

Samoa reinstated as a primary hotspot trail

- Anthony A.P. Koppers*** Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California–San Diego, La Jolla, California 92093, USA, and College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Administration Building, Corvallis, Oregon 97331, USA
- Jamie A. Russell** Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California–San Diego, La Jolla, California 92093, USA
- Matthew G. Jackson** Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02540, USA
- Jasper Konter** Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California–San Diego, La Jolla, California 92093, USA, and Department of Geological Sciences, San Diego State University, 5500 Campanile Drive, San Diego, California 92182, USA
- Hubert Staudigel** Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California–San Diego, La Jolla, California 92093, USA
- Stanley R. Hart** Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02540, USA

ABSTRACT

The classical model for the generation of hotspot tracks maintains that stationary and deep-seated mantle plumes impinge on overriding tectonic plates, thereby generating age-progressive trails of volcanic islands and seamounts. Samoa has played a key role in discrediting this model and the very existence of mantle plumes, because early geochronological work failed to demonstrate a linear age progression along this chain of islands. Specifically on Savai'i Island, the bulk of the subaerial volcanics is younger than 0.39 Ma, much younger than the 5.1 Ma age predicted from the classical hotspot model and a constant 7.1 cm/yr Pacific plate motion. This discrepancy led to alternative magma-producing mechanisms that involve the cracking of the lithosphere beneath the Samoan islands, as a result of the extensional regime generated by the nearby Tonga Trench. Here we report $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the submarine flanks of Savai'i Island showing that its volcanic construction began as early as 5.0 Ma and in a true intraplate setting. This reinstates Samoa as a primary hotspot trail associated with a deep mantle plume and a linear age progression.

Keywords: primary hotspots, $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology, Pacific plate, plate extension, seamounts, Samoa.

INTRODUCTION

Hotspots by and large are defined as focused regions of anomalous intraplate volcanism, yet the mechanisms driving this volcanism are subject to vigorous debate. One model assumes that deep-seated mantle plumes drive hotspot volcanism and generate linear age progressions in the hotspot trails they leave behind. These are the so-called “primary” hotspot trails (Morgan, 1972; Courtillot et al., 2003; Koppers et al., 2004) of which only three have been identified in the Pacific basin: the Hawaii–Emperor, Louisville, and Easter seamount trails (Watts et al., 1988; Clague et al., 1989; Courtillot et al., 2003; Duncan and Keller, 2004; Koppers et al., 2004). The absence of clear age progressions along other hotspot trails, however, has been used as an argument against the role for mantle plumes in seamount trails, favoring alternative models of lithospheric extension and the release of melt from shallow mantle sources or plumelets (Davis et al., 2002; Koppers et al., 2003; Koppers and Staudigel, 2005; Natland and Winterer, 2005).

In the case of Samoa, the omnipresence of subaerial volcanic rocks younger than 0.39 Ma on Savai'i Island (Natland and Turner, 1985; Workman et al., 2004) appears to argue against the mantle plume model, because a 7.1 cm/yr Pacific plate motion would predict a hotspot age of 5.1 Ma for this volcano (Hawkins and Natland, 1975; Natland, 1980; Foulger and Natland, 2003; Natland and Winterer, 2005). This led to claims that this volcanic island has been constructed entirely as the result of the cracking of the subducting Pacific plate, where it responds to its bending and tearing along the northern terminus of the Tonga Trench. It thus follows that distinguishing plume from nonplume origins for hotspot volcanoes is critically dependent on our understanding of the age progressions along these volcanic island and seamount trails.

Unlocking the age systematics in linear volcanic trails is not a trivial exercise. Sample collections that cover all the islands and seamounts from a given trail are sparse, and hydrothermal and seawater alteration makes the dating of submarine basalts complicated. Furthermore, the surface exposure on islands (as well as on

seamount summits) often involves a sampling bias toward younger lavas that may have been erupted well after a volcano has passed the hotspot (Pringle et al., 1991; Koppers et al., 2000, 2003). To overcome these problems, it is necessary to sample deep submarine flanks on these volcanoes in order to access lavas erupted during the earliest shield-building stages, and to remove alteration in these samples using extensive acid-leaching procedures.

In this study, we provide $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating age data from a representative sample set of deep submarine shield-building lavas at Savai'i Island (Fig. 1). Our work provides a high-quality and concordant age data set that demonstrates that the submarine part of Savai'i Island formed ca. 5.0 Ma as a typical intraplate volcano above a deep mantle plume, which currently is located near Vailulu'u, the volcanically active seamount at the eastern end of the Samoan trail (Hart et al., 2000, 2004; Staudigel et al., 2004).

SAVAI'I ISLAND AND SAMPLING

Savai'i is the westernmost island in the Samoan Archipelago. The subaerial portion of this island has been completely covered with young posterosional lava flows dating back to at least 0.39 Ma and continuing to historic eruptions in 1905–1911 (Natland and Turner, 1985; Workman et al., 2004). A central rift zone, aligned approximately in the direction of Pacific plate motion, is marked by the presence of many young, uneroded volcanic cones. Evidence for possible late shield-stage volcanism is limited to a single K/Ar age of 2.1 Ma on a trachytic stream cobble (Workman et al., 2004). The island is further characterized by a relatively large volume ($2.4 \times 10^4 \text{ km}^3$), and it rises more than 6.2 km above the seafloor, whereby only 3% of this volcanic edifice appears above sea level. Its underwater morphology is dominated by two major east-west submarine rift zones, connecting to

*E-mail: akoppers@coas.oregonstate.edu.

Upolu Island in the east, and running in a west-ern direction for at least 75 km (Fig. 1).

The submarine portion of this volcano was first sampled by the ALIA expedition in April 2005 (<http://earthref.org/ERESE/projects/ALIA> including maps and cruise data). Two dredge sites were placed as deep as possible on the southwest flank of Savai'i Island, while a third dredge was placed on a satellite seamount (named Taumatau) located on the northeast flank of Savai'i (Fig. 1). The ALIA-D114 and ALIA-D115 dredge sites sampled the steep slopes of two volcanic ridges that are abundantly present on the southern flanks of most Samoan seamounts. Together, our dredges resulted in a collection of relatively fresh volcanic rocks of diverse composition, ranging from picrite (D114-03), transitional tholeiite (D128-21), and alkalic trachybasalt (D115-03) to hawaiiite (D115-18, D115-28). Based on their geochemistry and isotope composition, these rocks are representative of the typical Samoan shield-building phase (Jackson et al., 2007).

