mercer, C.M., Phillips, D., Rivera, T.A., Jourdan, F., Matchan, E.L. and Hemming, S.R., 2021. Interpreting and reporting 40Ar/39Ar geochronologic data. *Bulletin*, *133*(3-4), pp.461-487.
Steinberger, B. and O'Connell, R.J., 2000. Effects of mantle flow on hotspot motion. Washington DC American Geophysical Union Geophysical Monograph Series, 121, pp.377-398.
Steinberger, B. and Antretter, M., 2006. Conduit diameter and buoyant rising speed of mantle plumes: Implications for the motion of hot spots and shape of plume conduits. Geochemistry, Geophysics, Geosystems, 7(11).
Steinberger, B., Nelson, P.L., Grand, S.P. and Wang, W., 2019. Yellowstone plume conduit tilt caused by large-scale mantle flow. *Geochemistry, Geophysics, Geosystems*, *20*(12), pp.5896-5912.
Strak, V. and Schellart, W.P., 2018. A subduction and mantle plume origin for Samoan volcanism. Scientific Reports, 8(1), p.10424.
Torsvik, T.H., Steinberger, B., Gurnis, M. and Gaina, C., 2010. Plate tectonics and net lithosphere rotation over the past 150 My. *Earth and Planetary Science Letters*, *291*(1-4), pp.106-112.
Wessel, P., Kroenke, L.W., 2008. Pacific absolute plate motion since 145 Ma: An assessment of the fixed hot spot hypothesis. Journal of Geophysical Research: Solid Earth (1978–2012) 113.

9