

# Role of the deep mantle in generating the compositional asymmetry of the Hawaiian mantle plume

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**Linear chains of volcanic ocean islands are one of the most distinctive features on our planet. The longest, the Hawaiian-Emperor Chain, has been active for more than 80 million years, and is thought to have formed as the Pacific Plate moved across the Hawaiian mantle plume, the hottest and most productive of Earth's plumes. Volcanoes fed by the plume today form two adjacent trends, including Mauna Kea and Mauna Loa, that exhibit strikingly different geochemical characteristics. An extensive data set of isotopic analyses shows that lavas with these distinct characteristics have erupted in parallel along the Kea and Loa trends for at least 5 million years. Seismological data suggest that the Hawaiian mantle plume, when projected into the deep mantle, overlies the boundary between typical Pacific lower mantle and a sharply defined layer of apparently different material. This layer exhibits low seismic shear velocities and occurs on the Loa side of the plume. We conclude that the geochemical differences between the Kea and Loa trends reflect preferential sampling of these two distinct sources of deep mantle material. Similar indications of preferential sampling at the limit of a large anomalous low-velocity zone are found in Kerguelen and Tristan da Cunha basalts in the Indian and Atlantic oceans, respectively. We infer that the anomalous low-velocity zones at the core-mantle boundary are storing geochemical anomalies that are enriched in recycled material and sampled by strong mantle plumes.**

Mantle plumes and their related hotspot volcanism constitute one of the main processes affecting the cooling and internal differentiation of the Earth's mantle and crust. The mantle plumes form in response to cooling of the Earth's core<sup>1,2</sup>. Whereas plume heads contribute huge volumes of lava to the Earth's surface over short periods of time, plume tails create chains of volcanoes, some extending for thousands of kilometres. For example, Hawai'i in the Pacific Ocean (Fig. 1a) and Kerguelen and Réunion in the Indian Ocean are three mantle plumes associated with long surface tracks that represent important features of the Earth's lithosphere<sup>3</sup>. Mantle plumes may originate in the lower mantle<sup>4</sup>, from near the core-mantle boundary (CMB)<sup>5-7</sup>, and decompression of the rising material generates melting at shallow depth as it approaches the surface<sup>5</sup>.

Geochemical studies of ocean island basalts (OIB) brought to the surface by a deep mantle plume indicate that the Earth's mantle is chemically and isotopically heterogeneous at scales ranging from centimetres to thousands of kilometres<sup>8-11</sup> and provide essential information about its composition and evolution. OIBs present different isotopic compositions. Radiogenic isotopic ratios (a 'fingerprint' of their mantle source) show that these differences result from time-integrated evolution, over millions to billions of years, of compositionally distinct source regions with different history and parent-daughter fractionation<sup>11,12</sup>. Radioactive isotope parents (<sup>87</sup>Rb, <sup>147</sup>Sm, <sup>176</sup>Lu, <sup>238</sup>U, <sup>235</sup>U and <sup>232</sup>Th) decay with a very long half-life into daughter isotopes (in our case <sup>87</sup>Sr, <sup>143</sup>Nd, <sup>176</sup>Hf, <sup>206</sup>Pb, <sup>207</sup>Pb and <sup>208</sup>Pb, respectively). As a result the daughter isotope ratios reflect the long-term history of the basalt-source reservoirs in the mantle: they are the 'fingerprint' of their mantle sources. Systematic relationships of OIB compositions in binary isotopic diagrams are commonly interpreted as resulting from mixing between well-defined mantle endmembers<sup>9,13</sup>. These