⁴⁰Ar/³⁹Ar AGE DATING

Detailed ⁴⁰Ar/³⁹Ar incremental heating experiments were performed on five groundmass samples and two mineral separates of plagioclase and K-feldspar in the laboratory of Oregon State University. As can be seen from our results, the seven submarine age determinations fall into a distinctly older age range, between 4.1 and 5.0 Ma (see age boxes in Fig. 1), when compared to the younger than 0.39 Ma ages that characterize the subaerial volcanics on Savai'i Island. The GSA Data Repository¹ contains all the age plateaus of these experiments in Figure DR1, summary analytical data in Table DR1, a description of the applied techniques, and a detailed description of the samples analyzed.

The oldest ages were measured on samples recovered from the deepest Savai'i dredge site, ALIA-D115. The ages from this dredge site define a narrow range between 4.98 and 5.06 Ma, with the exception of the slightly older age of 5.29 ± 0.21 Ma measured on a plagioclase mineral separate from sample ALIA-D115-18. This latter analysis, however, has a significantly larger uncertainty due to the low potassium concentration in plagioclase, making it statistically indistinguishable from the narrow age range observed in the other samples. Together, these samples give a weighted average of 5.02 ± 0.03 Ma ($n = 5$) for dredge site ALIA-D115. Groundmass samples ALIA-D114-03 and ALIA-D128-21 are both

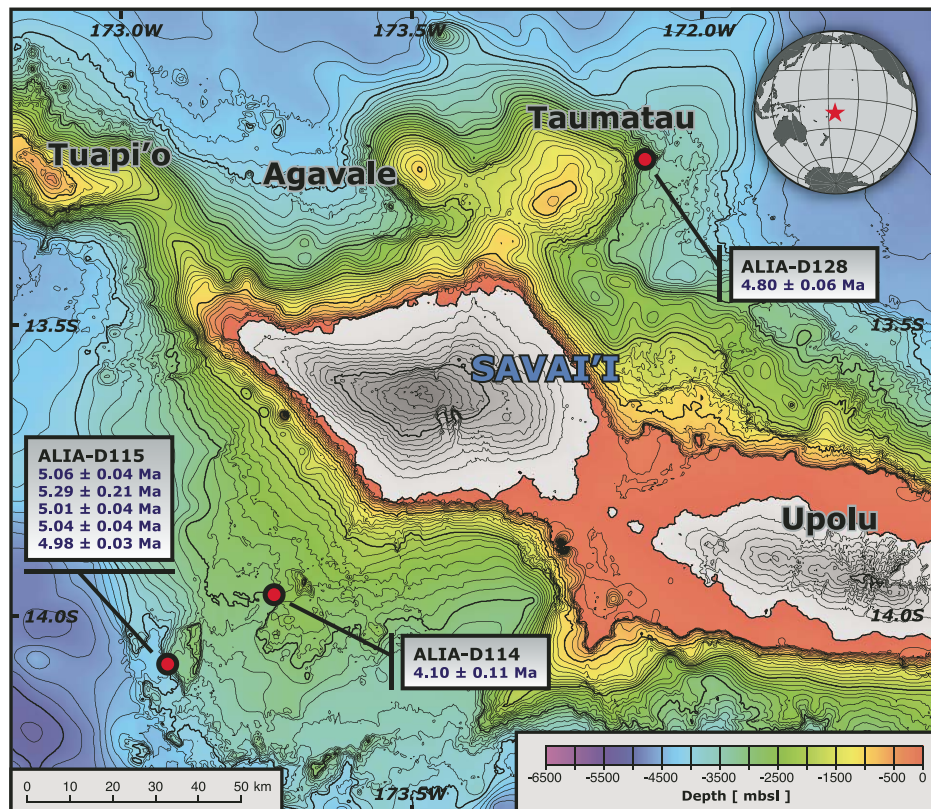


Figure 1. Bathymetric map for Savai'i Island in the Samoan seamount trail based on a combination of multibeam data from the 2005 ALIA expedition onboard the R/V *Kilo Moana*, global predicted bathymetry data (Smith and Sandwell, 1997), and Shuttle Radar Topography Mission (SRTM) data (U.S. Geological Survey EROS Data Center). The map has a 125 m contour interval and shows the dredge locations and measured ⁴⁰Ar/³⁹Ar plateau ages. See *Seamount Catalog*, <http://earthref.org/cgi-bin/sc.cgi?id=SMNT-137S-1725W>, for more detailed bathymetric maps, grid files, and multibeam data.

younger at 4.10 ± 0.11 Ma and 4.80 ± 0.06 Ma, but they still are decidedly older than the oldest 2.1 Ma age measured on subaerial samples.

The age results meet strict quality criteria: (1) Between 62% and 100% of the released argon gas is used in the age calculations; (2) between eight and 21 incremental heating steps define each of the age plateaus; (3) ⁴⁰Ar/³⁶Ar isochron intercepts are within error of the 295.5 value for atmospheric argon; and (4) plateau, total fusion, and isochron age estimates are internally consistent in all cases. Excellent agreement was achieved between a groundmass (5.04 ± 0.04 Ma) and a K-feldspar mineral separate (4.98 ± 0.03 Ma) from sample ALIA-D115-28. Overall, we can be confident that the new 4.1–5.0 Ma ages represent the crystallization age of the submarine lavas and that these ages mark the early stages of shield building on Savai'i Island.

LEAD ISOTOPE GEOCHEMISTRY

Pb isotopic data are diagnostic in establishing a Samoan pedigree for the dated samples, and provide geochemical evidence consistent with

their old 4.1–5.0 Ma age. In contrast to the young posterosional (rejuvenated) basalts erupted subaerially on Savai'i, the dated submarine samples exhibit Pb isotope ratios that are similar to Samoan shield-phase volcanoes (Fig. 2). Wright and White (1986) first noted the distinctive Pb isotope difference between shield and posterosional volcanism in Samoa, and recent work has borne this out (Hart et al., 2004; Workman et al., 2004). While no subaerial shield basalts are known from Savai'i, posterosional basalts from Savai'i and Upolu are less radiogenic than Upolu shield basalts, and significantly less radiogenic than shield basalts from the eastern volcanic province (i.e., the Vai Trend and Malumalu basalts), which all erupted between 0.39 Ma and the present (Hart et al., 2004; Workman et al., 2004). The submarine basalts from dredges D114, D115, and D128 were dredged 135 km apart on opposite deep flanks of Savai'i, yet all three dredges exhibit similar extreme isotopic compositions with ⁸⁷Sr/⁸⁶Sr ratios ranging up to 0.720469 (Jackson et al., 2007). This may suggest that Savai'i Island was characterized by an early phase of shield-stage volcanism that

