Samoan hot spot track on a “hot spot highway”:
Implications for mantle plumes and a deep
Samoan mantle source

Matthew G. Jackson
Department of Earth Sciences, Boston University, Boston, Massachusetts 02215, USA (jacksonm@bu.edu)

Stanley R. Hart
Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02540, USA

Jasper G. Konter
Department of Geological Sciences, University of Texas at El Paso, El Paso, Texas 79968, USA

Anthony A. P. Koppers
College of Oceanic and Atmospheric Sciences, Oregon State University, 104 COAS Administration Building, Corvallis, Oregon 97331, USA

Hubert Staudigel
Institute of Geophysics and Planetary Physics, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093, USA

Mark D. Kurz
Department of Marine Chemistry, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02540, USA

Jerzy Blusztajn
Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02540, USA

John M. Sinton
Department of Geology and Geophysics, University of Hawai‘i at Mānoa, Honolulu, Hawai‘i 96822, USA

[1] We report new geochemical data for submarine lavas from the Samoan region that greatly enhance the
geochemical data set for volcanoes from the hot spot. Additionally, two volcanoes dredged in the northern
Lau Basin, Futuna Island and Manatu seamount, are young (<5 Ma), appear to be genetically related, and
may have been generated by melting a component of Samoan mantle that has been advected into the
region. We also find evidence for three seamounts and one atoll along the Samoan hot spot track that
are not geochemically related to Samoa. We use a plate motion model to show that three non-Samoan hot
spots, currently active in the Cook–Austral Islands, provided volcanism to the Pacific Plate now in the
Samoan region approximately 10–40 Ma. The four interloping volcanoes in the Samoan region exhibit geo-
chemical affinities with the three hot spots. All three hot spots would have left a depleted, viscous, refractory
keel that is coupled to the base of the Pacific lithosphere that has been “rafted” to the Samoan region. There-
fore, the new data also have implications for the origin of the Samoan hot spot as its origin has been suggested
to be a result of either a deep-seated mantle plume or a consequence of lithospheric cracking. Without major
modification of the current “propagating lithospheric cracks” model, it is not clear how such cracks could
yield melts from the refractory keel present under the Samoan lithosphere. Instead, a region of buoyantly
upwelling mantle, or plume, is suggested to generate the shield stage volcanism in the Samoan region.
1. Introduction

The Samoan hot spot has many features typically associated with an upwelling, deep-seated mantle plume. Velocity anomalies beneath Samoa can be traced to the lower mantle (Montelli et al., 2004). The surface expression of Samoan volcanism exhibits a clear age progression with geology (Duncan, 1985; Hart et al., 2004; Koppers et al., 2008) (anchored by a young, active seamount, Vaiulu'u, at the leading end of the hot spot) that is consistent with the hot spot being fed by a laterally fixed plume that is upwelling beneath Samoa (Figure 1). Samoan lavas have high 3He/4He ratios (up to 33.8 Ra, or ratio to atmosphere [Farley et al., 1992; Jackson et al., 2007b]). Samoan lavas also host signatures for recycled, continentally derived sediment that are inconsistent with the incorporation of modern marine sediment at shallow crustal depths [Jackson et al., 2007a]. Instead, a more likely scenario is that the sediment signature in Samoan lavas requires an ancient subduction event that injected the sediments into the mantle [White and Hofmann, 1982], followed by recent entrainment of this recycled material in the region by focused mantle upwelling. Despite this evidence for a deep-seated mantle plume beneath Samoa, Samoa finds itself in the middle of a protracted debate about hot spots versus mantle plumes or whether hot spot volcanism is simply the result of “top-down,” tectonically driven melt extraction [e.g., Foulger and Natland, 2003; Anderson, 2001].

In spite of these “smoking gun” features associated with deep-seated mantle plumes, the interpretation of the origin of volcanism in Samoa is complicated by its juxtaposition with the northern terminus of the Tonga trench, which is located just over 100 km south of the westernmost Samoan island of Savai’i. This unique hot spot-trench juxtaposition has been suggested to enhance melting and melt extraction along the hot spot via lithospheric cracking, which is in turn driven by tectonic stresses from the nearby trench [e.g., Hawkins and Natland, 1975; Natland, 2009; J. H. Natland, The Samoan chain: A shallow lithospheric fracture system, 2003, available at http://www.mantleplumes.org]. The westernmost Samoan island, Savai’i, is closest to the Tonga trench and shows clear evidence for enhanced rejuvenated volcanism that is voluminous that the entire island has been completely “resurfaced” with recent (<1 Ma) lava flows.

The excessive volume of rejuvenated volcanism on Savai’i is not typical of late stage hot spot volcanic activity, and contrasts with the relatively low volumes of rejuvenated volcanism on the Hawaiian islands [Clague and Dalrymple, 1987]. As a result, Hawkins and Natland [1975] and Natland [1980] suggested that a simple plume-driven hot spot model was insufficient to describe the volcanism in Samoa, and they suggested that plate flexure associated with the Tonga trench is responsible for generating volcanism along the entire hot spot track via stress-induced cracks in the lithosphere. However, recent geochronological data on lavas recovered from the deep flanks of Savai”i indicate a 5.0 Ma age for the inception of volcanism, when the Tonga Trench was positioned 1400 km to the west of Savai’i and well out of range to affect early, shield building volcanism at the island. The 5.0 Ma age is consistent with that predicted by the mantle plume hypothesis [Koppers et al., 2008]. While it is clear that volcanism at Savai’i was not initiated by tectonic stresses from the Tonga trench, we cannot exclude the possibility that the recent, anomalously voluminous, rejuvenated volcanism on Savai’i may have been enhanced by tectonic stresses from the nearby trench.

We report new geochronological data for samples from three dredging cruises in the Samoan region that complement existing data and expand the
Figure 1. (top) Map of the Samoan region. The WESAM (western Samoan) and the ESAM (eastern Samoan) volcanic provinces are labeled, and Savai’i demarcates the arbitrary separation of the ESAM–WESAM provinces. (bottom) An expanded view of the entire ESAM province. Alexa Bank is located ~7°WNW of Combe and plots off the map. There are a number of volcanoes in the Samoan region shown to have non-Samoan geochemical signatures, and they are likely associated with the Cook-Austral hot spots: Rose Atoll, Malulu, Waterwitch, and Papatua. Several volcanoes located to the south of the Vitiaz may be related to melting of material from the Samoan mantle that has leaked into the northern Lau Basin, and the volcanoes include the Futuna, Manatu, Rochambeau and (possibly) Niuafou’ou [Regelous et al., 2008] volcanic centers. Plate boundaries are taken from Ruellean et al. [2003]; the western portion of the Vitiaz is not clear and is marked (with question marks). The maps use Smith and Sandwell’s [1997] bathymetry, SRTM (Shuttle Radar Topography Mission [Farr and Kobrick, 2001]) topography, and multibeam bathymetry as data sources (multibeam available from the Seamount Catalog at http://www.earthref.org). Dredge locations are labeled: Dredges beginning with “DR” in the map are from the ALIA cruise, those beginning with “AVON” are from the AVON cruise, and those beginning with “KK” are from the Kana Keoki cruise.
known isotopic variability of the Samoan hot spot. In particular, we find that lavas from the older, western region of the Samoan volcanic province are consistent with the hypothesis that the Samoan hot spot is long lived and geochemically distinct [Hart et al., 2004]. Additionally, two volcanoes dredged in the northwest Lau Basin, located just south of the western Samoan volcanic province, exhibit geochemical characteristics that are consistent with the Samoan mantle being advected into the Lau Basin [e.g., Regelous et al., 2008; Turner and Hawkesworth, 1998; Wendt et al., 1997], where it is mixed with ambient mantle and melted.