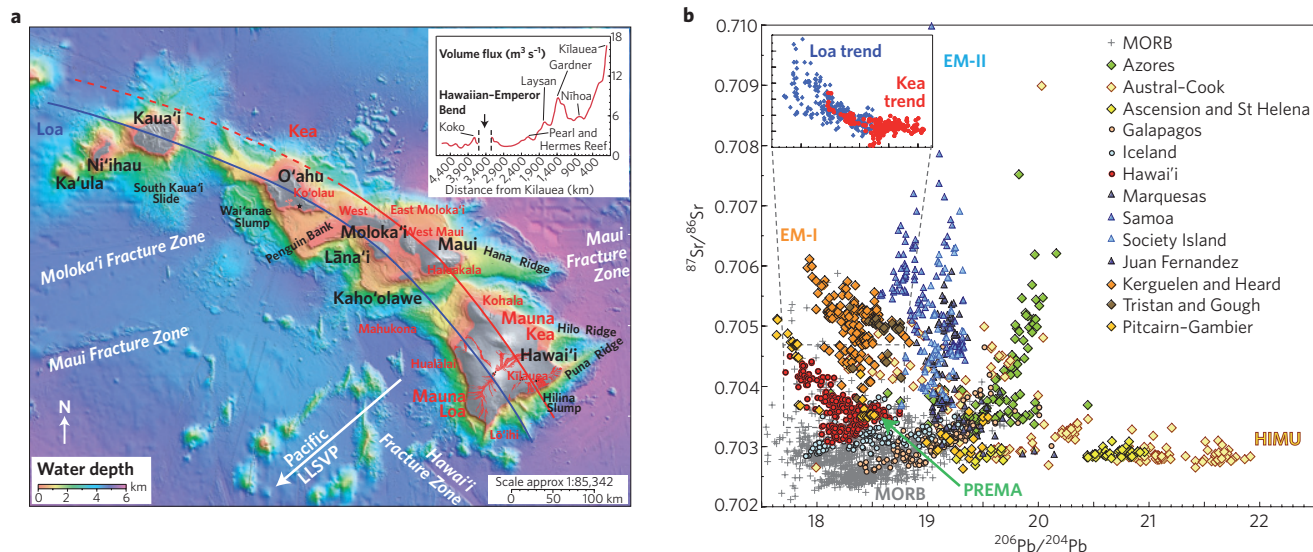
endmembers, expressed at the surface in OIB, do not correspond to any systematic geographical distribution (Fig. 1b). For example, EM-I (enriched mantle type-I) signatures are found in basalts from Indian, south Atlantic and Pacific islands, and HIMU (high U/Pb) signatures in basalts from Atlantic and Pacific islands.

These 'mantle reservoirs' probably reflect contributions from both the early solidification and differentiation of the Earth's mantle<sup>14,15</sup> as well as minor contributions from sediments, oceanic crust and continental crust, and sublithospheric mantle introduced into the deep mantle by subduction and plate-scale mantle stirring<sup>16,17</sup>. The presence of specific and traceable components in the mantle source of oceanic basalts provides a framework for discussing the origins of mantle plumes, the source of the differences from island to island<sup>18,19</sup>, and as a result, the dynamics of mantle geochemical cycling<sup>11</sup>.

## Hawai'i as the archetype of mantle plumes

Wilson<sup>20</sup> recognized that the source of oceanic island volcanoes such as Hawai'i was fixed in space relative to plate motions and, thus, that it must be ultimately deeper than the lithosphere and upper mantle involved in plate tectonics. Hawai'i is the archetypical example of intraplate volcanism<sup>5</sup>. It is the longest island chain on Earth, extending almost 6,000 km in length, and has been active for over 80 million years. The Hawaiian islands are surrounded by a 1,000-km-wide bathymetric swell, the Hawaiian swell, commonly associated with a sublithospheric hot buoyant mantle plume<sup>1,2,21</sup> that extends well into the lower mantle<sup>4</sup> and possibly to the CMB<sup>22</sup>, although seismic resolution at this depth (~2,800 km) is problematic<sup>23</sup>. The Hawaiian mantle plume has the largest buoyancy flux of any plume<sup>1,2,21</sup> and has been the subject of a large number of geochemical, fluid-dynamical and geodynamical studies<sup>21,24-29</sup>.

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**Figure 1 | Key bathymetric and isotopic features of the Hawaiian Islands.** **a**, Bathymetric map ( $18^{\circ}$  to  $23^{\circ}2'$  N,  $161^{\circ}$  to  $154^{\circ}$  W) of the Hawaiian Islands<sup>102</sup>. The Loa and Kea trends are defined. Arrow points to the location of the Pacific LLSVP<sup>66</sup>. Temporal variation of volume flux of magma calculated assuming regional compensation<sup>95</sup> is shown in the inset. **b**, Sr–Pb isotope diagrams of oceanic basalts<sup>103</sup>. Inset shows recent data (including this study) on Hawaiian tholeiitic shield lavas. Kea volcanoes point towards average mantle compositions (PREMA<sup>9</sup>) and Loa volcanoes towards enriched compositions (EM-I type<sup>9</sup>).