¹GSA Data Repository item 2008109, ⁴⁰Ar/³⁹Ar techniques, applied quality criteria, data, and sample descriptions and geochemistry, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

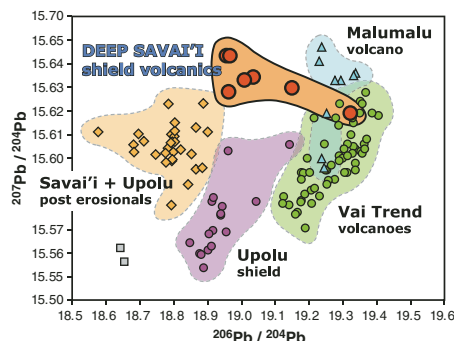


Figure 2. Pb isotope plot of basalts from throughout the eastern volcanic province of Samoa, showing distinctive isotopic signatures for the various islands and submarine lineaments. The Vai Trend volcanoes (green circles) include the active submarine volcano Vailulu'u and subaerial shield basalts from Ta'u, Ofu, and Olosega Islands. Malumalu Volcano (blue triangles) is a young submarine volcano anchoring the eastern end of the 90 km submarine lineament running SE from Tutuila Island. Subaerial basalts from the eastern and western shields of Upolu Island are shown as purple circles, and the posterosional basalts that have resurfaced Upolu and Savai'i Islands are shown as yellow diamonds. The 5.0 Ma shield basalts dredged from three localities deep on the NE and SW flanks of Savai'i are shown as large orange circles. Previous data from Workman et al. (2004).

erupted large volumes of enriched lava, with a significant admixture of recycled upper continental crust sediments in the Samoan mantle plume (Jackson et al., 2007).

ON THE EVOLUTION OF THE SAMOAN HOTSPOT TRAIL

The new 5.0 Ma age in this study is practically identical to the 5.1 Ma age that a present-day 7.1 cm/yr Pacific plate motion would predict for the onset of hotspot volcanism on Savai'i Island (Fig. 3). A similar match is apparent when comparing the new ages to the latest WKH06 plate motion model of Wessel et al. (2006) based on six Pacific hotspots (Hawaii, Louisville, Caroline, Foundation, Pitcairn, Cobb) excluding Samoa (Fig. 3). This provides an independent assessment showing that the 5.0 Ma Savai'i age is consistent with age progressions observed in at least six other Pacific hotspot trails. However, the models used in these comparisons are both based on the conjecture that hotspots remain fixed in the mantle over extended periods of geological time, whereas plate circuit modeling and paleomagnetic data provide evidence to the contrary and are indicating substantial hotspot motions (Tarduno et al., 2003). Nevertheless, rapid and large-scale motion of Pacific hotspots appears limited to the period from the

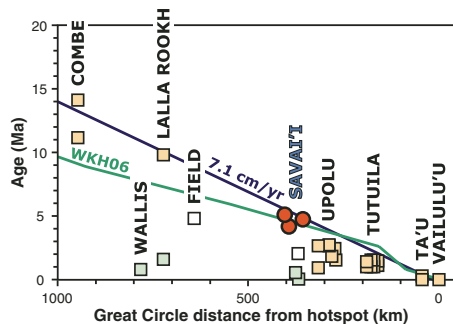


Figure 3. Sample age versus distance from Vailulu'u, illustrating the age progression for the Samoan island and seamount trail. The new 5.0 Ma shield ages (orange circles) for Savai'i closely fit the linear age progression predicted by a Pacific plate motion of 7.1 cm/yr and the latest plate motion model (WKH06) of Wessel et al. (2006). In both models Vailulu'u (zero age) is taken as the current location of the Samoan hotspot (Hart et al., 2000; Staudigel et al., 2004). Ages for the other Samoan volcanoes are referenced in Hart et al. (2004) and Workman et al. (2004) and are indicated to belong to either the shield stage (light orange squares), the posterosional stage (light green squares), or an undetermined volcanic stage (uncolored squares) as based on their geochemistry.

Late Cretaceous to the Paleocene (e.g., Sager et al., 2005), and although hotspot motion has been proposed for the last five million years on the basis of geodynamic modeling (e.g., Steinberger, 2000), it is small and can be ignored in the context of our present study.

In addition to the above observations, the tectonic framework of the southwestern Pacific shows that extension and cracking of the lithosphere could not have been responsible for the early eruption of the Savai'i lavas at 5.0 Ma (see detailed discussion in Hart et al., 2004). Due to the rollback of the downgoing Pacific slab, the Tonga Trench moved rapidly east through geological time. Over the same time interval, Savai'i has been moving slowly in the opposition direction (Fig. 4). This simplified plate reconstruction reveals that the northern terminus of the trench was located 1500 km to the west of Savai'i Island at 5.0 Ma and could not possibly have influenced its shield-building volcanic stage.

Instead, the $^{40}\text{Ar}/^{39}\text{Ar}$ age dates, the Pb isotope geochemistry, and the plate reconstructions all suggest that the greater part of the Savai'i shield volcano was formed around 5.0 Ma in a "true" intra-plate setting. Furthermore, based on the deep submarine sampling of the lavas dated in this study, the lavas are likely to represent the earliest shield-building phase for Savai'i Island. This is in contrast to the shield basalts sampled and dated for Upolu and Tutuila, which are more likely to represent

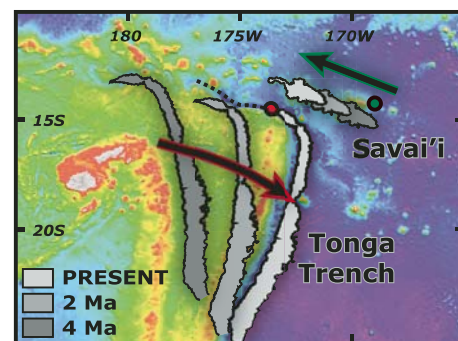


Figure 4. Simplified tectonic map of the Samoa region showing the major rollback of the Pacific plate over the last four million years at the Tonga Trench and with reference to the Samoan hotspot. The northern termination point of this trench and the present location of the Samoan hotspot beneath the Vailulu'u submarine volcano are indicated by red and green circles, respectively. In this reconstruction the current shape and size of the Tonga Trench are kept constant for simplicity. For a more detailed discussion of the tectonic evolution of this region, we refer to Hart et al. (2004) and Ruellan et al. (2003).

later phases in their shield building. Because the total duration of the shield-building stage may be as long as a few million years, an age offset is expected, whereby late-stage shield lavas of Upolu and Tutuila plot decidedly below the expected age-distance lines (Fig. 3).