Within the new data set, we also find strong evidence that up to three hot spots, presently active in the Cook–Austral Islands and seamounts, provided volcanism in the Samoan region between 105 and 40 Ma. This “interloping” trinity of Cook–Austral hot spots likely “left behind” a number of non–Samoan seamounts in the region now occupied by the volcanically active Samoan hot spot. We refer to this corridor of the Pacific plate as the “hot spot highway,” owing to the unusual number of hot spots (Samoa is the fourth) that have been hosted in the region; all four hot spots that have traversed the hot spot highway are currently active over the inferred location of the South Pacific superplume [Hart, 1984; Staudigel et al., 1991], an observation that may explain the unusual number of hot spots tracks emerging from the region. The absolute plate motion model of Wessel and Kroenke [2008] suggests that volcanic features from the Raratonga, Ruurutu (younger series) and MacDonald hot spots could now be present in the Samoan region [Chauvel et al., 1997; Konter et al., 2008], and the Samoan hot spot appears to be burning through and thus crosscutting the trails of these older hot spots. Consistent with this hypothesis, we find that three seamounts and an atoll in the Samoan region show stronger geochemical affinities to the three Cook–Austral hot spots than they do to the Samoan hot spot: the four interloping volcanoes in the Samoan region host a variable HIMU (high $^{238}$U/$^{204}$Pb, or “µ”) component that is unlike the EM2 (enriched mantle 2) signature found in many Samoan lavas. Melt extraction from the mantle beneath each of the Cook–Austral hot spots would have depleted the asthenosphere, and the resulting depleted asthenosphere would be highly viscous and refractory and form a “keel” coupled to the base of the overlying mantle lithosphere [Philips Morgan et al., 1995; Hirth and Kohlstedt, 1996; Ito et al., 1999; Hall and Kincaid, 2003]. The passage of the Pacific lithosphere over each successive Cook–Austral hot spot would have thickened the depleted keel in an additive fashion, and the thickness of the keel would extend to the solidus depth of the Cook–Austral hot spots. Owing to its high viscosity following melt depletion, the lithospheric keel beneath the hot spot highway is unlikely to be replaced with fertile, fusible mantle. If volcanoes in the Samoan region were generated by propagating lithospheric cracks, the cracks would sample the thick, threedepleted, refractory keel, as cracks cannot extend below the brittle–ductile boundary within the lithosphere. Without major modification of the current “propagating lithospheric cracks” model, it is not clear how such cracks could yield melts from the refractory keel present under the Samoan lithosphere. Instead, a region of anomalously hot, upwelling mantle (a mantle plume) is needed to feed the Samoan hot spot.

2. Sample Locations and Tectonic Setting

All samples reported here were recovered during the 1999 AVON2/3 cruise of the R/V Melville, the 2005 cruise of the R/V Kilo Moana, and the 1982 KK820316 cruise of the R/V Kana Keoki. This manuscript reports new geochemical data for samples dredged from both the younger, eastern Samoan (ESAM) and older, western Samoan (WESAM) provinces of the Samoan hot spot. The ESAM is bounded by the largest island, Savai’i, on the west, and extends to the youngest seamounts on the east, including Vailulu’u seamount, the youngest, active Samoan volcano [Hart et al., 2000; Staudigel et al., 2004, 2006]. The WESAM seamounts, shown by Hart et al. [2004] to be genetically related to the Samoan hot spot, were suggested to extend as far west as Alexa Bank, 1700 km to the west of Vailulu’u seamount.

Four volcanoes, located in the Samoan region, but found to be geochemically unrelated to the hot spot currently active in the Samoan region (see section 4.4.3), were dredged and the geochemical data on the recovered samples are reported in Data Set S1.1 During the 1999 AVON2/3 cruise of the R/V Melville [Workman et al., 2004], Rose atoll and the small nearby Malulu seamount were dredged. Located 100 and 50 km ESE of Vailulu’u seamount, the two volcanoes appear to extend the geographical extent of the ESAM to the east. Rose Atoll has a

well-developed reef and has long complicated the apparent lack of age progression along the Samoan hot spot, as the Hawaiian hot spot analog shows that the easternmost region of a Pacific hot spot should also be the youngest [e.g., Dana, 1849]. In stark contrast to the fresh material dredged from nearby ESAM islands and seamounts, samples from Rose and Malulu are extremely altered and provide no useful material for geochronological work. Papatua seamount, which lies ~50 km south of the ESAM island of Tutuila, was dredged during the ALIA expedition in 2005 [Jackson et al., 2007a; Koppers et al., 2008]. Like Rose and Malulu, dredges from this seamount returned extremely altered material. Similarly, dredges from one seamount in the WESAM province, Waterwitch, returned material that is significantly more altered than other Samoan seamounts in the vicinity. All told, lavas dredged from these four volcanoes appear to have suffered much longer periods of seafloor alteration than their younger Samoan neighbors. In sections 4 and 5, we will show that these four volcanoes are also geochemically unrelated to the hot spot currently active in the Samoan region.

[8] The bathymetry of the ESAM is dominated by two en echelon ridges, previously referred to as the “Malu” and “Vai” ridges [Workman et al., 2004]. These ridges are isotopically distinct and may be the Samoan equivalents of the Hawaiian “Loa” and “Kea” trends [e.g., Tatsumoto, 1978; Stille et al., 1983; Abouchami et al., 2005; Xu et al., 2007]. While the en echelon ridges in Samoa may be the result of cracks generated in response to the stress field imposed by the nearby Tonga trench, this model would obviously not work for Hawaii.

[9] The tectonics of the Samoan region are dominated by the nearby Tonga subduction zone, where the Pacific plate is being subducted beneath the Australian plate. Due to trench rollback, the northern terminus of the Tonga trench is migrating eastward at ~190 mm/yr (absolute plate motion), and is approaching the Samoan hot spot at ~260 mm/yr. North of this terminus, the Pacific plate “tears” and, instead of subducting into the trench, continues to the west and forms a boundary with the Australian plate, which is referred to as the Vitiyaz Lineament [Brocher, 1985; Hart et al., 2004]. Hart et al. [2004] suggested that the segment of the Vitiyaz lineament east of 180°W was formed by the migration of the hinge of the Pacific plate tearing as the as the Tonga trench has swept eastward toward the active end of the Samoan hot spot over the last 4–5 Myr. Calmant et al. [2003] suggest that the region just south of the Vitiyaz Lineament (including Futuna and Rotuma islands) moves with the Pacific plate, which would imply that the Vitiyaz is a fossil boundary and that any transcurent motion between the Australian and Pacific plates is occurring well to the south of the boundary. The entire length of the Vitiyaz Lineament has also been suggested to be a pre–Tongan “fossil” subduction zone marking subduction of the Pacific plate under the Australian plate until ~12 Ma, when the Ontong–Java plateau collided with the trench and forced subduction along the Vitiyaz to a halt [e.g., Brocher, 1985; Yan and Kroenke, 1993; Pelletier and Auzende, 1996; Pearce et al., 2007].

[10] Manatu and Futuna were dredged during the 1982 KK820316 cruise of the R/V Kana Keoki, and both volcanoes are located south of the Vitiyaz lineament. Manatu seamount was dredged (DR126) again during the 2005 ALIA dredging expedition. In section 4 we suggest that these seamounts may have a complex geochemical relationship with the Samoan hot spot. Rochambeau Bank, also located south of the Vitiyaz lineament, is geochromically similar to Futuna and Manatu, and was found to exhibit high 3He/4He ratios [Poreda and Craig, 1992; Lupton et al., 2009]. Futuna, Manatu and Rochambeau Bank exhibit geochemical similarities that suggest that they are related to each other, and they may host a mantle component advected from the Samoan hot spot (see section 4.4.3).

3. Techniques

[11] We employ standard geochemical techniques for measurement of major and trace element concentrations and Sr, Nd, Pb and He isotopic compositions. A detailed description of the techniques is available in Appendix A.

4. Geochemistry of the New Lavas From the Samoan Region

4.1. Major Element Classification

[12] The Macdonald and Katsura [1964] scheme for basalt classification shows that most Samoan lavas are alkalic (Figure 2), an observation that is already well established in the literature [e.g., Natland, 1980; Workman et al., 2004; Hart et al., 2004]. Tholeiites are rare in Samoa, even in shield stage lavas, and only a small number of lavas from volcanoes in the ESAM province plot on the tholeiitic side of the MacDonald and Katsura division. Lavas from Alexa in the far western Samoan province straddle the alkali-tholeiite division [Hart et al., 2004].
Several lavas from the ALIA cruise are also tholeiitic; samples from dredge DR128 of Savai’i straddle the alkali/tholeiite line, and sample DR128/uni2010 21 is solidly tholeiitic, as is a picrite dredged from Muli seamount, sample DR104/uni2010 04. Two other ALIA dredge samples, Manatu sample DR126/uni2010 06 and Waterwitch sample DR122/uni2010 03, are tholeiitic. The Manatu and Futuna lavas dredged on the Kana Keoki cruise are also tholeiitic, but as discussed in section 4.4.3, Manatu and Futuna exhibit a complicated relationship with Samoa, and Waterwitch is unrelated to the Samoan hot spot.

The new dredge data also include some of the most evolved lavas observed in Samoa. With MgO contents varying from 0.32 to 0.99 wt %, the new dredge samples from Tulaga (dredge DR109), which are phonolites, and Tama’i (dredge DR111), which are trachytes, also exhibit extreme compositions in a SiO₂ versus total alkalis diagram (Figure 2). These evolved lavas exhibit peculiar “spiky” spider diagrams (see section 4.3), and this may owe to fractionation of trace phases that are stable only at high degrees of magmatic differentiation.