The Hawaiian mantle plume was the target of a deep drilling study, the Hawai'i Scientific Drilling Project (HSDP), which provided a continuous sampling of  $\sim 3,255$  m of the Mauna Kea volcano with ages between  $\sim 240$  and  $>650$  kyr (ref. 30), and represented a unique opportunity to study a significant portion of the life history of a plume-related volcano<sup>7,31</sup>. As Hawaiian volcanoes grow, they are slowly carried to the northwest by the moving Pacific plate at a speed of 9–10 cm per year<sup>32</sup>, passing over the Hawaiian mantle plume. As the magma-producing region is roughly 100 km in diameter<sup>21</sup>, the volcano takes about 1 million years to cross this region<sup>33</sup>. Numerous petrological and geochemical studies were carried out on the drill core samples to characterize the mantle source for the lavas and constrain the time-averaged rates of melt production, delivery to the crust and eruption at the surface. Together with results from complementary models of the Hawaiian plume, this combined effort represents a considerable leap forward in our understanding of plume-related volcanism in general<sup>25,30,34–38</sup>.

During the past 5 Myr, Hawaiian volcanoes formed two parallel chains<sup>39,40</sup> (Fig. 1a) that are distinct geographically and geochemically<sup>8</sup>. These two chains, or Loa and Kea trends, are named after their tallest volcanoes, Mauna Loa and Mauna Kea, both on the Island of Hawai'i. High-precision lead isotope compositions show that there is little overlap between volcanoes from the two trends, with Loa-trend volcanoes characterized by higher  $^{208}\text{Pb}/^{204}\text{Pb}$  for a given  $^{206}\text{Pb}/^{204}\text{Pb}$  than Kea-trend volcanoes<sup>27</sup>. If the connection between mantle plume and hotspot is robust, these trends define azimuthally asymmetric compositional zoning in the plume conduit<sup>26,29</sup> that is difficult to reconcile with the popular concentrically zoned model of the mantle plume for Hawai'i<sup>12,35,64,1</sup>.

The so-called bilateral compositional asymmetry of the Hawaiian mantle plume was initially defined on the basis of the Pb isotopic analyses of  $\sim 120$  shield samples, dominantly from the Island of Hawai'i (Fig. 1a) for Kea-trend volcanoes (that is, Kilauea, Mauna Kea and Kohala) and from 8–15 samples per volcano for Loa-trend volcanoes<sup>27,35,42</sup> (Lō'ihi, Mauna Loa, Lāna'i, Kaho'olawe and Kō'olau). Half of these samples were from the HSDP core from Mauna Kea volcano. Here we present new data on 120 Mauna Loa lavas, which

are then integrated in a compilation of over 700 high-precision Pb isotopic compositions for shield-stage lavas from all the main islands of the chain (Fig. 2a and b), and also about 585 for Sr and Nd, and 485 samples for Hf isotopic compositions. All data for the different isotopic ratios have been normalized to the same standard values (see Supplementary Information for analytical techniques). The shield building phase represents  $\sim 98\%$  of the volume of an average Hawaiian volcano<sup>43</sup>. The distinct Pb isotopic signatures of Loa- and Kea-trend volcanoes are clearly defined with only a few exceptions (29 out of 713 analysed samples, or 4% of the data set). Most of the distinctive samples have already been reported in the literature<sup>27,35,44–48</sup>.

### Isotopic study of the largest active volcano on Earth

Mauna Loa is the largest active volcano on the Earth, with a volume<sup>49</sup> of about 80,000 km<sup>3</sup>. Surprisingly, only a few studies have reported geochemical data on this volcano. In light of its significance in the Hawaiian chain, and the availability of new samples from both submarine and subaerial phases of volcano activity, we selected 120 new samples for this study (Fig. 3 and Supplementary Fig. S1, Table S1), covering: (1) a 1.6-km-thick submarine landslide section, called the Mile High Section, that allows continuous stratigraphic sampling analogous to HSDP<sup>50</sup> with ages between 120 and 470 kyr (ref. 51); (2) submersible and dredged samples along the submarine southwest rift zone; (3) radial vents on the southwest part of the Big Island<sup>52</sup>; (4) subaerial prehistoric and historic lavas<sup>53</sup>; and (5) a few samples from the 245 m of Mauna Loa recovered in the HSDP-2 core. A brief description of the sample location and geological context is given in the Supplementary Information. Combined with recently published isotopic data from Mauna Loa samples<sup>34,42,45</sup>, our results confirm that the compositions of Mauna Loa lavas are distinct from those of Mauna Kea lavas. Mauna Loa tholeiitic basalts have  $^{206}\text{Pb}/^{204}\text{Pb}$  between 18.05 and 18.26, with three landslide samples extending the compositional range up to 18.40, which is within the range of values for Lō'ihi<sup>27</sup>. There is no overlap in  $^{206}\text{Pb}/^{204}\text{Pb}$  between Mauna Loa ( $<18.26$ ) and Mauna Kea ( $>18.4$ ) lavas. In a Pb–Pb isotope diagram (Fig. 2a), the analyses for the lavas are distributed systematically on either side of the Kea–Loa

boundary, with only three prehistoric Mauna Loa samples crossing this boundary<sup>45</sup>.

