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LETTERS

The return of subducted continental crust in Samoan lavas

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Substantial quantities of terrigenous sediments are known to enter the mantle at subduction zones, but little is known about their fate in the mantle[1]. Subducted sediment may be entrained in buoyantly upwelling plumes and returned to the Earth's surface at hotspots[2–5], but the proportion of recycled sediment in the mantle is small, and clear examples of recycled sediment in hotspot lavas are rare[6,7]. Here we report remarkably enriched ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd isotope signatures in Samoan lavas from three dredge locations on the underwater flanks of Savai'i island, Western Samoa. The submarine Savai'i lavas represent the most extreme ^{87}Sr/^{86}Sr isotope compositions reported for ocean island basalts to date. The data are consistent with the presence of a recycled sediment component (with a composition similar to the upper continental crust) in the Samoan mantle. Trace-element data show affinities similar to those of the upper continental crust—including exceptionally low Ce/Pb and Nb/U ratios[8]—that complement the enriched ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd isotope signatures. The geochemical evidence from these Samoan lavas significantly redefines the composition of the EM2 (enriched mantle 2; ref. 9) mantle endmember, and points to the presence of an ancient recycled upper continental crust component in the Samoan mantle plume.

The Earth's mantle, as sampled by ocean island basalts erupted at hotspots, is chemically and isotopically heterogeneous. However, the origin of the geochemical heterogeneity of the mantle is not well understood. One model for the geochemical evolution of the mantle assumes that much of the chemical diversity is a result of subduction, a tectonic process that introduces enriched oceanic crust and compositionally heterogeneous sediment into a largely primitive (or slightly depleted) mantle[5,10,11]. Following subduction, these surface materials mix with a peridotitic mantle, thus imprinting their enriched chemical and isotopic signatures on its various domains. A number of isotopically distinct geochemical reservoirs, as sampled by ocean island basalts, have resulted from this process. The isotopic endmembers are often referred to as HIMU (high $\mu = {}^{238}$U/^{204}Pb), EM1 (enriched mantle 1) and EM2 (enriched mantle 2) and DMM (depleted mid-ocean-ridge basalt mantle)[9]. Although the most radiogenic Pb isotope ratios observed in the HIMU component have been proposed to result from a contribution of recycled oceanic crust[9,12], most models for the creation of the EM1 and EM2 mantle reservoirs invoke a small portion of lithologically distinct sediments that have been recycled into the mantle[9,13].

The volcanically active Samoan islands and seamounts define a hotspot track with a classical EM2 pedigree[7,14,15]. The first high-precision ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd measurements from Samoan lavas were interpreted as evidence of sediment recycling[5]. Recently, however, the proposed recycled sediment origin of the enriched Samoan basalts has been questioned (see Supplementary Discussion), and an alternative model favouring source enrichment by metasomatic processes was proposed[7]. The extreme isotopic and chemical enrichment in the new Samoan EM2 lavas exhibit distinctly continental fingerprints, and argue for a role for a component similar to ancient recycled upper continental crust (UCC) in the Samoan plume (see Supplementary Discussion for the ALIA 2005 cruise dredge locations and geochemical data).

The most isotopically enriched Samoan whole-rock ^{87}Sr/^{86}Sr signature (0.720469, Mg# = 57.2) is recorded in a trachyandesite, dredge sample D115-21, which was taken from the southwestern flank of Savai'i. Clinopyroxene mineral separates from the same sample yielded an even higher ^{87}Sr/^{86}Sr ratio (0.721630). A trachybasalt (D115-18) hosts the second-most-enriched ^{87}Sr/^{86}Sr (0.718592, Mg# = 58.7), and clinopyroxene mineral separates from the sample also gave more enriched ratios (0.720232–0.720830). Six other lavas recovered in the same dredge also exhibit enriched ^{87}Sr/^{86}Sr ratios (0.708175–0.716394, Mg# = 52.0–65.1). Dredge D118, located on the far western end of the Savai'i lineament, contained an alkali basalt with enriched ^{87}Sr/^{86}Sr (0.710337, measured on fresh clinopyroxene). Dredge D128, taken on the northeastern flanks of Savai'i, yielded a transitional basalt with a high ^{87}Sr/^{86}Sr ratio (0.712500, Mg# = 70.5) and several other basalts with less enriched ^{87}Sr/^{86}Sr (0.706397–0.708170, Mg# = 61.2–63.9). Dredge D114, taken on the southwestern flanks of Savai'i, provided younger shield basalts of transitional chemistry and normal ^{87}Sr/^{86}Sr (0.705422–0.705435, Mg# = 67.2 and 76.3).