4.2. Determining the Extent of Alteration

Before identifying possible mantle source characteristics, it is important to consider various trace element indicators to determine the extent of...
alteration. Owing to long periods of residence on
the seafloor, some of the samples exhibit high LOI
(loss on ignition), and these highly altered samples
are all from dredges DR115 (Savai’i), DR118
(Si’usiu), DR122 (Waterwitch) and DR129 (Papatua)
(Figure 3). Nevertheless, most new dredge samples
exhibit relatively good trace element preservation.

The Th/U ratio is a useful indicator of alteration,
owing to the fact that Th is relatively immobile and
U is quite mobile. The Th/U ratios of nearly all of
the new dredge samples fall within the range (4.5 ±
1.5) that Workman et al. [2004] determined for a
suite of relatively fresh young lavas from the ESAM.

Notable exceptions include the ALIA dredge lava
from Manatu seamount, which exhibits extreme U
addition (note that the other Manatu lava, KK82-03–
10-10, has “normal” Th/U), and three of the five
Futuna samples, which also show U addition; note
that the U addition may owe to the addition of a
U-rich subduction component to the mantle sources
of these lavas (see section 4.4.3). Rose sample 65–
18 has suffered U loss; the loss of U is associated
with subaerial weathering, and may indicate that
this sample was erupted subaerially, and was later
transported to 3600–4000 m water depth. Alteration
need not be the cause for Th/U fraction in lavas from
Tamai’i and from Si’usiu. Extreme magmatic dif-
ferentiation may also have fractionated Th/U (and
Ba/Rb, see below) in the Tamai’i lavas, which are
very fresh but extremely evolved, with MgO of
0.3–0.5 wt %. The high Th/U in the Si’usiu lavas
does not appear to be a result of U loss, as Nb/U
ratios are similar to (or somewhat higher than) the
canonical Nb/U ratio for OIB (47 ± 10 [Hofmann
et al., 1986]). Instead, high Th/U in Si’usiu seems
to be a result of Th enrichment in the source of these
lavas, an observation supported by the elevated
208\(^{\text{Pb}}\)/204\(^{\text{Pb}}\) in Si’usiu lavas compared to other
Samoa lavas.

[15] Ba/Rb ratios can also be useful for determining
the extent of alteration, but is a somewhat more
complicated proxy for alteration owing to the fact
that both Ba and Rb can be mobile elements during
alteration. With increasing LOI values, there is
greater scatter in the Ba/Rb ratios in the lavas
(Figure 3). However, most samples have Ba/Rb
within the range (9.3 ± 3.6, 2σ) determined for
fresh ESAM lavas (Figure 3) [Workman et al.,
2004]. The three lavas with the lowest Ba/Rb
ratios are also extremely evolved and have rela-
tively low LOI values (see DR109 and DR111 la-
avas in Data Set S1), suggesting that differentiation,
not alteration, may have fractionated the Ba/Rb
ratios; two of these three lavas also have unusually
high Th/U (see above). Three of the four samples
with the highest LOI have clearly suffered from
alteration, and they have high Ba/Rb ratios: Si’usiu
sample DR118–23, Waterwitch sample DR122–03,
and Savai’i sample DR115–07. These three samples
can serve to illustrate some of the different ways in
which a lavas can gain high Ba/Rb ratios; assuming
that Nb is relatively immobile during alteration
(Figures 3c and 3d), DR118-23 has gained Ba and
lost Rb, DR122-03 has lost Rb, and DR115-07 has
gained both Ba and Rb (but has gained more pro-
portionately more of the former than the latter); note
that dredge 115 lavas tend to have elevated Rb at a
given Nb concentration compared to other lavas
examined here, and excluding the altered sample
DR115-07, the high Rb likely owes to a Rb-rich
sediment contribution to the EM2 mantle source of
the dredge 115 samples [Jackson et al., 2007a].

Figure 3. Trace element indicators of alteration for the lavas recovered during the AVON2/3 (1999, R/V Melville),
ALIA (2005, R/V Kila Moana), and KK820316 (1982, R/V Kana Keoki) dredging cruises. (a) Th/U and (b) Ba/Rb
are used as indices of alteration, and they are plotted against LOI (loss on ignition; see Data Set S1 legend for
calculation of LOI). (c and d) Owing to the fact that Ba and Rb are both mobile during weathering, Ba and Rb are
plotted against Nb, as Nb is thought to be relatively immobile during weathering. The dashed lines in Figure 3a
encompass the Th/U range (4.5 ± 1.5) determined for fresh ESAM lavas [Workman et al., 2004]; the dashed lines in
Figure 3b represent the 2σ variability about the average Ba/Rb (9.3 ± 3.6, 2σ) determined for young ESAM lavas [see
Workman et al., 2004]. Rb and U loss are generally considered to reflect subaerial weathering, and Rb and U gain
occur in submarine environments. The ALIA-dredged Manatu lava and the three Futuna lavas with low Th/U and/or
high Ba/Rb are relatively fresh in hand samples, and their variable Th/U and Ba/Rb ratios may reflect the presence of
a subduction component and may not be an indicator of alteration. The highly evolved lavas from DR109 and DR111
exhibit highly fractionated Th/U and Ba/Rb, even though they have relatively low LOI, and this may owe to frac-
tionation of trace phases at high degrees of magmatic differentiation; all four samples from DR109 and DR111 plot
outside of Figures 3c and 3d. The elevated Th/U in the DR118 lavas may partly owe to elevated Th in their mantle
source, as discussed in the text. Using 238\(^{\text{U}}\)/232\(^{\text{Th}}\) data measured in fresh EM2 lavas, Sims and Hart [2006] calculated
that the EM2 mantle has a Th/U ratio of 5.1 to 5.5, and the EM2 mantle Th/U may be even higher in the more extreme
EM2 lavas reported here and by Jackson et al. [2007a]. Symbols are the same as in Figure 2.
Anomalous Ba/Rb ratios are also apparent in a number of samples with LOI < 4 wt %: Both lavas from Fa’a’afavisi dredge DR125 have lost Rb, Soso sample DR110–39 with high MnO (10.1 wt %) has gained Ba but not Rb, Toafilemu sample DR119–01 has lost Rb (and may have gained some Ba), Bayonnaise sample DR124–11 has lost Rb, and two of the three Futuna samples with low Th/U have lost...
439 Futuna lavas may owe to the presence of a subduction component in the mantle source of these lavas; see section 4.4.3). Unusually, sample 65-18 from Rose has lost Ba and has “normal” Rb (this sample also has high Th/U). Note, however, that the high Ba/Rb in Savai’i sample (DR116-01) owes to Ba enrichment in the mantle source of this rejuvenated lava, as high Ba/Nb (and Ba/Sm, Ba/Th) is a feature observed in fresh rejuvenated lavas [Workman et al., 2004] (see section 4.3).

450 The three proxies of alteration used here (Th/U, Ba/Rb and LOI) suggest that elements equally or less mobile than U, Ba and Rb provide useful petrogenetic information for most samples [Workman et al., 2004]. However, trace element data from the most highly altered samples should be treated with caution. These include the four lavas with LOI > 6 wt % (DR115-07, DR122-03, DR129-05 and DR118-23), the remaining two St’u’u samples from dredge DR118, Rose sample 65-18, and Soso sample DR110-39. In particular, Papatua sample DR129-05 exhibits a negative Ce anomaly and a positive Y anomaly, which mirrors similar anomalies in seawater, and is consistent with the extreme alteration of this sample inferred from LOI; DR129-05 also exhibits enrichment in the heavy rare earth elements, likely owing to accumulation of a phosphate alteration phase, as evidenced by the high (3.58 wt %) P₂O₅ concentration. Owing to our intensive acid leaching before isotopic analyses (Appendix A), we consider all the isotope ratios in the most altered rocks to be reliable for evaluating (or ruling out) a Samoan pedigree in the new sample suite. For example, Rose Island sample 65-18 exhibits Ba/Rb and Th/U ratios consistent with severe alteration, but the other Rose sample (66-1) is not as severely altered (Figure 3). While alkali elements and U are quite mobile in at least one of the two Rose lavas, Sr isotopes, which are generally more easily influenced by alteration than Nd and Pb isotopes, exhibit only a 300 ppm difference between the two Rose lavas. Such low Sr isotope variability is not consistent with alteration, and suggests that intensive leaching remove much of the alteration component in the oldest, most altered rocks presented in this study.