Among the 120 Mauna Loa samples analysed here, some of the older samples (~470 kyr)<sup>51</sup>, collected at the lower levels of the landslide section on the submarine southwest rift zone, show different isotopic signatures, not observed anywhere else in Hawai'i (see Fig. 2b inset and Supplementary Fig. S1). These samples have higher <sup>208</sup>Pb/<sup>204</sup>Pb for a given <sup>206</sup>Pb/<sup>204</sup>Pb and lower <sup>143</sup>Nd/<sup>144</sup>Nd for a given <sup>87</sup>Sr/<sup>86</sup>Sr. These signatures document the presence of more heterogeneities in the Loa source, especially in the earlier shield-building stage, than in the Kea source.

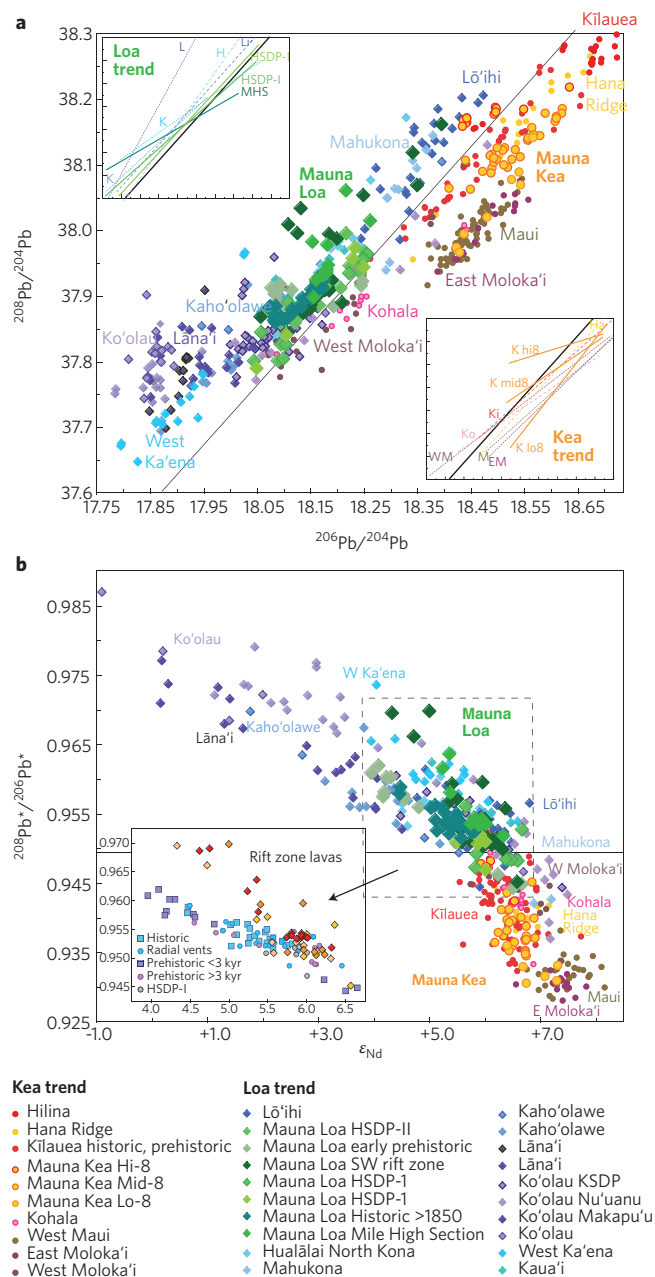
The difference between Loa- and Kea-trend volcanoes is best seen using <sup>208</sup>Pb\*/<sup>206</sup>Pb\* (ref. 32), which is a measure of the radiogenic addition to <sup>208</sup>Pb/<sup>204</sup>Pb and <sup>206</sup>Pb/<sup>204</sup>Pb during the Earth's history and is calculated by subtracting the primordial (initial) isotope ratios from the measured values: <sup>208</sup>Pb\*/<sup>206</sup>Pb\* reflects the ratio of Th/U integrated over the history of the Earth. Loa-trend volcanoes have <sup>208</sup>Pb\*/<sup>206</sup>Pb\* values above 0.9475, whereas Kea-trend volcanoes have lower values (Figs 2b, 4b). In addition, Loa-trend volcanoes show a wider range of variations in all isotopic systems by a factor of about 1.5. For example, <sup>206</sup>Pb/<sup>204</sup>Pb varies from 17.8 (West Ka'ena)<sup>54</sup> to 18.5 (Lō'ihi)<sup>27</sup>, whereas Kea-trend volcanoes range from 18.2 (Kohala)<sup>27</sup> to 18.74 (Hilina)<sup>55</sup>. Similarly, ε<sub>Nd</sub>, a measure of the deviation of <sup>143</sup>Nd/<sup>144</sup>Nd from the chondritic value (<sup>143</sup>Nd/<sup>144</sup>Nd = 0.512638), varies about twice as much in Loa-trend volcanoes (from -0.9 to +7.5, Kō'olau)<sup>48</sup> than in Kea-trend volcanoes (from +5.1 in Haleakalā<sup>56</sup> to +8.2 in West Maui<sup>57</sup>). There is limited overlap between the two trends in isotopic signatures. The range of variations is larger in Loa-trend volcanoes, as expressed by two standard deviations on the average of isotopic analyses of lavas of each individual volcano, and increases with increasing age along the Hawaiian chain (that is, farther away from Kilauea; Fig. 4a and b).