It is remarkable that late-stage shield lavas have never been sampled at Savai'i, because a blanket of anomalously young 0.39 Ma volcanics covers the entire island surface. The timing of this posterosional volcanism places Savai'i directly northwest of the northern terminus of the Tonga subduction zone (Fig. 4). As similar posterosional volcanics have been identified on the islands of Upolu and Tutuila, this suggests that the bending of the subducting Pacific plate may have induced a lithospheric fracture, ~300 km long and following the axis of the Samoan hotspot trail, along which shallow mantle melts are allowed to seep through and produce multiple centers of simultaneous posterosional volcanism (Hawkins and Natland, 1975; Natland, 1980). We thus conclude that Savai'i Island is characterized by two distinct stages in its volcanic evolution: (1) an early hotspot/plume stage, which constructed the largest part of the volcanic island, beginning ca. 5.0 Ma, and (2) a later stage, driven by lithospheric cracking, which formed the pervasive posterosional volcanic cap on top of Savai'i Island, starting much later, ca. 0.39 Ma.

Including the new $^{40}\text{Ar}/^{39}\text{Ar}$ age dating results from Savai'i Island, the Samoan hotspot trail now depicts a linear age progression between young shield volcanoes in the east (Ta'u, Vailulu'u) and older seamounts in the

west (Combe, Lalla Rookh). This is consistent with both a constant 7.1 cm/yr plate motion and the latest plate motion models, assuming fixed hotspots. This observation rules out the principal objection to a plume origin for the Samoan trail, and reinstates it as a primary hotspot trail in the Pacific basin. Along with the Hawaii-Emperor, Louisville, and Easter trails, Samoa performs like a textbook hotspot with a well-understood age progression and with a likely deep origin in the mantle, based on persistent velocity anomalies in S- and P-wave tomographic images (Montelli et al., 2006).

Our observations, on the other hand, are in contrast to recent geochronological studies that show that many seamount trails in the Pacific do not exhibit clear age-progressive volcanism (e.g., Gilbert Ridge, Tokelau seamounts, West Pacific seamount province). These latter hotspots require alternative processes such as lithospheric extension and cracking of the Pacific plate (Koppers et al., 2003; Koppers and Staudigel, 2005). A one-model-fits-all approach thus seems improbable and undesirable for settling the scientific debate regarding the existence of mantle plumes. In the case of Samoa, a complex tectonomagmatic history is now illuminated by our observations, yet the role for plume-driven intraplate volcanism is evident.

ACKNOWLEDGMENTS

We acknowledge funding from National Science Foundation grant OCE-0002875. In particular, we thank R.A. Duncan and J. Huard for the use of their laboratory. We are grateful to the R/V *Kilo Moana* crew and to John Helly, Laurent Montes, Rhea Workman, Alison Koleszar, Julie Rumrill, Samantha Allen, Scott McBride, Daniel Staudigel, Ryan Delaney, Blake English, and Shaun Williams for making the 2005 ALIA expedition a success. We thank Paul Wessel, Jim Hawkins, Godfrey Fitton, and an anonymous reviewer for their thoughtful comments.