464 4.3. Trace Element Characteristics of the New Samoan Lavas

488 Trace elements can place important constraints on the mantle origin of Samoan lavas. Primitive mantle normalized trace element patterns reveal that the most isotopically enriched (high Sr and low Nd) Samoan EM2 lavas from dredges DR115, DR128 and DR118 exhibit enrichment in Pb low Ce/Pb) and depletion in the elements Ti, Ta and Nb (e.g., low Nb/U [see Jackson et al., 2007a, Figures 2 and 3]), which is consistent with the observation that the EM2 mantle has Ce/Pb and Nb/U ratios that are lower than the canonical ratios found in oceanic lavas [Hofmann et al., 1986]. By contrast, isotopically depleted, high ³He/⁴He lavas from Samoa [Farley et al., 1992; Jackson et al., 2007b] exhibit enrichment in Ti, Ta and Nb (TITAN) on a primitive mantle normalized spidergram, and there is a correlation between Ti and Nb anomalies and ³He/⁴He in Samoan lavas [Jackson et al., 2008]. Trace elements can also be used to identify the volcanic stage of Samoan lavas. On a primitive mantle-normalized spidergram, subaerial rejuvenated stage lavas from ESAM tend to have large positive Ba anomalies (high Ba/Nb, Ba/Th, Ba/Sm [Workman et al., 2004; Hart et al., 2004]), while shield stage lavas generally do not. Figure 4 presents primitive mantle-normalized trace element patterns (spidergrams) for the new Samoan lavas, and some lavas (e.g., DR116) exhibit positive Ba anomalies, suggesting a rejuvenated origin, and other lavas exhibit the positive TITAN anomalies (e.g., DR119) associated with the high ³He/⁴He mantle beneath Samoa.

18 When Ba/Sm is plotted against Ba/Th, ESAM shield and rejuvenated lavas form separate fields with little overlap, and only one shield lava (from Upolu) trends into the ESAM rejuvenated field in Figure 5. It is important to note that the field for rejuvenated lavas (Figure 5) is based on data gathered from subaerial samples from Tutuila, Upolu and Savai’i, where it is possible to map out the extent of, and boundaries between, shield stage and rejuvenated volcanism. However, identifying rejuvenated signatures in the western Samoa province is complicated by the fact that erosional unconformities generated by subaerial erosion during volcanic quiescence (historically used to distinguish shield stage from rejuvenated, or posterosional, lavas) are not present in submarine volcanoes. Instead, we use geochemical distinctions that have been observed between the subaerial shield and rejuvenated stage volcanoes in the ESAM to infer the volcanic stage of lavas in the WESAM. This approach does not provide the degree of certainty that field relations would provide, as geochemical distinctions between shield and rejuvenated lavas in the ESAM may not apply to the volcanic stages of the older, less studied WESAM region. The difficulty of identifying clear examples of shield and
rejuvenated volcanism in the WESAM owes to an additional factor: The small number of samples analyzed from each WESAM seamount make it difficult to characterize its geochemical evolution from the shield to rejuvenated stages.

[19] With these caveats in mind, a number of samples from the new Combe lava field in the ESAM rejuvenated field, and several WESAM lavas exhibit isotopic signatures that may suggest an origin by rejuvenated volcanism. DR116-04, dredged on the shallow flank of Savai’i, clearly plots in the rejuvenated field in Figure 5. The new Pasco lava (DR120-06) also plots in the rejuvenated field and provides a clearer rejuvenated signature than the highly silica undersaturated (39.8 wt % SiO₂) sample previously reported from this seamount [Hart et al., 2004]. The rejuvenated signature is also suggested in various isotope projections, except Sr-Nd isotope space, where DR120-06 plots in the ESAM shield field (Figure 6). Using trace elements, the Wallis lavas (DR127) also plot squarely in the rejuvenated field (Figure 5), and this is also reflected in isotope space (Figure 6). While the two Combe samples reported by Hart et al. [2004] plot well within the field for WESAM shield lavas in Figure 5, the two new Combe samples (DR123) plot in the field for rejuvenated lavas, close to the field for ESAM shield lavas, indicating that a clear designation of volcanic stage cannot be made using trace elements alone. The isotopic compositions of the new Combe lavas paint an equally ambiguous picture, as they plot close to, or just inside of, the ESAM rejuvenated field, depending on the isotope projection (Figure 6). Similarly, the Bayonnaise and Fa’avevisi samples plot on the fringes of the ESAM rejuvenated field near the shield field (Figure 5). However, with the exception of the Sr-Nd isotope projection, the isotopic compositions for three of the Bayonnaise and Fa’avevisi lavas are similar to ESAM shield lavas, but one lava (DR124-22) is similar to ESAM rejuvenated lavas. Combe, Bayonnaise and Fa’avevisi samples with age dates fall on the age progression for the Samoan hot spot (A. A. P. Koppers et al., Age systematics of two young en echelon Samoan volcanic trails, manuscript in preparation, 2010), indicating a shield stage origin for these lavas, but age data are not available for DR124-22. Samples from two other WESAM volcanoes, Toafilemu and Lalla Rookit, plot in the rejuvenated field in Figure 5, but isotope projections put these lavas in the ESAM shield field. Age constraints are not available for Toafilemu, but one of the LallaRookit lavas has an age of 1.6 Ma, indicating a rejuvenated origin for the latter volcano. The example from Lalla Rookit illustrates the difficulty inherent to classifying the volcanic stage of a WESAM volcano using geochemical criteria adapted from ESAM volcanoes, as the trace element and/or isotopic compositions characteristic of both Samoan shield stage and rejuvenated lavas are

Figure 4. (a–g) Primitive mantle [McDonough and Sun, 1995] normalized trace element patterns (“spidergrams”) for the new Samoan lavas. In comparison to the relatively smooth trace element patterns of most Samoan lavas presented here (Figures 4a–4g), the patterns are jagged for the four highly differentiated lavas from Tulaga (DR109) and Tamai’i (DR111) seamounts (Figure 4a); with 0.32 to 0.99 wt % MgO, these are the most evolved Samoan samples analyzed for trace elements by ICP-MS, and they reveal how extreme magmatic fractionation can change the shape of the spidergram of Samoan lavas: Nb and Ta are neither clearly enriched nor clearly depleted in the most evolved lavas, but Ti is strongly depleted, as is V (not shown), suggesting oxide removal may be responsible for the Ti depletion; Zr and Hf are enriched in all four of the extremely evolved lavas; Sr and Eu are highly depleted in these lavas, and this represents a clear signature of plagioclase fractionation; DR111-05 has a large negative Ba anomaly, which is consistent with the fractionation of K feldspar; Pb anomalies are both positive (low Ce/Pb; DR109) and negative (high Ce/Pb; DR111) in these evolved lavas; and K anomalies are only weakly negative, in stark contrast to the strongly negative K anomalies observed in most Samoan lavas. Figure 4b shows spidergrams for lavas that are somewhat evolved (2–4 wt % MgO) but less evolved than the lavas in Figure 4a. Figures 4c–4g show even less evolved, run-of-the-mill Samoan lavas; some exhibit positive Ba anomalies (suggesting rejuvenated origin?), and others exhibit positive TITAN anomalies (suggesting high ⁴He/³He characteristics?). (h) By contrast, lavas from the non–Samoan “interloping” seamounts from the Cook-Austral exhibit spidergrams that differ markedly from Samoan lavas; the light rare earth elements measured in the Waterwitch sample have a slope that is shallower than observed in Samoa lavas, and Malulu exhibits negative Zr and Hf anomalies, similar to those observed in HIMU lavas from the Cook–Austral [e.g., Hart and Gaetani, 2006]. The extreme alteration from the Papatua seamount lava obscures much of the petrogenetic information recorded in the trace element pattern, but isotopic compositions obtained on leached powders indicate that Papatua is not genetically Samoan. (i) Lavas from the northern Lau Basin, located south of the Vitiace lineament. Manatu and Futuna samples are tholeiitic and exhibit depleted spidergrams that are unlike those found in the Samoan hot spot to the north. The spidergrams for lavas from DR114, DR115, DR118, and DR128 are discussed by Jackson et al. [2007a] and are not included here.
likely to have changed over the past 13 Ma since the Bayonnaise lavas erupted.

4.4. Isotopic Signatures of the New Lavas

4.4.1. New Dredges in the Eastern Samoan Volcanic Province

Jackson et al. [2007a] reported geochemical data for lavas recovered from two ALIA dredges (DR115 and DR128) on the deep submarine flanks of Savai‘i that show remarkable isotopic and trace element enrichment. A lava from DR115 has $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.72047, and hosts fresh cpx with even higher Sr isotopes (0.72163). The lavas from dredge 128 have $^{87}\text{Sr}/^{86}\text{Sr}$ ratios up to 0.71250.