Kea-trend volcanoes define Pb–Pb isotope mixing arrays (Fig. 2a, inset) that converge towards radiogenic Pb ratios (<sup>206</sup>Pb/<sup>204</sup>Pb = ~18.5–18.6, <sup>208</sup>Pb/<sup>204</sup>Pb = ~38.1–38.2), which Tanaka *et al.*<sup>48</sup> called the Kea component. A few of the Kea volcano arrays cross the Kea–Loa boundary, indicating that one of the least radiogenic endmembers of the Kea volcanoes belongs to the Loa compositional field. In contrast, the Loa-trend volcanoes define Pb–Pb mixing arrays (Fig. 2a, inset) that are mostly subparallel to the Kea–Loa boundary and that rotate slightly around a common point close to Mauna Loa average compositions (<sup>206</sup>Pb/<sup>204</sup>Pb = ~18.1–18.2, <sup>208</sup>Pb/<sup>204</sup>Pb = ~37.9), which shows that this is a prevalent composition on the Loa side of the boundary. A few older Loa-trend volcanoes (Lāna'i, Kō'olau Makapu'u stage, Kaho'olawe) define Pb–Pb mixing arrays with either steeper or shallower slopes. These arrays intersect close to the average composition of the enriched Hawai'i endmember, the enriched Makapu'u component (EMK) of Tanaka *et al.*<sup>48</sup>, that is interpreted to reflect the presence of recycled oceanic crust and sediments<sup>58</sup>. The different organization of Pb–Pb isotope mixing arrays for Loa- and Kea-trend volcanoes indicates the presence of distinct endmember compositions in the source of the two geographic trends of Hawaiian volcanoes.