REFERENCES CITED

- Clague, D.A., Dalrymple, G.B., Wright, T.L., Klein, F.W., Koyanagi, R.Y., Decker, R.W., and Thomas, D.M., 1989, The Hawaiian-Emperor chain, in Winterer, E.L., et al., eds., *The geology of North America: The eastern Pacific Ocean and Hawaii*: Boulder, Colorado, Geological Society of America, Series N, p. 187-287.
- Courtillot, V., Davaille, A., Besse, J., and Stock, J., 2003, Three distinct types of hotspots in the Earth's mantle: Earth and Planetary Science Letters, v. 205, p. 295-308, doi: 10.1016/S0012-821X(02)01048-8.
- Davis, A.S., Gray, L.B., Clague, D.A., and Hein, J.R., 2002, The Line Islands revisited: New $^{40}\text{Ar}/^{39}\text{Ar}$ geochronologic evidence for episodes of volcanism due to lithospheric extension: *Geochemistry, Geophysics, Geosystems*, v. 3, 1018, doi: 10.1029/2001GC000190.
- Duncan, R.A., and Keller, R.A., 2004, Radiometric ages for basement rocks from the Emperor Seamounts, ODP Leg 197: *Geochemistry, Geophysics, Geosystems*, v. 5, Q08L03, doi: 10.1029/2004GC000704.
- Foulger, G.R., and Natland, J.H., 2003, Is "hotspot" volcanism a consequence of plate tectonics?: *Science*, v. 300, p. 921-922, doi: 10.1126/science.1083376.
- Hart, S.R., Staudigel, H., Koppers, A.A.P., Blusztajn, J., Baker, E.T., Workman, R., Jackson, M., Hauri, E., Kurz, M., Sims, K., Fornari, D., Saal, A., and Lyons, S., 2000, *Vailulu'u under-sea volcano: The new Samoa*: *Geochemistry, Geophysics, Geosystems*, v. 1, doi: 10.1029/2000GC000108.
- 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*, v. 227, p. 37-56, doi: 10.1016/j.epsl.2004.08.005.
- Hawkins, J.W., and Natland, J.H., 1975, Nephelinites and basanites of the Samoan linear volcanic chain: Their possible tectonic significance: *Earth and Planetary Science Letters*, v. 24, p. 427-439, doi: 10.1016/0012-821X(75)90150-8.
- Jackson, M.G., Hart, S.R., Koppers, A.A.P., Staudigel, H., Konter, J., Blusztajn, J., Kurz, M.D., and Russell, J.A., 2007, The return of subducted continental crust in Samoan lavas: *Nature*, v. 448, p. 684-687, doi: 10.1038/nature06048.
- Koppers, A.A.P., and Staudigel, H., 2005, Asynchronous bends in Pacific seamount trails: A case for extensional volcanism?: *Science*, v. 307, p. 904-907, doi: 10.1126/science.1107260.
- Koppers, A.A.P., Staudigel, H., and Wijbrans, J.R., 2000, Dating crystalline groundmass separates of altered Cretaceous seamount basalts by the $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating technique: *Chemical Geology*, v. 166, p. 139-158, doi: 10.1016/S0009-2541(99)00188-6.
- Koppers, A.A.P., Staudigel, H., Pringle, M.S., and Wijbrans, J.R., 2003, Short-lived and discontinuous intraplate volcanism in the South Pacific: Hot spots or extensional volcanism?: *Geochemistry, Geophysics, Geosystems*, v. 4, 1089, doi: 10.1029/2003GC000533.
- Koppers, A.A.P., Duncan, R.A., and Steinberger, B., 2004, Implications of a nonlinear $^{40}\text{Ar}/^{39}\text{Ar}$ age progression along the Louisville seamount trail for models of fixed and moving hot spots: *Geochemistry, Geophysics, Geosystems*, v. 5, Q06L02, doi: 10.1029/2003GC000671.
- Montelli, R., Nolet, G., Dahlen, F.A., and Masters, G., 2006, A catalogue of deep mantle plumes: New results from finite-frequency tomography: *Geochemistry, Geophysics, Geosystems*, v. 7, Q11007, doi: 10.1029/2006GC001248.
- Morgan, W.J., 1972, Deep mantle convection plumes and plate motions: *American Association of Petroleum Geologists Bulletin*, v. 56, p. 42-43.
- Natland, J.H., 1980, The progression of volcanism in the Samoan linear volcanic chain: *American Journal of Science*, v. 280-A, p. 709-735.
- Natland, J.H., and Turner, D.L., 1985, Age progression and petrological development of Samoan shield volcanoes: Evidence from K-Ar ages, lava compositions and mineral studies, in Brocker, T.M., ed., *Geological investigations of the northern Melanesian borderland*: Houston, Texas, Council for Energy and Mineral Resources, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 3, p. 139-172.
- Natland, J.H., and Winterer, E.L., 2005, Fissure control on volcanic action in the Pacific, in Foulger, G.R., et al., eds., *Plumes, plates, and paradigms: Geological Society of America Special Paper* 388, p. 687-710, doi: 10.1130/2005.2388(39).
- Pringle, M., Staudigel, H., and Gee, J., 1991, Jasper Seamount: Seven million years of volcanism: *Geology*, v. 19, p. 364-368, doi: 10.1130/0091-7613(1991)019<0364:JSSMYO>2.3.CO;2.
- Ruellan, E., Deltail, 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*, v. 4, 8909, doi: 10.1029/2001GC000261.
- Sager, W.W., Lamarche, A.J., and Kopp, C., 2005, Paleomagnetic modeling of seamounts near the Hawaiian-Emperor bend: *Tectonophysics*, v. 405, p. 121-140.
- Smith, W.H.F., and Sandwell, D.T., 1997, Global seafloor topography from satellite altimetry and ship depth soundings: *Science*, v. 277, p. 1956-1962.
- Staudigel, H., Hart, S.R., Koppers, A.A.P., Constable, C., Workman, R., Kurz, M., and Baker, E.T., 2004, Hydrothermal venting at Vailulu'u Seamount: The smoking end of the Samoan chain: *Geochemistry, Geophysics, Geosystems*, v. 5, Q02003, doi: 10.1029/2003GC000626.
- Steinberger, B., 2000, Plumes in a convecting mantle: Models and observations for individual hotspots: *Journal of Geophysical Research, B, Solid Earth and Planets*, v. 105, p. 11,127-11,152.
- 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., and Carvallo, C., 2003, The Emperor Seamounts: Southward motion of the Hawaiian hotspot plume in Earth's mantle: *Science*, v. 301, p. 1064-1069, doi: 10.1126/science.1086442.
- Watts, A.B., Weissel, J.K., Duncan, R.A., and Larson, R.L., 1988, Origin of the Louisville Ridge and its relationship to the Eltanin fracture zone system: *Journal of Geophysical Research*, v. 93, p. 3051-3077.
- Wessel, P., Harada, Y., and Kroenke, L., 2006, Toward a self-consistent, high-resolution absolute plate motion model for the Pacific: *Geochemistry, Geophysics, Geosystems*, v. 7, Q03L12, doi: 10.1029/2005GC001000.
- 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*, v. 5, Q04008, doi: 10.1029/2003GC000623.
- Wright, E., and White, W.M., 1986, The origin of Samoa: New evidence from Sr, Nd, and Pb isotopes: *Earth and Planetary Science Letters*, v. 81, p. 151-162, doi: 10.1016/0012-821X(87)90152-X.

Manuscript received 29 November 2007

Revised manuscript received 22 January 2008

Manuscript accepted 24 January 2008

Printed in USA

ONLINE GSA DATA REPOSITORY ITEM

⁴⁰Ar/³⁹Ar TECHNIQUES

The ⁴⁰Ar/³⁹Ar age determinations were performed on crystalline groundmass separates (210-300 μm) and plagioclase and K-feldspar mineral separates using a continuous, 10W CO₂ laserprobe combined with a MAP-215/50 mass spectrometer. Sample preparation and acid leaching procedures are described in Koppers et al. (2000). Irradiated samples were loaded into Cu-planchettes designed with a variety of pans that hold up to 50 mg of material, which are then pumped within a sample chamber fitted with a ZnSe window that is transparent to the CO₂ laser wavelength. Software allows for scanning across samples in a preset pattern with a defocused beam, to evenly heat the geological material. Gas cleanup was accomplished with a series of Zr-Al getters. All ages were calculated relative to the flux monitor standard FCT-3 biotite (28.04 ± 0.18 Ma, 1σ, Renne et al., 1994) and calculated using the corrected Steiger and Jäger (1977) decay constant of $5.530 \pm 0.097 \times 10^{-10}$ 1/yr (2σ) as reported by Min et al. (2000). For a detailed description of the analytical facility and the constants used in the age calculations we refer to Koppers et al. (2003). Incremental heating plateau ages and isochron ages were calculated using the ArArCALC v2.4 software from Koppers (2002) that is available from the <http://earthref.org/tools/ararcalc.htm> website. In this paper, all errors on the ⁴⁰Ar/³⁹Ar ages are reported at the 95% confidence level (2σ), unless otherwise indicated.

⁴⁰Ar/³⁹Ar QUALITY CRITERIA

In this study we adopted the following quality criteria: (1) age plateaus should include more than three incremental heating steps and at least 50% of the total amount of ³⁹Ar released, (2) the plateau, isochron and total fusion ages should be concordant at the 95% confidence level, (3) the ⁴⁰Ar/³⁶Ar intercepts on the isochron diagrams should be concordant with the atmospheric value of

295.5 at the 95% confidence level, and (4) the mean square of weighted deviations for both the plateau ages ($\text{MSWD} = \text{SUMS}/N-1$) and isochron ages ($\text{MSWD} = \text{SUMS}/N-2$) should be sufficiently small when compared to student's t-test and F-statistic critical values for significance.