The ^{87}Sr/^{86}Sr isotopes in the basalts from all three ultra-enriched sampling localitites are complemented by enriched (low) ^{143}Nd/^{144}Nd and the lowest ^{3}He/^{4}He ratios (4.31–4.93 Ra, or ratio to atmosphere) observed in Samoan basalts. Together, the new data extend the Samoan isotope array to a region outside the global ocean island basalt field (Fig. 1). Highly enriched EM2 signatures have previously been observed only in metasomatized xenoliths from Savai'i (^{87}Sr/^{86}Sr up to 0.712838; ref. 16), and the Samoan EM2 basalts provide the first evidence that the enriched component hosted in these xenoliths also occurs as erupted basalts. The enriched ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd isotope ratios, coupled with the low ^{3}He/^{4}He, are consistent with a recycled UCC component in the mantle source of the Samoan EM2 basalts.

The UCC reservoir exhibits several diagnostic trace-element characteristics that can be useful for detecting its presence in Samoan EM2 lavas. Compared to ocean island basalt and mid-ocean-ridge basalt lavas, UCC displays exceptional depletion in Nb (and Ta), Ti and Eu, and enrichment in Pb (Fig. 2). Samoan basalts have

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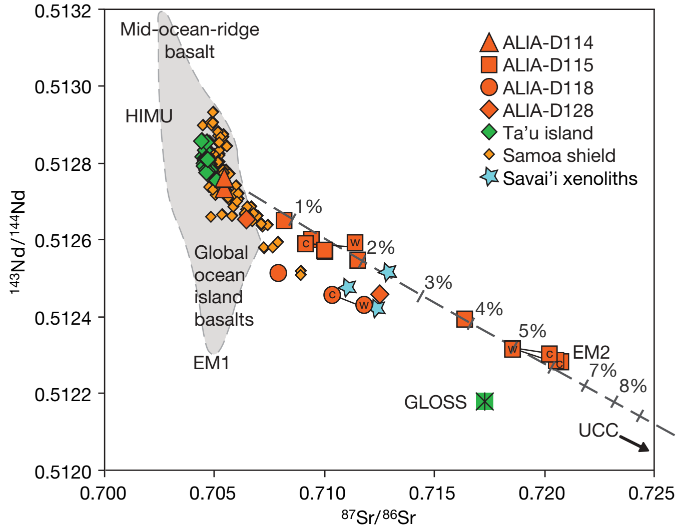

Figure 1 | ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd isotope ratios of new enriched Samoan lavas. The values are compared with other Samoan shield basalts[7], global ocean island basalt compositions and GLOSS (global subducting sediment)[1]. Analyses in which whole-rock (w) powders and clinopyroxene (c) analyses are performed on the same sample are connected by a tie-line. A model mixing line between depleted Ta'u peridotite and UCC is marked at 1% intervals, with increasing contribution from the latter component. The hypothetical UCC mixing endmember lies outside the figure. Approximately 5% UCC is required to produce the spidergram of sample D115-18 (see Supplementary Discussion), and ~6% is required to generate the ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd in D115-21.