The termination of a ridge extending ~80 km to the west of Savai‘i (technically part of the WESAM) called Si‘usi‘u (“The Tail” in Samoan), hosts shoots of lavas with $^{87}\text{Sr}/^{86}\text{Sr}$ as high as 0.71181 (DR116). The data from Combe exhibit a continuous spectrum, ranging from shield stage into the rejuvenated field. One submarine Savai‘i lava (ALIA DR116-04) also plots in the rejuvenated field. One shield stage lava from Savai‘i (ALIA DR115-03) plots at the fringes of the rejuvenated field. Sample U10 from Upolu plots in the rejuvenated field. Sample U10 is not included in the field for ESAM shield lavas, but it is plotted and labeled in Figure 5. The following samples are not plotted: the non-Samoan “interloping” Cook-Austral hot spot volcanoes, lavas from the northern Lau Basin (e.g., Manatua and Futuna), the highly evolved (and fractionated) lavas from DR111 and DR109, and five extremely altered Samoan samples (including the Soso sample with high MnO, sample DR115-07, and all three samples from DR118).

Figure 5. Rejuvenated and shield stage lavas resolved using Ba/Sm and Ba/Th. Symbols are the same as in Figure 2. The dark gray field encompasses previously published ICP-MS data for subaerial rejuvenated lavas from the ESAM islands of Upolu and Savai‘i; the light gray field encompasses all published ICP-MS data for shield stage ESAM lavas [Workman et al., 2004; Jackson et al., 2007b]. A number of lavas from WESAM volcanoes plot in the rejuvenated field, including Pasco, Fa‘avevisi, Bayonnaise, Wallis, Combe, Lalla Rookh, and Toa Filemu. However, isotopic and geochronological constraints for these samples are not necessarily consistent with these lavas being rejuvenated in origin (see section 4). The data from Combe exhibit a continuous spectrum, ranging from shield stage into the rejuvenated field. A submarine Savai‘i lava (ALIA DR116-04) also plots in the rejuvenated field. One shield stage lava from Savai‘i (ALIA DR115-03) plots at the fringes of the rejuvenated field. Additionally, one shield stage lava (sample U10) from Upolu plots in the rejuvenated field. Sample U10 is not included in the field for ESAM shield lavas, but it is plotted and labeled in Figure 5. The following samples are not plotted: the non-Samoan “interloping” Cook-Austral hot spot volcanoes, lavas from the northern Lau Basin (e.g., Manatua and Futuna), the highly evolved (and fractionated) lavas from DR111 and DR109, and five extremely altered Samoan samples (including the Soso sample with high MnO, sample DR115-07, and all three samples from DR118).
Savai’i rejuvenated lavas may be erupted at great depth. This is significant, as the entire surface of Savai’i has been resurfaced with large volumes of rejuvenated volcanism. The presence of submarine rejuvenated lavas may indicate that estimates of the volume proportion of Savai’i volcano that is rejuvenated may need to be revised upward. As a cautionary note, DR116/uni2010 was dredged on a steep scarp ∼15 km from shallow water, so it is possible that it is part of a flow that simply ran downslope, or that it is simply a talus block that originated at shallow depths.

By contrast, two lavas from DR114 are isotopically shield-like, and DR114/uni2010 has an age of 4.24 Ma that is consistent with eruption during the shield stage of volcanism at Savai’i [Koppers et al., 2008]. In SrNdPb isotope space, both lavas from DR114 plot between Vailulu’u and Ta’u volcanoes, two of the youngest volcanoes in the Samoan chain, suggesting that the early shield stages of Savai’i generated lavas at 4.24 Ma that are geochemically similar to lavas being erupted in the present day. With a 3He/4He ratio of 18.6 Ra (Data Set S1), sample DR114-01 has moderately high helium, similar to that found on Ta’u [Workman].

Figure 6. Plots of 87Sr/86Sr-143Nd-144Nd-206Pb-204Pb-207Pb-208Pb Pb for new ESAM and WESAM lavas and previously published Samoan shield (light gray field) and subaerial rejuvenated (dark gray field) lavas from the ESAM. Samoan rejuvenated and shield lavas have long been known to be isotopically distinct [e.g., Wright and White, 1987]. New data from interloping Cook-Austral volcanoes are plotted, as are lavas from volcanoes in the northern Lau Basin. Symbols are the same as in Figure 2. Isotopic data for Cook-Austral are the same as in the work by Konter et al. [2008] and are represented by a single data field. Two groups of volcanoes generally plot outside of the Samoan field: (1) Manatū, Futuna and Rochambeau Bank (and Niuafou’u, not shown) lavas have compositions that are more depleted than has been identified in Samoan lavas and (2) the non-Samoan “interloper” seamounts form an array that trends away from the Samoan field and tends to lie in the range of isotopic compositions previously identified in volcanoes from the Cook-Austral. Published isotopic data for Alexa [Hart et al., 2004] are included, but Alexa’s true geochemical pedigree (Samoan?) is unknown [see Hart et al., 2004]. The Sr-Nd-Pb isotopic composition of lavas from Rochambeau Bank are from Volpe et al. [1988] and Poreda and Craig [1992] (note that the Rochambeau Pb isotopic compositions are estimated from Poreda and Craig [1992, Figure 4]). The extreme Samoan EM2 lavas from Savai’i have 87Sr/86Sr Sr ratios that range up to 0.722 [Jackson et al., 2007a], and these samples plot outside of the top two plots. With the exception of the Rose, Malulu, and Rochambeau samples (and many of the published Cook-Austral samples), Pb isotope data generated by unspiked TIMS techniques are excluded. Depleted MORB mantle, or DMM, is the mantle source of MORB. An Uo Mamea lava is plotted [Regelous et al., 2008] and has isotopic characteristics that may describe the end-member compositions sampled by Samoan rejuvenated lavas. The Northern Hemisphere Reference Line (NHRL) is from [Hart, 1984].
et al., 2004], but lower than found on Tutuila (25 Ra
[Farley et al., 1992]) or Ofu (33.8 Ra [Jackson et al.,
2007b]).

Twelve additional dredges were made in the
ESAM region: DR101 (Vailulu’u seamount), DR102
(Vailulu’u), DR103 (Ofu), DR104 (Muli seamount),
DR106 (Malumalu seamount on the eastern end of
the Malu ridge), DR107 (Ofu), DR108 (central
region of the Malu Ridge), DR109 (Tulaga, located
on the Malu ridge), DR110 (Soso seamount), DR111
(Tamai’s seamount), DR112 (Tutuila on the western
end of the Malu ridge), DR113 (Tisa seamount).

However, with the exception of four lavas, the iso-
topic variability in lavas from the new ESAM dredge
suite lies within the range previously defined for the
ESAM; the four other lavas (both DR111 lavas,
DR110-21, and DR107-09) only slightly expand the
fields for isotopic data for ESAM lavas (Figure 6).

4.4.2. Shield Stage and Rejuvenated Volcanism
in the Western Samoan Volcanic Province

Rejuvenated lavas are abundant on Savai’i and
Upolu, and are present in smaller volumes on Tutuila.
Samoan rejuvenated lavas from the ESAM have
positive Ba anomalies (high Ba/Nb, Ba/Th, Ba/Sr)
[Workman et al., 2004], and in Sr–Nd isotopic space
they form a positively sloping trend (contrary to the
negatively sloping global OIB trend) extending
from the Samoan shield array to a region with lower
433Nd/144Nd at a given 87Sr/86Sr than found in Samoan
shield lavas (Figure 6). In the WESAM province, the two new Combe lavas recovered from
Hart et al. [2004] found evidence for shield volcanism that isotopically resembles the younger lavas
erupted in the ESAM; three Combe lavas were found
to be clearly shield stage, as were two lavas from
Lalla Rookh. They also found hints of lavas transition-
ing into the rejuvenated stage of volcanism; a Pasco lava was found to exhibit a transitional shield-
rejuvenated geochemical signature, and sample 3–26
from Lalla Rookh sample gave a young age (1.6 Ma)
that requires a rejuvenated origin [Hart et al., 2004].

Here we provide complementary evidence for shield
and rejuvenated volcanism in the WESAM, and we
find that there is a paucity of lavas that are similar to
the ESAM shield stage lavas in all isotope projections. Similarly, in the new ALIA dredges, clear
rejuvenated geochemical characteristics are difficult
to discern in Samoan seamounts west of Savai’i.