$^{40}\text{Ar}/^{39}\text{Ar}$ DATA

In Table DR1 a summary of the results of our seven new $^{40}\text{Ar}/^{39}\text{Ar}$ analyses have been listed. The age plateau diagrams are all depicted in Figure DR1, whereas the dredge locations are displayed on top of a 3D rendition of Savai'i Island in Figure DR2.

SAMPLE DESCRIPTIONS AND GEOCHEMISTRY

In Table DR2 we provide summary of the sample descriptions (Russell, 2007). In Table DR3 we list the major and trace element geochemistry and isotope ratios of the six dredge samples (Jackson et al., 2007) that also were dated using the $^{40}\text{Ar}/^{39}\text{Ar}$ technique in this study. For a detailed description of the analytical techniques used we refer to the Supplementary Table 3 in Jackson et al. (2007).

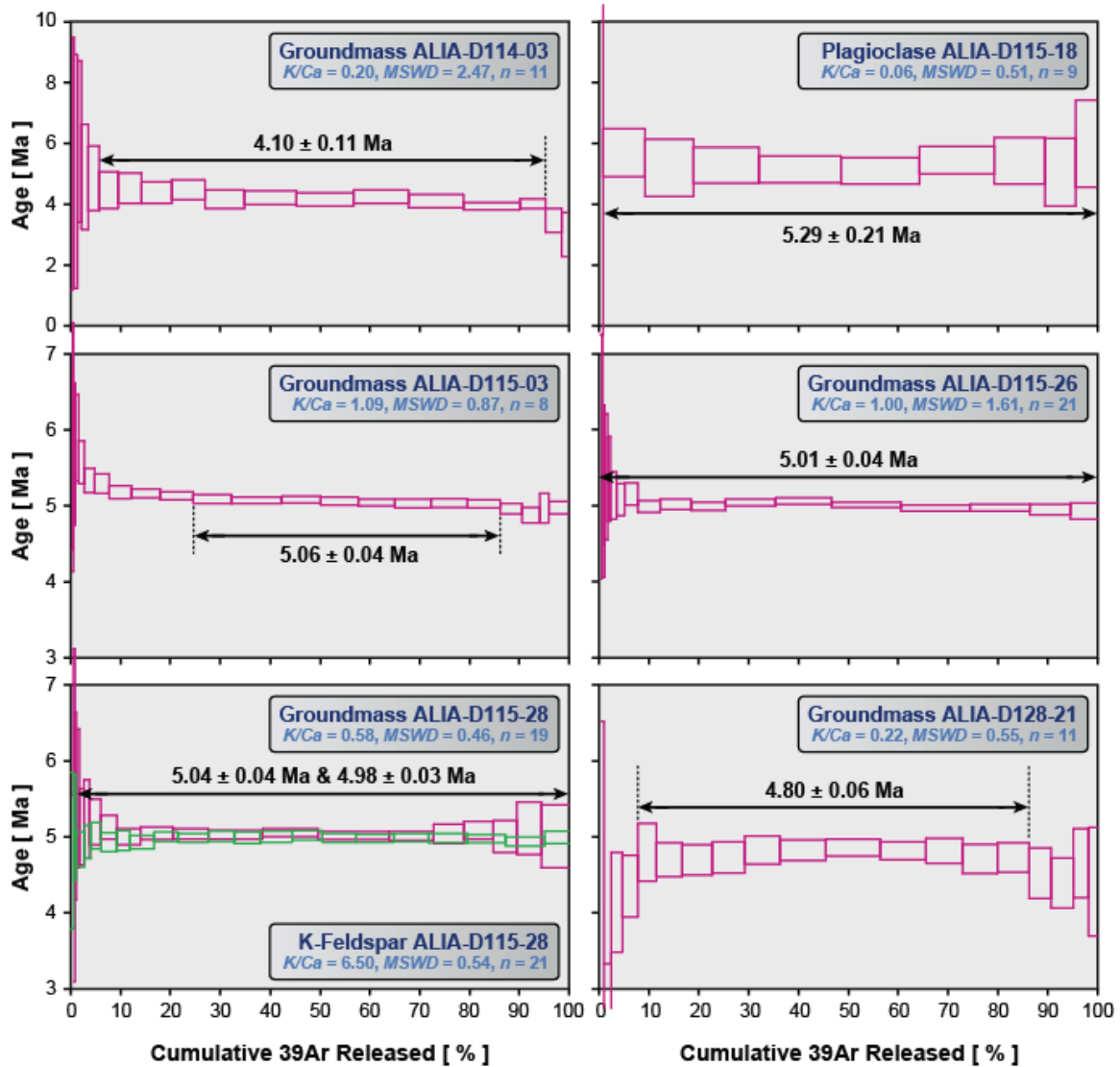


Figure DR1. New $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for the submarine Savai'i basalts. The reported ages are weighted age estimates with errors reported at the 95% confidence level, including 0.3-0.4% standard deviations in the J-value. Note that the groundmass age spectrum for sample ALIA-D115-28 was reproduced within the 95% confidence limit in a second incremental heating experiment with a K-feldspar mineral separate (green lines).

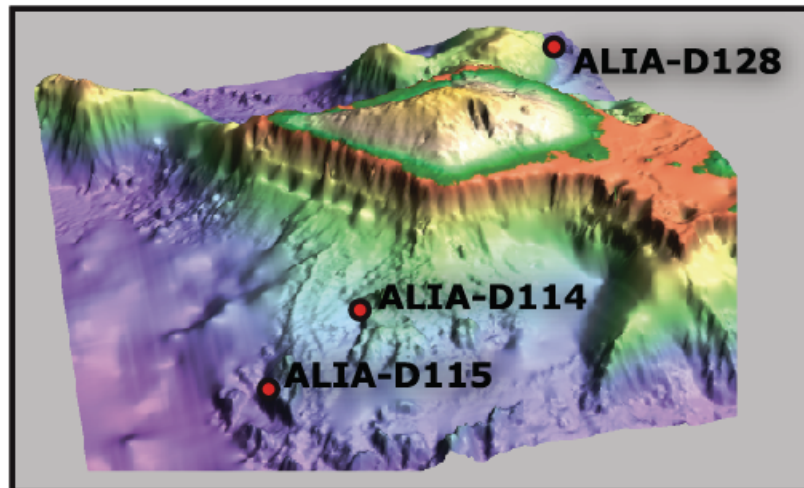


Figure DR2. 3D rendition of Savai'i Island looking from the SW with dredge locations. Visit the *Seamount Catalog* to find detailed bathymetric maps, grid files and multibeam data by using the <http://earthref.org/cgi-bin/sc.cgi?id=SMNT-137S-1725W> web link.