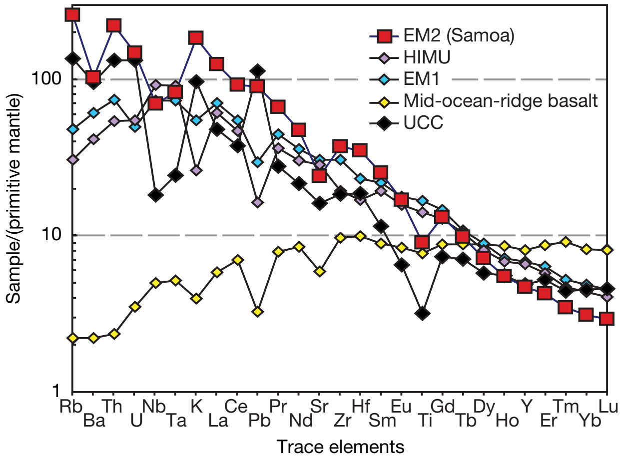

Figure 2 | Primitive-mantle-normalized[27] trace-element patterns for the Samoan EM2 endmember. The EM2 spidergram is the most isotopically enriched Samoan lava, sample D115-21 (^{87}Sr/^{86}Sr = 0.720469, Mg# = 57). The other mantle endmembers (corrected to Mg# numbers of 60–62) and UCC[17] are plotted for comparison. Similar to UCC, the Samoan EM2 lava exhibits large negative Ti and Nb (and Ta) anomalies and an excess of Pb (and K).

trace-element characteristics that are increasingly similar to UCC with more enriched ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd values (Fig. 3). Although the most isotopically depleted basalts from Samoa show slight positive anomalies in Nb and Ti, the magnitude of these anomalies decreases monotonically towards the most enriched Samoan EM2 basalts. Similarly, a correlation exists between greater Pb enrichment and increasing isotopic enrichment in Samoan basalts. Importantly, the Eu anomaly is increasingly negative in the most isotopically enriched Samoan EM2 lavas (excluding basalts with MgO < 6.5 wt%), and the Rb/Sr and U/Pb are too low in the lower (or middle) continental crust[17] to be consistent with the new Samoan Sr and Pb isotope data; these observations rule out the involvement of lower (or middle) continental crust. Furthermore, rare xenoliths with enriched ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd from the subcontinental lithospheric mantle[9] suggest that this mantle domain can be isotopically enriched. However, the subcontinental lithospheric mantle does not appear to exhibit the trace-element anomalies observed in the most isotopically enriched Samoan lavas[18]. Instead, isotope ratios