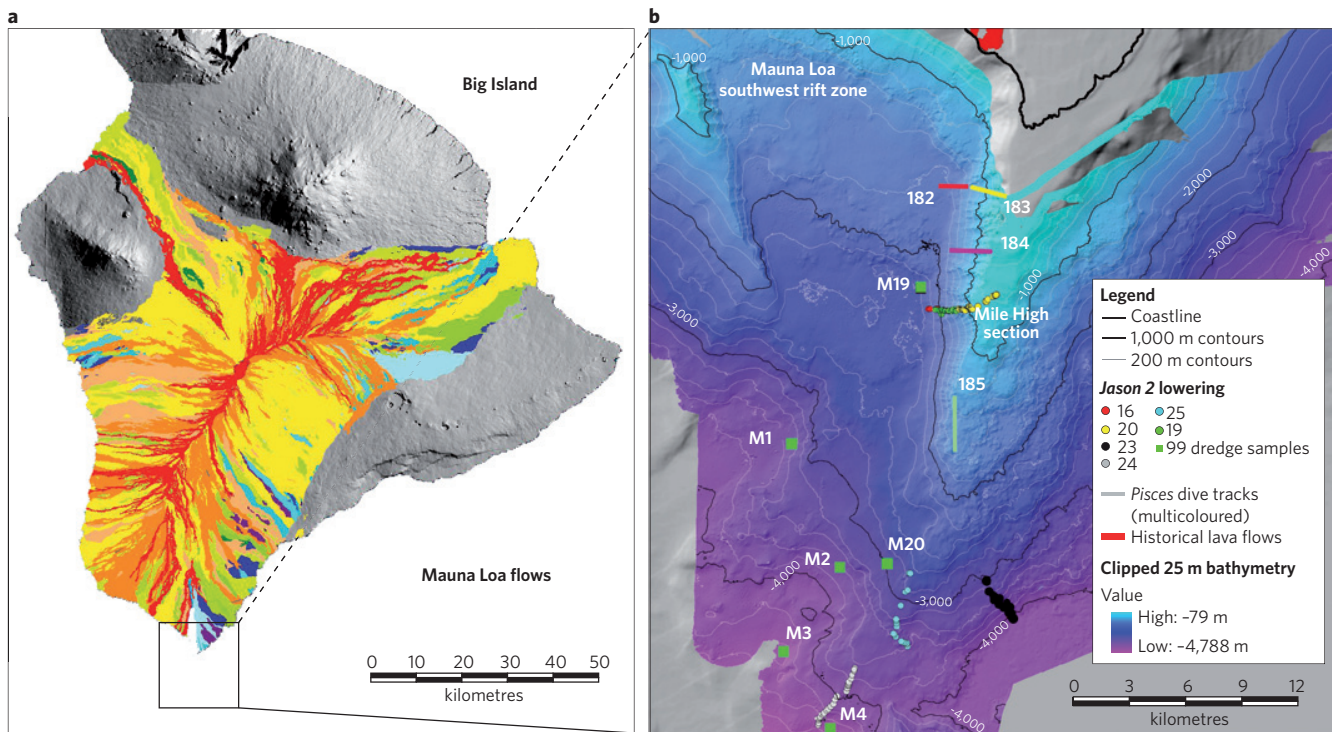
The geochemical differences between the Loa- and Kea-trend volcanoes probably reflects compositional variations in the plume source region at or near the CMB. These differences have persisted for at least 5 million years<sup>54,59</sup> and are not related to temporal variations in the degree of melting, although we do not yet know when the Loa and Kea trends emerged in the volcanic record at the surface. Below we examine what the geochemical differences between the Loa and Kea trends imply in terms of the bulk composition and structure of the deep source of the plume.

### Geochemical trends linked with deep mantle structure

The source region for the Hawaiian plume is widely recognized to be complex in structure, physical properties, constitution and composition<sup>60</sup>. Inferences from recent seismological studies<sup>61</sup>, together with



**Figure 2 | Isotopic data for Hawaiian shield lavas. a**, Plot of <sup>208</sup>Pb/<sup>204</sup>Pb against <sup>206</sup>Pb/<sup>204</sup>Pb for all Hawaiian shield lavas (normalized to same standard values). Mauna Loa and Mauna Kea samples have larger symbols. Thick black line indicates boundary separating volcanoes on the Mauna Loa (diamonds and cool colours) and Mauna Kea (circles and warm colours) trends based on Pb isotopic composition<sup>27</sup>. Insets: Pb–Pb arrays among some of the individual volcanoes. Solid lines indicate Mauna Loa (HSDP-I and Mile High Section, MHS) and Mauna Kea (low-, mid- and high-8)<sup>35</sup>. Dashed lines indicate other Hawaiian volcanoes or features (Li, Lō'ihi; H, Hualālai; L, Lāna'i; K, Kaho'olawe; Ha, Hana Ridge; Ki, Kilauea; Ko, Kohala; M, Maui; EM, East Moloka'i; WM, West Moloka'i). **b**, Plot of <sup>208</sup>Pb\*/<sup>206</sup>Pb\* against ε<sub>Nd</sub> for Hawaiian shield lavas. Inset: plot of <sup>208</sup>Pb\*/<sup>206</sup>Pb\* against ε<sub>Nd</sub> detail of Mauna Loa lavas (this study, plus prehistoric lavas <3 kyr old<sup>45</sup>, radial vents<sup>52</sup>), where older samples (red, yellow and orange diamonds; see also Supplementary Fig. S1) sampled along the submarine southwest rift zone define a unique mixing trend. Darker outline indicates triple-spike literature data. See Supplementary Information for all data sources.