Sample Number	Lab Number	Lat	Lon	Depth (mbsf)	Sample Type	Age Spectrum				Total Fusion		Inverse Isochron Analyses		
						Age $\pm 2\sigma$ (Ma)	^{39}Ar (%)	K/Ca	MSWD	n	Age $\pm 2\sigma$ (Ma)	Age $\pm 2\sigma$ (Ma)	$^{40}\text{Ar}/^{36}\text{Ar}$ intercept	MSWD
ALIA-D114-03	06C3569	13°58.7'S	172°44.4'W	3,100-2,600	Groundmass	4.10 $\pm$ 0.11	89.9	0.20	2.47	11	4.22 $\pm$ 0.09	5.11 $\pm$ 0.06	229.7 $\pm$ 64.9	0.57
ALIA-D115-03	06C3034	14°05.5'S	172°56.5'W	4,100-3,200	Groundmass	5.06 $\pm$ 0.04	61.7	1.09	0.87	8	5.10 $\pm$ 0.04			
ALIA-D115-18	06C3069				Plagioclase	5.29 $\pm$ 0.21	99.5	0.06	0.51	9	5.35 $\pm$ 0.23			
ALIA-D115-26	06C3540				Groundmass	5.01 $\pm$ 0.04	100.0	1.00	1.61	21	5.02 $\pm$ 0.04	5.02 $\pm$ 0.04	290.1 $\pm$ 8.3	1.56
ALIA-D115-28	06C2898				Groundmass	5.04 $\pm$ 0.04	99.6	0.58	0.46	19	5.07 $\pm$ 0.05	5.03 $\pm$ 0.04	296.2 $\pm$ 2.7	0.47
	06C3509				K-Feldspar	4.98 $\pm$ 0.03	100.0	6.50	0.54	21	4.97 $\pm$ 0.03	4.99 $\pm$ 0.05	279.1 $\pm$ 66.0	0.55
ALIA-D128-21	06C3007	13°12.7'S	172°05.8'W	2,600-2,500	Groundmass	4.80 $\pm$ 0.06	78.6	0.22	0.55	11	4.70 $\pm$ 0.07	4.84 $\pm$ 0.10	282.0 $\pm$ 23.6	0.48

Table DR1. Summary of $^{40}\text{Ar}/^{39}\text{Ar}$ age data on dredge samples from the submarine flanks of Savai'i Island. All samples were monitored against FCT-3 biotite (28.04 ± 0.18 Ma) as calibrated by Renne et al. 1998 (1998). Reported errors on the $^{40}\text{Ar}/^{39}\text{Ar}$ ages are at the 95% confidence level including 0.3-0.4% standard deviation on the J-value. All input parameters to the calculations are published in Table 2 of Koppers et al. 2003 (2003), whereas the ArArCALC v2.4 age calculations are described in Koppers 2002 (Koppers, 2002). Detailed data sets are available in the Supplementary Materials and all ArArCALC age calculation files can be downloaded separately from the *EarthRef.org Digital Archive* (ERDA).

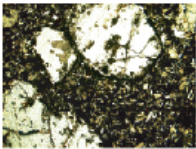
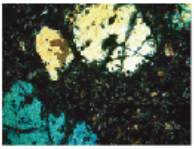
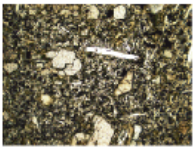
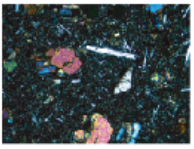
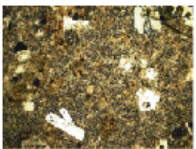
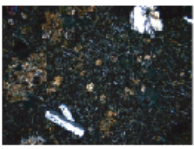
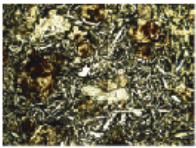
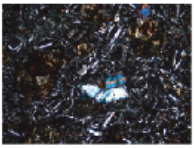
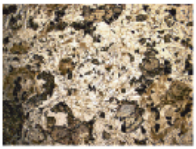
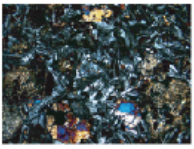
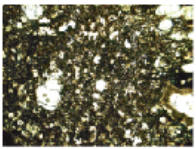
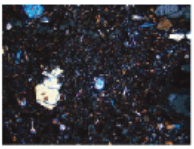
ALIA 2005 Dredge	Thin Section Photograph		Description	Material(s) Age Dated
	Plain Polarized Light	Cross Polarized Light		
D114-03			Non-vesicular picritic basalt; phenox = 20% cpx, 5% olivine; grndm = hypocrySTALLINE with 40% plg; alt = all of olivine, 5% in groundmass, 2% in cpx; other = thin Mn crust	Groundmass Leached (2X), magnet handpicked 109.6 mg
D115-03			Vesicular (1%) hawaiite; phenox = 25% cpx, 10% plg; grndm = hypocrySTALLINE with 60% plg, 10% cpx; alt = 10% in groundmass	Groundmass Leached handpicked 112.3 mg
D115-18			Vesicular (20%) trachybasalt; phenox = 5% plg, 3% cpx; grndm = holocrystalline with 20% plg; alt = 10% in groundmass; other = thin Mn crust	K-Feldspar Magnet, leached handpicked 30.9 mg
D115-26			Vesicular (5%) trachybasalt; phenox = 5% plg, 3% cpx, <1% olivine; grndm = holocrystalline with 95% plg and 5% cpx; alt = 3% in phenocrysts, 1% in groundmass	Groundmass Magnet, leached handpicked 103.9 mg
D115-28			Vesicular (5%) hawaiite; phenox = 5% cpx; grndm = holocrystalline with 90% plg and kfs; alt = 5% in groundmass	Groundmass Magnet, leached handpicked 111.1 mg K-Feldspar Magnet, leached handpicked 64.3 mg
D128-21			Vesicular (40%) alkali basalt; phenox = 25% cpx; grndm = hypocrySTALLINE with 20% cpx, 10% plg; alt = 20% in groundmass	Groundmass Magnet, leached handpicked 103.9 mg

Table DR2. Sample descriptions and thin section pictures of Savai'i dredge samples. After Russell (2007).