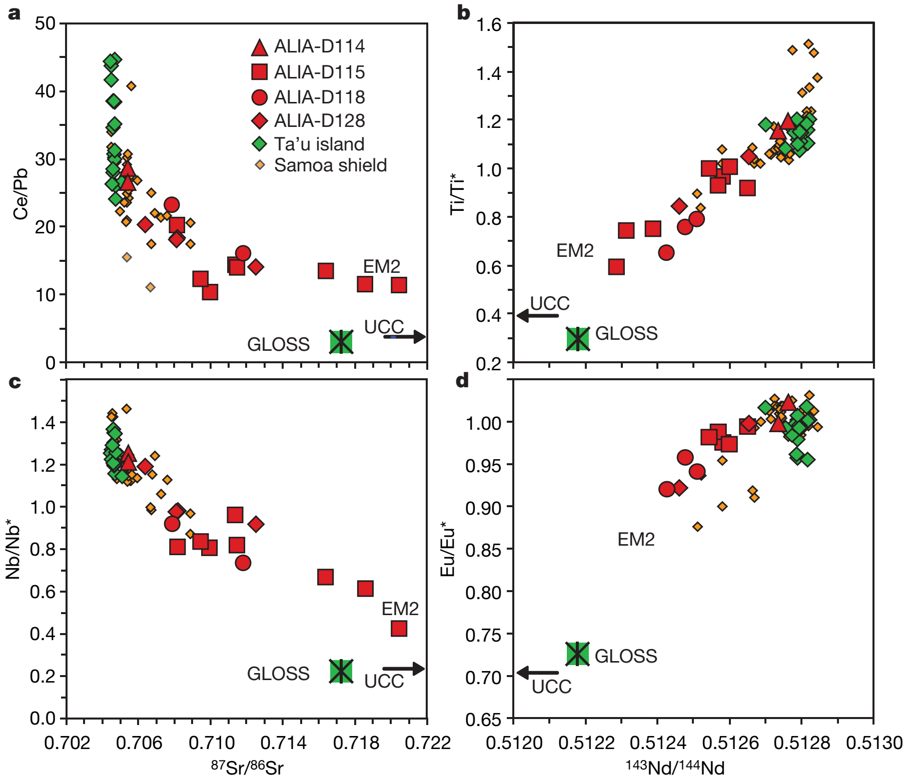

Figure 3 | ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratios suggest the presence of a UCC component in Samoan EM2 lavas. The ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratios are plotted against diagnostic UCC trace-element indicators in Samoan basalts: the more isotopically enriched Samoan basalts exhibit trace-element characteristics that are increasingly similar to UCC. UCC[17] plots outside the panels, and its trace-element and isotopic composition is indicated by the level (and direction) of the arrows. **a**–**c**, All submarine Savai'i samples are plotted, as are other Samoan shield lavas with MgO > 6.5 wt%. **d**, Submarine Savai'i samples with MgO < 6.5% are excluded (avoiding possible effects of plagioclase fractionation). All trace-element data shown are by ICP-MS (inductively coupled plasma mass spectrometry). Element anomalies are calculated as follows (where subscript N means normalized to primitive mantle[27]): $\mathrm{Ti/Ti^* = Ti_N/(Nd_N^{-0.0555} \times Sm_N^{0.333} \times Gd_N^{0.722})}$; $\mathrm{Nb/Nb^* = Nb_N/\sqrt{(Th_N \times La_N)}}$; $\mathrm{Eu/Eu^* = Eu_N/\sqrt{(Sm_N \times Gd_N)}}$.

and trace-element anomalies (Nb, Ti, Eu and Pb) in Samoan basalts generate arrays that trend towards a composition similar to UCC.

We can exclude a shallow origin for the anomalous enrichment observed in the Samoan EM2 lavas. Owing to the close proximity of the Tonga trench, located only 120 km south of Savai'i, rapid cycling of sediment from the subduction zone into the Samoan plume was proposed as a mechanism for generating the extreme isotopic enrichment in Samoan lavas[14]. However, at the time that the submarine Savai'i lavas were erupted 5 Myr ago[31], plate reconstructions indicate that the northern terminus of the Tonga trench was located 1,300 km to the west of Savai'i (ref. 19), and sediment input from the Tonga trench can be ruled out as a source of enrichment in these lavas.

Evidence from Pb isotopes suggests that it is unlikely that shallow-level contamination by modern marine sediments is responsible for the isotopic enrichment in the Samoan EM2 basalts. In $\Delta^{207}Pb/^{204}Pb - \Delta^{208}Pb/^{204}Pb$ isotope space, Samoan basalts and global marine sediments[1] exhibit non-overlapping fields with diverging trends (Fig. 4). Moreover, three composite cores taken from the Samoan region, and a single ferromanganese crust from the flanks of Savai'i, plot in the global marine sediment field and exhibit no geochemical relationship with the extremely enriched Samoan lavas. It is also unlikely that the Samoan plume has been contaminated by stranded continental crust, such as was found beneath the Kerguelen plateau[20] and the southern Mid-Atlantic Ridge[21], or by ancient limestone blocks like those discovered in the Romanche fracture zone[22]. The tectonic history of the Samoan region places it neither at the locus of continental rifting, which was responsible for the marooned Kerguelen and southern Atlantic continental blocks, nor in proximity to any Pacific fracture zones[23].

Large quantities of sediment derived from UCC have entered the mantle at subduction zones over geologic time[1], and such a reservoir is ideally suited as an enriched source for the Samoan plume. The array formed by the Samoan EM2 basalts in $^{143}Nd/^{144}Nd–^{87}Sr/^{86}Sr$ isotope space is anchored on the depleted end by basalts from Ta'u, one of the youngest, easternmost Samoan islands. The $^{143}Nd/^{144}Nd–^{87}Sr/^{86}Sr$ array suggests mixing between this dominant, slightly depleted Ta'u component and a rare, enriched component that exhibits isotope and trace-element characteristics similar to UCC. The proportion of the enriched component in the Samoan EM2 lavas can be estimated by calculating trace-element concentrations in the depleted Ta'u mantle and mixing this composition with UCC (see Supplementary Discussion). A contribution of 5% UCC to the depleted Ta'u mantle generates a composition that, after mixing and melting, produces a trace-element pattern similar to that observed in Samoan EM2 sample D115-18 (with $^{87}Sr/^{86}Sr$ of 0.718592). Fixing the proportions of the depleted and UCC components in the Samoan EM2 source in this way then defines the $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ isotopic composition of this material as 0.7421 and 0.5117, respectively. The most isotopically enriched Samoan lavas have higher $^{87}Sr/^{86}Sr$ than the average continental crust inferred from suspended river sediments ($^{87}Sr/^{86}Sr \approx 0.716$; ref. 24) and global marine sediments (~0.717; ref. 1), values that are biased towards younger continental crust. However, composites of directly sampled ancient continental shield rocks show isotopically enriched compositions[25] that bracket the calculated composition of the recycled UCC sediment in the Samoan mantle. The new ultra-enriched EM2 lavas suggest an unusually enriched recycled protolith in the Samoan mantle.