Toafilemu seamount (DR119) yielded a lava
that is isotopically similar to the Tutuila Masefau
shield lavas [see Farley et al., 1992] in Sr–Nd-Pb
space. However, this sample has a large positive Ba
anomaly that places it in the field for rejuvenated
lavas (Figure 5). In the absence of geochronologi-
cal data, it is difficult to assign a shield stage or
rejuvenated origin for the lavas from Toafilemu
(Figure 6).

Hart et al. [2004] suggested that the strongest
candidate for rejuvenated volcanism in the WE-
SAM province came from a nephelinite (sample
239-1) dredged from Pasco seamount, but its true
origin (shield or rejuvenated) is ambiguous. In Sr–Pb
isotope space, they noted that sample 239-1 plots
between the ESAM shield and rejuvenated stages.
This sample also hosts a relatively large positive Ba
anomaly and plots on the fringes of the ESAM
rejuvenated field in Figure 5, and is neither clearly
shield stage nor rejuvenated in origin. DR120
resampled Pasco seamount, and the resulting lava
has a rejuvenated signature in Pb isotope space
(Figure 6); the DR120 lava plots on an extension of
the ESAM rejuvenated array and trends away from
the Samoan shield stage, plotting near the field of
Wallis Island lavas (see below). However, in trace
element space (Figure 5) and Sr–Nd isotope space
(Figure 6), the sample plots between the shield and
rejuvenated fields. Unfortunately, no age data are
available for DR120-06 to test the hypothesis for a
rejuvenated origin.

The two new Combe lavas recovered from
DR123 have ages (~11 Ma) that are expected for
Samoan shield volcanism (Koppers et al., manu-
script in preparation, 2010). However, both DR123
lavas plot in the fields for ESAM rejuvenated lavas
in Pb isotope space, and they trend slightly below
the ESAM shield Sr–Nd isotope array toward the
rejuvenated field. DR123 lavas also have trace element characteristics that are transitional
between the ESAM shield and rejuvenated fields in
Figure 5. By contrast, the three lavas were previ-
ously reported from Combe [Hart et al., 2004], one
of which has a step release 40Ar/39Ar plateau age of
11 Ma, have isotopic characteristics similar to
ESAM shield lavas. Together with earlier geo-
chemical data on Combe lavas from Hart et al.
[2004], the DR123 lavas from Combe may repre-
sent shield stage volcanism and volcanism transi-
tional between shield and rejuvenated volcanism.

The westernmost dredges of the ALIA expedi-
tion sampled Bayonnaise (DR124) and Fa‘avevisi
(DR125) seamounts. Koppers et al. (manuscript in
preparation, 2010) obtained geochronological data
from three of the four Bayonnaise and Fa‘avevisi
samples presented here, and the ages (~13 Ma) fit a
hot spot age progression and are consistent with a
rejuvenated shield stage origin for these lavas. These three lavas
plot in the ESAM field for shield lavas in Pb iso-
otope space. In Sr-Nd isotope space, however, all
three lavas trend further below the Samoan array
than the DR123 Combe lavas. While this may be a
feature consistent with rejuvenated volcanism in the
ESAM province, the Pb isotopes are not consistent
with ESAM-type rejuvenated volcanism. Like the
Combe lavas, the early (~13 Ma) history of the
Samoan hot spot, as captured by the Fa’avevisi and
Bayonnease lavas, may have erupted shield stage
lavas that are geochronologically unlike the shield stage
found in the younger ESAM province.

Nevertheless, Bayonnease sample DR124-22
has Pb isotope characteristics that, compared to the
other Bayonnease and Fa’avevisi lavas, place it
closest to the ESAM rejuvenated field (Figure 6).
Similarly, compared to the other Bayonnease and
Fa’avevisi samples, DR124-22 extends furthest
into the ESAM rejuvenated field in the trace ele-
ment plot (Figure 5). No geochronological data are
available for this sample, but if it represents a reju-
venerated stage for Bayonnease seamount, it would
be expected to have a younger age (~13 Ma) than
found in the other lavas from Fa’avevisi and
Bayonnease. Alternatively, this sample may repre-
sent a new type of shield stage geochemistry not
observed in the ESAM region.

A dredge of Wallis Island (DR127) returned
extreme fresh samples that complement the geo-
chemical features of Pasco sample DR120-06. In
206\(^{Pb}\)/204\(^{Pb}\) versus 208\(^{Pb}\)/204\(^{Pb}\) and in 206\(^{Pb}\)/204\(^{Pb}\)
versus 207\(^{Pb}\)/204\(^{Pb}\) isotope spaces, the new Wallis
samples plot closer to the field for ESAM rejuven-
ated lavas than Pasco sample DR120-07. How-
ever, in Sr-Pb and Sr-Nd isotope spaces, the new
Wallis and Pasco lavas both plot near the field for
ESAM rejuvenated lavas. This is also true of sub-
aerial lavas from Wallis (S. R. Hart and R. C. Price,
unpublished data, 2010). This raises the question
as to whether Wallis is genetically Samoan, or
whether Wallis hosts an extreme Samoan rejuvena-
ted composition not previously recognized in the
ESAM. The new Wallis lavas have trace element
characteristics that place them in the ESAM reju-
venerated field (Figure 5). Wallis lavas were found to
be very young (0.08–0.8 Ma [Duncan, 1985; Price
et al., 1990]), and are 11 Ma too young to belong to
the Samoan shield stage and are also much too
young to have origins as typical rejuvenated lavas.
A very late stage of rejuvenation at Wallis may
have been triggered by tectonic stresses associated
with the nearby Tonga trench [Hawkins and Natland,
1975; Natland and Turner, 1985; Hart et al., 2004],
as the northern terminus of the trench is only ~250 km
from Wallis (and was even closer at 0.8 Ma). Cur-
iously, in Sr-Nd-Pb isotope space, the Wallis lavas
trend away from the ESAMs rejuvenated field
toward a depleted mantle composition. If tectonic
stresses can enhance rejuvenated volcanism in Sa-
moa, perhaps ambient depleted mantle is incorpo-
rated into the melts of very late stage rejuvenated
lavas.

4.4.3. Samoan Mantle “Leaking” Into
the Northern Lau Basin

In contrast to the trace element enriched lavas
from the Samoan hot spot and the interloping
HIMU seamounts (see section 4.4.4), a dredge
(DR126-06) of Manatu seamount yielded a lava
with extremely depleted trace element and isotopic
characteristics. The spidergram for this lava is
MORB-like (Figure 4), and it has high 143\(^{Nd}\)/144\(^{Nd}\)
(0.51301) and low 206\(^{Pb}\)/204\(^{Pb}\) (18.43). An earlier
dredge of this seamount yielded a sample (KK-
03-10-7) with similarly depleted geochemical
characteristics (Figure 6 and Data Set S1). Manatu
seamount is not part of the HIMU group defined by
Rose, Malulu, Waterwitch and Papatu (see section
4.4.4), and in multi-isotope space it plots outside of
the field defined by Samoan lavas. However, this is
not surprising, as Manatu is located well to the
south of the Samoan hot spot in the northern Lau
Basin. What is surprising is that the two Manatu
lavas have relatively young ages that postdate
subduction along the Vitiaz lineament (4.4 and
1.8 Ma [Duncan, 1985; Koppers et al., manuscript
in preparation, 2010]). We will argue below that
Manatu hosts a component of the Samoan plume
that has been advected south of the Vitiaz and
melted.

Futuna Island is also located south of the Vitiaz
lineament, and lavas dredged from Futuna are
depleted and geochemically similar to Manatu. One
Futuna lava was dated at 4.9 Ma [Duncan, 1985],
and this young age also postdates subduction along
the Vitiaz. A suite of high He/He lavas from nearby
Rochambeau bank (also located in the northern Lau
Basin south of the Vitiaz) exhibit a range of isotopic
compositions that overlap with the Manatu and
Futuna lava compositions (Figure 6), and He/He
ratios of up to 28 Ra have been reported in the region
around Rochambeau [Poreda and Craig, 1992; Lupton
et al., 2009]. These high He/He ratios at
Rochambeau were attributed to “leakage” of the
Samoan plume into the northern Lau Basin [Poreda
and Craig, 1992; Turner and Hawkesworth, 1998;
Regelous et al., 2008; Lupton et al., 2009]. Rocham-
beau, Futuna and Manatu line on a ridge and form a three-point geographic trend in Figure 1. Together with the isotopic similarities, the geographic relationships suggest that Manatu, Futuna and Rochambeau may share a common origin.