Sample Number Rock Type	ALIA-D114-03 Picritic Basalt	ALIA-D115-03 Hawaiite	ALIA-D115-18 Trachybasalt	ALIA-D115-26 Trachybasalt	ALIA-D115-28 Hawaiite	ALIA-D128-21 Alkali Basalt
Latitude	13°58.7'S	14°05.5'S	14°05.5'S	14°05.5'S	14°05.5'S	13°12.7'S
Longitude	172°44.4'W	172°56.5'W	172°56.5'W	172°56.5'W	172°56.5'W	172°05.8'W
Depth Range (m)	3,100-2,600	4,100-3,200	4,100-3,200	4,100-3,200	4,100-3,200	2,600-2,500
40Ar/39Ar Age	4.10 ± 0.11 Ma	5.06 ± 0.04 Ma	5.29 ± 0.21 Ma	5.01 ± 0.04 Ma	5.04 ± 0.04 Ma 4.98 ± 0.03 Ma	4.80 ± 0.06 Ma
SiO₂	44.92	49.16	52.28	51.88	50.00	48.95
Al₂O₃	7.42	12.59	14.20	14.26	13.44	12.11
TiO₂	3.00	3.50	2.45	2.71	3.30	2.28
FeO	12.33	9.74	7.09	7.46	7.86	9.67
MnO	0.18	0.13	0.07	0.09	0.12	0.17
CaO	8.89	8.17	6.08	7.27	9.62	9.81
MgO	20.07	7.97	5.09	4.08	6.37	11.65
K₂O	0.83	3.09	4.01	3.52	2.73	1.23
Na₂O	1.55	2.85	3.64	3.50	3.15	2.12
P₂O₅	0.36	0.51	0.36	0.42	0.52	0.25
Total	99.55	97.71	95.27	95.19	97.11	98.24
Mg#	76.32	61.84	58.73	52.02	61.63	70.46
LOI	0.00	1.90	4.40	4.42	2.51	1.43
Ni (ppm)	820	222	116	106	180	265
Cr	1418	370	244	494	464	713
V	258	237	154	221	270	261
Ga	13	24	27	27	24	19
Cu	76	41	23	53	52	41
Zn	127	120	111	150	103	115
Cs	0.22	0.7	0.59	0.58	0.66	0.41
Rb	14.2	83.1	97.4	99.8	81.4	28.4
Ba	177	569	646	586	510	240
Th	3.28	7.13	10.74	10.31	8.89	4.29
U	0.63	1.63	1.84	2.1	1.77	0.72
Nb	33.64	54.12	47.48	47.73	54.31	31.26
Ta	2.31	3.68	3.17	3.23	3.61	2.17
La	28.05	53.17	66.92	59.58	61.04	32.25
Ce	60.69	104.2	130.1	118.6	119.4	66.79
Pb	2.28	7.27	11.29	8.84	11.61	4.77
Pr	7.75	11.97	15.02	14.39	13.76	8.55
Nd	32.01	48.31	55.89	55.43	52.43	34.67
Sr	374	617	511	5.28	645	363
Zr	186	305	341	320	313	179
Hf	4.8	8.02	8.86	8.26	7.88	5.02
Sm	7.06	10.69	10.66	11.24	10.46	7.5
Eu	2.22	3.14	3	3.2	3.14	2.17
Gd	6.2	9.02	8.34	9.2	9.01	6.86
Tb	0.9	1.25	1.13	1.28	1.24	1.02
Dy	4.89	6.44	5.67	6.66	6.65	5.49
Ho	0.86	1.06	0.97	1.15	1.15	1.03
Y	20.58	27.26	24.05	28.79	28.16	25.78
Er	2	2.36	2.2	2.65	2.69	2.47
Tm	0.25	0.3	0.28	0.33	0.33	0.34
Yb	1.41	1.59	1.47	1.87	1.89	1.98
Lu	0.2	0.22	0.21	0.27	0.27	0.29
Sc	29.9	19.8	15.2	19.8	24.4	28.9
87Sr/86Sr	0.705435	0.711409	0.718592	0.716394	0.709985	0.712500
143Nd/144Nd	0.512763	0.512593	0.512314	0.512389	0.512570	0.512459
206Pb/204Pb	19.322	19.011	18.957	19.009	19.034	18.963
207Pb/204Pb	15.619	15.633	15.643	15.644	15.634	15.628
208Pb/204Pb	39.475	39.347	39.399	39.452	39.419	39.273

Table DR3. Major and trace element data and isotope ratios on Savai'i dredge samples. After Jackson et al. (2007).

References

- Jackson, M.G., Hart, S.R., Koppers, A.A.P., Staudigel, H., Konter, J., Blusztajn, J., Kurz, M.D., and Russell, J.A., 2007, The return of subducted continental crust in Samoan lavas: *Nature*, v. 448, p. 684-687, doi:10.1038/nature06048.
- Koppers, A.A.P., 2002, ArArCALC - software for Ar-40/Ar-39 age calculations: *Computers & Geosciences*, v. 28, p. 605-619.
- Koppers, A.A.P., Staudigel, H., and Duncan, R.A., 2003, High-resolution Ar-40/Ar-39 dating of the oldest oceanic basement basalts in the western Pacific basin: *Geochemistry Geophysics Geosystems*, v. 4.
- Koppers, A.A.P., Staudigel, H., and Wijbrans, J.R., 2000, Dating crystalline groundmass separates of altered Cretaceous seamount basalts by the Ar-40/Ar-39 incremental heating technique: *Chemical Geology*, v. 166, p. 139-158, doi: 10.1016/S0009-2541(99)00188-6.
- Min, K.W., Mundil, R., Renne, P.R., and Ludwig, K.R., 2000, A test for systematic errors in Ar-40/Ar-39 geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite: *Geochimica Et Cosmochimica Acta*, v. 64, p. 73-98.
- Renne, P.R., Deino, A.L., Walter, R.C., Turrin, B.D., Swisher III, C.C., Becker, T.A., Curtis, G.H., Sharp, W.D., and Jaouni, A.-R., 1994, Intercalibration of astronomical and radioisotopic time: *Geology*, v. 22, p. 783-786.
- Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998, Intercalibration of standards, absolute ages and uncertainties in $^{40}\text{Ar}/^{39}\text{Ar}$ dating: *Chemical Geology*, v. 145, p. 117-152.
- Russell, J.A., 2007, Linear Age Progressions in Samoan Sub-Parallel Intra-Plate Volcanic Trails, University of California, San Diego, M.Sc. Thesis, 100 p.
- Steiger, R.H., and Jager, E., 1977, Subcommittee on geochronology: convention on the use of decay constants in geo- and cosmochemistry: *Earth and Planetary Science Letters*, v. 36, p. 359-362.