Despite the large volumes of sediment entering the mantle at subduction zones (estimated at 0.5–0.7 $km^3 yr^{-1}$; ref. 1), isotopic signatures associated with recycled UCC are rare in ocean island basalts[26]. This enriched component is also uncommon in the Samoan plume, where the highly enriched Samoan EM2 lava D115-18 is calculated to have only 5% recycled UCC (and 95% depleted Ta'u source), and 90% of the remaining Samoan basalts exhibit depleted $^{143}Nd/^{144}Nd$ ratios (>0.512638). In addition to being rare in other ocean island basalts, recycled UCC may exist in low abundance in the Samoan plume. The reason for this may be that most subducted sediment melts and is rapidly returned to the surface in subduction zone volcanoes, or is simply scraped off onto the forearc and is never subducted. Alternatively, if a significant portion of UCC has been subducted over the past 4 Gyr (0.5–0.7 $km^3 yr^{-1}$) and has survived subduction zone melting, the resulting accumulated reservoir in the mantle will constitute only ~0.15% of its mass. Such a small reservoir may be diluted by the ambient mantle after convective stirring, a mechanism that efficiently attenuates mantle heterogeneities. Therefore, recycled crustal signatures can be greatly diluted and difficult to detect. By contrast, the recycled UCC component in the Samoan plume is an anomalous survivor in a chaotic mantle.

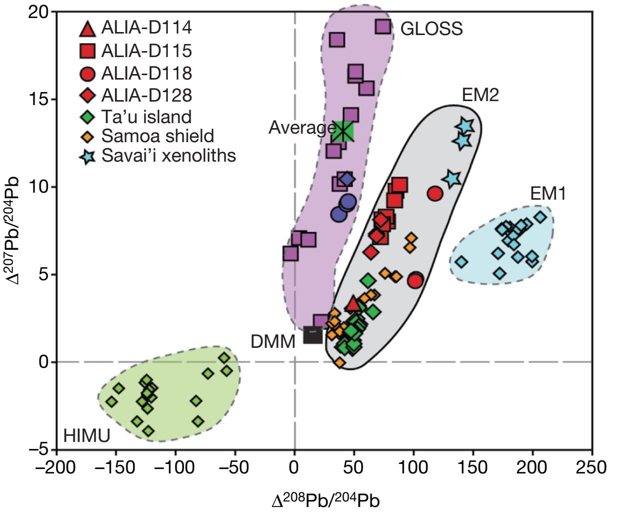

Figure 4 | ΔPb isotope compositions of Samoan lavas and marine sediment samples indicate that the Samoan EM2 lavas are not contaminated with modern marine sediment. Samoan basalts show no overlap with oceanic sediments contributing to GLOSS[1] (purple squares, where the GLOSS average composition is represented by a green crossed 'average' square), composite sections from three sediment cores taken in the Samoan region (blue circles), and a Samoan ferromanganese rind (blue diamond). Pb-isotope data for mantle endmembers DMM (using data from mid-ocean ridge basalt normal segments, as defined and catalogued by ref. 28), EM1 (Pitcairn), and HIMU (Mangaia and Tubuai) are from the literature (see Supplementary Information for reference citations). The use of ΔPb isotope notation[29] to identify sediment components in ocean island basalts is discussed elsewhere[30]. All Samoan data shown are determined using a high-precision Tl-spike protocol[7].

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions M.G.J. performed most of the experimental work, developed the model and wrote the paper. S.R.H. and H.S. conceived the project, and were co-chiefs of the ALIA expedition. A.A.P.K. and J.K. were responsible for the cruise bathymetry, and A.A.P.K. greatly improved the figures. J.B. and M.K. provided analytical assistance and access to facilities. A.A.P.K., J.B., J.K. and J.A.R. helped with sample preparation. All authors participated in the discussion and interpretation of results, and commented on the manuscript.

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