**Figure 3 | Mauna Loa flows and southwest submarine rift zone. a,** Topographic shaded relief map of the Big Island of Hawai'i, highlighting Mauna Loa flows<sup>104</sup>. Flow colours indicate relative age (red, young; blue, old). Inset, area of Fig. 3b. **b,** Bathymetric map of the Mauna Loa submarine southwest rift zone showing the dredge and dive locations, and the Mile High Section sampled by the ROV *Jason 2* and *Pisces 5* dives. Contours from UTM Zone 5 NAD27, bathymetric map produced by G. Kaye, USGS-HVO, from data collected on the Mauna Loa HUGO (Hawai'i Undersea Geo-Observatory) oceanographic cruise (2002).

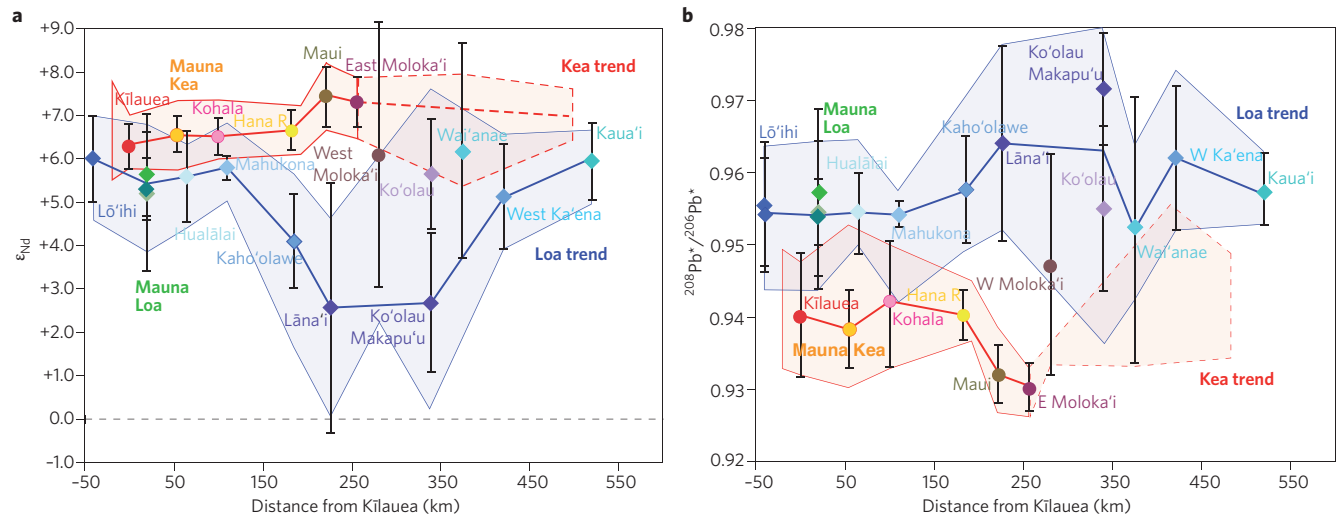
kinematic mantle flow models<sup>62</sup>, show that the location of Hawai'i, when projected down to the CMB region, overlies the northeastern edge of the 'large low-shear-velocity province' (LLSVP)<sup>63–65</sup> in the Pacific Ocean (Fig. 5c, adapted from ref. 66). The province is an anomalously dense, compositionally distinct<sup>67</sup> region, steep-sided and several hundred kilometres high. The Loa and Kea volcanoes straddle the LLSVP boundary with the Loa side of the Hawaiian plume located above the LLSVP and the Kea side overlying average Pacific lower mantle. One explanation for the distinct geochemical character of the Loa and Kea trends (Fig. 5b) is that they continuously sample these two qualitatively different types of mantle. This implies that the LLSVP mantle is, on average, more enriched in incompatible elements and more variable isotopically, whereas the Pacific lower mantle, preferentially sampled by the Kea side, is less heterogeneous.