The Manatu and Futuna lavas exhibit variable enrichment in K, U, Ba and Rb (Figure 4), and these geochemical signatures might result from subduction contamination. Subduction influence, including slab or sediment-derived melts and fluids, from the Tonga and Vanuatu arcs is clear in arc and back arc basin lavas in the Lau and North Fiji basins [e.g., Eissen et al., 1994; Auzende et al., 1995; Regelous et al., 1997; Turner et al., 1997; Ewart et al., 1998; Peate et al., 2001; Hergt and Woodhead, 2007; Exerig et al., 2009], and subduction influence from the earlier Vitiaz trench is likely pervasive in the region as well. Given the long history of subduction in the region, it may not be surprising that an arc-like signature was suggested to exist in high 3He/4He Rochambeau Bank lavas [Hawkins, 1995] in the northern Lau Basin. Unfortunately, major and trace elements (excluding Rb, Sr, Sm and Nd) remain unpublished for Rochambeau lavas [Volpe et al., 1988; Hawkins, 1995], and we cannot evaluate a possible subduction component.

The high 3He/4He in Rochambeau lavas has been attributed to Samoan plume material “leaking” into the northern Lau Basin [Poreda and Craig, 1992; Wendt et al., 1997; Turner and Hawkinsworth, 1998; Lapton et al., 2009], and lower 3He/4He samples may also be partially explained by such a model [Regelous et al., 2008]. Rollback of the Tonga slab is thought to induce flow of the upper mantle that entrains mantle from the Samoan region; this material is advected through a tear in the subducting Tonga slab (beneath the Vitiaz lineament) and into the northern Lau Basin. Regelous et al. [2008] and Pearce et al. [2007] proposed that, as mantle flows from the northern (Pacific) side of the Vitiaz lineament to the south, the southwestern flowing mantle experiences decompression melting as it passes below thick Pacific lithosphere (110–120 Ma) and upwells beneath the young (<5 Ma), thinner lithosphere in the northern Lau Basin. This decompression melting may be responsible for the young volcanism on Manatu and Futuna (ages for Rochambeau Bank are not available). In addition to material from the Samoan mantle, the depleted upper mantle is likely to be incorporated into the southward flow of mantle into the northern Lau Basin, and the latter component may explain the isotopic and trace element depletion in the Manatu, Futuna and Rochambeau lavas relative to Samoan lavas.

4.4.4. Non-Samoan “Interloper” Volcanoes Along the Samoan Archipelago

Located at the eastern end of Samoa and only ∼100 km east of Vailulu’u seamount, Rose Atoll has a well-developed coral reef and thus does not fit the morphological description of a young and active volcano at the leading edge of the hot spot. A dredge of Rose Atoll on the 1999 AVON2/3 cruise [see Workman et al., 2004] returned extremely altered samples with Fe–Mn rinds several cm thick, an observation that is also inconsistent with Rose Atoll anchoring the easternmost (i.e., youngest) end of the Samoan archipelago. The new isotopic data reported here confirm that Rose Atoll is isotopically distinct from Samoa. In 208Pb/204Pb versus 206Pb/204Pb and 206Pb/204Pb versus 87Sr/86Sr isotope spaces, Rose Atoll plots below the Samoan array (Figure 6) and does not have the required isotopic taxonomy (or necessary volcano morphology) to be associated with the Samoan hot spot.

A small seamount 56 km west of Rose Atoll, Malulu seamount, is not geochemically Samoan, and suggests that Rose may not be the only non-Samoan interloper in the region. In 206Pb/204Pb versus 208Pb/204Pb isotope space, Malulu plots well to the right of the Samoan field. With a 208Pb/204Pb value of 20.95 and a 87Sr/86Sr ratio of 0.7031, Malulu has a pronounced HIMU component. Like Rose, samples from Malulu are extremely altered and are covered with similarly thick Mn rinds. While Malulu is located ∼50 km east of Vailulu’u, it does not anchor the active end of the Samoan hot spot, but instead appears to be related to a different hot spot.

Located ∼50 km south of Tutuila, Papatua seamount (DR129) samples are extremely altered with thick (5 cm) Mn rinds. Papatua exhibits HIMU-like characteristics; radiogenic 206Pb/204Pb (20.0) and low 87Sr/86Sr (0.7030) indicate that Papatua has geochemical characteristics that are intermediate between Rose and Malulu in multi-isotope space, though 143Nd/144Nd in Papatua is actually higher than either Rose or Malulu (Figure 6). Xenoliths from this seamount were found to exhibit high 3He/4He [Poreda and Farley, 1992]. However, the seamount is clearly not geochemically Samoan, and this suggests that a second, non-Samoan high 3He/4He hot spot produced volcanism on the plate prior to its arrival at the Samoan hot spot.
In the WESAM volcanic province ~800 km west of Vailulu'u, a new sample from Waterwitch seamont (dredge DR122-03) plots between Rose and Papatua in multi-isotope space (Figure 6); Waterwitch seamont does not have a Samoan pedigree. Thus, four volcanoes, spread over ~925 km along the Samoan hot spot track, form a continuous spectrum of isotopic compositions that host a variable contribution from a HIMU component. Their geochemical signatures and state of alteration suggest a non-Samoan origin (see section 5).

5. Interloping Cook-Austral Volcanoes in the Samoan Archipelago: Implications for the Plume Hypothesis

Employing a series of geochemical arguments and plate reconstruction models, Konter et al. [2008] showed that three hot spots, currently active near Rarotonga Island, Rurutu Island and Macdonald seamont, laid down tracks in the Samoan region tens of millions of years before being overprinted by the currently active Samoan hot spot. When backtracked through time using the plate motion model of Wessel and Kroenke [2008], the Rurutu hot spot passed through the WESAM province in the region of Bayonnaise seamont, then its trajectory bent to the northwest with the production of the Gilbert chain (Figure 7). The Macdonald hot spot [Hémond et al., 1994] backtracks through the ESAM, and the hot spot reconstruction model has the chain turning northeast through the Tokelau chain [see also Koppers and Staudigel, 2005]. The reconstructed path of the Rarotonga hot spot passes along the southern fringes of the Samoan hot spot and trends through the Enriched Mantle 1 (EM1) seamonts in the Western Pacific Seamount Province (WSPC) [Koppers et al., 2003]. Lending credence to the plate reconstructions, each lineament exhibits isotopic affinities with its respective active hot spot [Konter et al., 2008]. In summary, evidence from plate motion models supports the hypothesis of a “hot spot highway”: Older volcanism left over from three earlier hot spots could be present in the Samoan region.

Geochemical evidence from several volcanoes in the Samoan region is also consistent with the contention that older hot spot tracks are present in the Samoan region. Rose Atoll, Malulu, Papatua and Waterwitch seamonts generally plot well outside the Samoan field in Sr-Nd-Pb isotopic space, suggesting that they are not genetically related to the Samoan hot spot. Samples from these four volcanoes form an array that extends to a HIMU component, indicating that the hot spot(s) responsible for their origin hosted a HIMU component. (Note that while the four interloping volcanoes do not sample a pure end-member HIMU component, they do host a variable contribution from the HIMU mantle.) The three hot spots that have reconstructed tracks in the Samoan region (Macdonald, Rarotonga, and young Rurutu) host a range of mantle components that include HIMU.

The Macdonald hot spot is thought to have generated the most extreme HIMU volcanoes globally, namely Tubuai and Mangai [e.g., Hémond et al., 1994; Chauvel et al., 1997; Lasier et al., 2003], and the oldest Macdonald hot spot lavas in the Tokelau have \(^{206}\text{Pb}/^{238}\text{Pb}\) ratios up to 20.77. Young Rurutu lavas exhibit a weaker HIMU signature \((^{206}\text{Pb}/^{204}\text{Pb}\) up to 20.45 [Chauvel et al., 1997]). Nonetheless, the HIMU signature in this hot spot is long lived, as Rurutu’s (young series) predecessors in the Gilberts have \(\text{Pb}\) isotopes that are similarly radiogenic (20.75 [Staudigel et al., 1991; Koppers et al., 2003; Konter et al., 2008]). lavas associated with the modern Rarotonga hot spot, including Rarotonga and young Aitutaki lavas, do not exhibit a HIMU signature, but lavas from the WPSP associated with the Rarotonga hot spot have \(^{206}\text{Pb}/^{204}\text{Pb}\) ratios up to 21 [Staudigel et al., 1991; Koppers et al., 2003]. In summary, the hot spots in the Cook-Austral Islands and seamonts and the older volcanic lineaments associated with these three active hot spots, the Tokelau, Gilbert and WPSP [Konter et al., 2008], have produced a wide range of isotopic compositions that embrace the range found in the interlopers in the Samoan region.

However, using geochemistry alone, it is difficult to determine which of the Cook-Austral hot spots are responsible for generating the Samoan interlopers. Age dates from Rose Atoll, Malulu, Papatua and Waterwitch seamonts would help to resolve which of the three Cook-Austral hot spots are responsible for their origin. For example, if Rose and Malulu are related to the Macdonald hot spot, they should be approximately 40 Ma, but they would be only ~10 or ~20 Ma, respectively, if they are related to the Rarotonga or Rurutu hot spots (see Figure 7). Unfortunately, dredged samples of the four interloping volcanoes in Samoa were unsuitable for age dating due to extreme alteration.

Plate reconstructions show that the non-Samoan geochemical pedigrees of 4 seamonts in the Samoan region may be explained by the geochemistry of several hot spots that populated the
The generation of a depleted, refractory, viscous keel is an inevitable consequence of melt extraction and mantle dehydration beneath a hot spot. If volcanoes in the Samoan region were generated by propagating lithospheric cracks, the cracks would sample the thrice-depleted, refractory keel that has had melt extracted before it was "rafted" from the Cook-Austral hot spots into the Samoan region (Figure 8). Without major modification of the current "propagating lithospheric cracks" model, it is not clear how such cracks could yield melts from the refractory keel present under the Samoan lithosphere.

The model for hot spot generation by lithospheric cracking suffers from at least two other shortcomings. First, in order for lithospheric cracks to propagate, the host lithosphere must be strong enough to resist the stresses generated by the cracks. Second, the generation of a depleted, refractory, viscous keel is an inevitable consequence of melt extraction and mantle dehydration beneath a hot spot. If volcanoes in the Samoan region were generated by propagating lithospheric cracks, the cracks would sample the thrice-depleted, refractory keel that has had melt extracted before it was "rafted" from the Cook-Austral hot spots into the Samoan region (Figure 8). Without major modification of the current "propagating lithospheric cracks" model, it is not clear how such cracks could yield melts from the refractory keel present under the Samoan lithosphere.

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observed along the Samoan hot spot, the cracks would have to propagate through the Pacific plate at the same velocity as the plate, which is 71 mm/yr in the Samoan region. However, without appealing to coincidence, it is not clear that a mechanism exists that would allow lithospheric cracks to propagate at the same velocity as the plate. If the cracking were due to tectonic stresses associated with the Tonga trench, it is not obvious how the cracks would propagate at 71 mm/yr, given that the Trench is approaching Samoa at a velocity of ~260 mm/yr [Hart et al., 2004]. Second, the cracking of the lithosphere itself should be detectable seismically. The Pacific lithosphere ~100 km south of Samoa is tearing, generating frequent earthquakes [Millen and Hamburger, 1998], and cracking of a portion of nearby Pacific lithosphere at the leading edge of the Samoan hot spot should also generate earthquakes. However, the only earthquakes measured at the leading edge of the Samoan hot spot are shallow and within Vailulu’u volcano [Konter et al., 2004], and there is no evidence for earthquakes that fall along a deep propagating lithospheric crack.

Owing to the fact that a depleted, refractory keel is unlikely to yield melts during lithospheric cracking, we suggest that volcanism in Samoa is most consistent with rapid, focused upwelling of fertile material from the deeper mantle. The upwelling plume of hot mantle material need not be stationary, but may blow in the “mantle wind” [Steinberger, 2000]. In the words of Wilson [1963, p. 869], “It is not necessary for the [hotspot] source to be immobile. It need only move more slowly than the near-surface current.” An upwelling plume consistent with the 71 mm/yr Pacific plate velocity [Koppers et al., also manuscript in preparation, 2010], and would be consistent with the lack of deep earthquakes along the Samoan hot spot (including the leading end of the hot spot).

**Appendix A**

Each sample was crushed in a plastic bag, and the freshest rock chips were picked under a microscope and rinsed in milliQ water. The freshest chips were then powdered in an agate mortar. Major and trace element analyses were performed on unleached whole-rock powders at the GeoAnalytical lab at Washington State University. Major elements and Ni, Cr, V, Ga, Cu and Zn were measured by XRF (X-ray fluorescence). The other trace elements were measured by ICP-MS (inductively coupled plasma mass spectrometer). Errors for measurement of major element errors range from 0.11% to 0.33% (1σ) of the amount present (SiO₂, Al₂O₃, TiO₂, P₂O₅) and 0.38%–0.71% (other major elements). Trace element analysis of basaltic powders by ICP-MS typically yields reproducibility of 0.77%–3.2% (1σ) for all elements except for U (9.5%) and Th (9.3%).

Portions of powder used for Sr, Nd and Pb isotope analyses at WHOI were leached for 3 h in 6.2 N HCl at 100°C. Previous work has shown that extensive leaching can remove the rock component associated with alteration and isolate primary magmatic values [Taras and Hart, 1987; White et al., 1993; Hart and Blusztajn, 2006]. However, some alteration components in a lava may be resistant to leaching [Taras and Hart, 1987], in which case sequential leaching experiments would not yield a primary magmatic value. We approached this...
problem in two ways. First, we subjected the lavas to rather severe leaching. Second, in a separate study of these lavas [Jackson et al., 2009b], we measured Sr and Nd isotopes in magmatic clinopyroxene separated from four samples with elevated LOI (2.3, 4.7, 5.2 and 9.4 wt % LOI). We found that the clinopyroxene separates rarely have Sr isotope ratios equal to those measured in leached whole rock powders [Jackson et al., 2009b]. However, this may not indicate that the whole rock Sr isotope signatures have been modified by alteration; two populations of fresh clinopyroxene from the same samples rarely give the same Sr isotope ratios [Jackson et al., 2009b], suggesting that there is heterogeneity inherent to the lavas before eruption (an observation consistent with Sr isotope variability observed in olivine-hosted melt inclusions from a single Samoan lava [Jackson and Hart, 2006]). Therefore, determining a single primary magmatic Sr, Nd and Pb isotopic composition for a lava may be complicated by isotopic heterogeneity present in lavas prior to eruption.

Following dissolution of the leached powders, Sr and Nd chemistry was performed with conventional ion chromatography using Dowex 50 cation resin and HDEHP-treated Teflon for Nd separation [Taras and Hart, 1987]. Pb separation was performed with a single column pass using the HBr-HNO3 procedure of Galer [1986] and Abouchami et al. [1999]. Sr, Nd, and Pb isotopes were analyzed on the NEPTUNE multicollector ICP-MS located at WHOI. The internal precision for 87Sr/86Sr and 143Nd/144Nd measurements is 5–10 ppm (2σ). After adjusting to 0.710240 (SRM987 Sr standard) and 0.511847 (La Jolla Nd standard), the external precision for Sr and Nd isotopes is estimated at 15–25 ppm (2σ). SRM997 Ti was used as an internal standard during Pb isotope analyses. The internal precision for Pb isotope measurements on 206Pb/204Pb, 207Pb/204Pb and 208Pb/204Pb ratios is 15–30 ppm, and external reproducibility following full chemistry ranges from 17 ppm (2σ) for 207Pb/206Pb to 117 ppm (2σ) for 208Pb/204Pb. Pb isotope ratios are adjusted to the SRM981 values of Todt et al. [1996]. Further documentation of the precision for Pb isotope measurement at WHOI (on a standard solution and a basalt) is given by Hart et al. [2002]. All Sr, Nd and Pb separation chemistry on ALIA lavas, and the corresponding Neptunian analytical sessions, were carried out at WHOI from 2006 to 2009. Sr, Nd and Pb measurements on AVON2/3 dredge samples from Malulu and Rose Atoll were done on the WHOI VG354 TIMS multicollector in the summer of 2000 following the methods of Hauri and Hart [1993].

After adjusting to the accepted values for the SRM987 (0.710240) and La Jolla (0.511847) standards, external precision is estimated to be 30 ppm. Using NBS 981 and the values given by Todt et al. [1996], Pb isotope ratios were corrected by ratio for fractionation; Pb isotope runs by TIMS have a precision of 0.05% per atomic mass unit. [40] Following crushing and magnetic separation, fresh phenocrysts were removed from select samples for helium isotope analysis. Helium isotopes were measured at WHOI following the analytical methods described by Kurz et al. [2004]. All helium data were obtained by crushing of clinopyroxene (cpx) and olivine in vacuum, and the data are reported in Data Set S1. Helium measurements are limited due to the requirement of phenocrysts and/or submarine glass (retaining magmatic helium), which are relatively rare in the new sample suite. The new helium isotope data complement helium measurements made on ALIA dredge lavas by Jackson et al. [2007a, 2009a].

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Jackson et al.: HOT SPOT HIGHWAY

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