Such a long-term physical link between the isotopic composition of the basalts and the source region requires that the root Hawaiian plume has remained approximately fixed at the edge of the LLSVP, and that there is little internal lateral or azimuthal stirring within the overlying the plume conduit. Steep-sided LLSVP piles, if over 50 km high, will introduce lateral temperature variations capable of driving an upward flow that will ultimately anchor the Hawaiian plume conduit<sup>6</sup>. The fixity of the plume to a LLSVP pile is therefore to be expected. The preservation of the spatially and chemically distinct Loa and Kea heterogeneities is perhaps surprising because the Hawaiian plume is strongly tilted<sup>62,68,69</sup>. Although lateral temperature variations can drive convection around the edges of a tilted conduit<sup>70</sup>, causing internal azimuthal stirring, as well as the entrainment and mixing of surrounding mantle across the conduit, such a process is negligible for the range of plume strength and plate flow conditions expected for the Earth<sup>26,71</sup>. Indeed, even strongly tilted plumes will preserve the essential heterogeneous structure of their source region.

The geometry and distribution of heterogeneities in the source region of the Hawaiian plume determine what is delivered to the melting region and sampled by the volcanoes<sup>29</sup>. An alternative view is that broadly concentric zoning of the plume is expected and that, at any given depth within the plume conduit, lateral mixing will result from the rheological variability across the plume conduit<sup>72</sup>. The extensive data set of new and published isotopic analyses presented here, on more than 700 Hawaiian basalt samples, shows the presence of two trends for at least 5 Myr from the Island of Hawai'i to Kauai with no evidence for concentric zoning.

If the variation in Pb isotopes in Loa basalts is related to entrainment of LLSVP mantle, then the heterogeneities may initially have a relatively low viscosity<sup>6</sup>. A low-viscosity tendril will be sheared at a greater rate and to a greater extent than the surrounding plume material in the conduit, giving rise to shear instabilities that could lead to entrainment and mixing across the conduit<sup>73</sup>. Such viscosity interfaces are never stable<sup>74</sup>, but the timescale for the growth of this instability is much longer than the time for plume material to rise across the mantle depth. Thus, the presence of such viscosity variations will probably not lead to lateral mixing and alter significantly our proposed connection between Hawaiian basalts and the composition of the source region.

From recent seismic imaging using scattered waves<sup>75</sup>, it has been inferred that the Hawaiian plume material ponds in the transition zone before travelling more than 1000 km east to Hawai'i. This study concludes that the hotspot is consequently decoupled from the source region and that isotope signatures of surface lavas cannot be used to map geochemical domains in the lower mantle. Partial ponding of rising plume material within the transition zone is, however, expected<sup>76,77</sup>. A stabilizing buoyancy effect and cooling related to the endothermic post-spinel phase transition at ~670 km will cause



**Figure 4 | Temporal evolution of isotopic compositions from Hawaiian volcanoes.** **a**, Plot of  $\epsilon_{\text{Nd}}$  against distance from Kīlauea in kilometres along the Hawaiian chain. **b**, Plot of  $^{208}\text{Pb}^*/^{206}\text{Pb}^*$  against distance from Kīlauea. Symbols, colour coding and data source (plus Wa'anae) as in Fig. 2. See Supplementary Information for data sources. Individual volcanoes are represented by the average of the analyses of shield lavas (thermal ionization triple-spike or multicollector inductively coupled plasma mass spectrometry data), with the two standard deviation on the mean used to indicate the variation around the average. Shaded fields indicate the total range of variation covered for each volcano.

plume material rising across this phase transition to slow down and the conduit to spread out to conserve mass. Ponding in the transition zone is, however, not consistent with body-wave studies based on an extensive regional network of ocean bottom seismometers network which identified a deep-seated low-velocity anomaly under Hawai'i and a deep source for the Hawaiian mantle plume<sup>22,69,78</sup>.

The crucial issue for the link between the Loa and Kea basalt compositions and their source regions is whether this spreading would introduce motions that stir the heterogeneities carrying the trends together or cause significant entrainment of ambient mantle material that would ultimately overwhelm the signal from the deep mantle source. Whereas the effects of phase transitions on the rise of starting plume head, and thus the composition of flood basalts, have received significant attention<sup>79,80</sup>, the effect on plume tails is less certain. However, the spreading of the conduit as a gravity current involves only an additional component of pure shear<sup>81</sup> that will widen the Loa and Kea anomalies, but will not cause them to mix.

Finally, it is still unclear at this stage if the partial ponding of plume material modelled in the transition zone 1,000 km west of Hawai'i<sup>75</sup> is indeed linked to the Hawaiian mantle plume, and, if so, what the physical link is with the volcanic activity observed on the Hawaiian Islands. Indeed, it would imply a transfer of material in the opposite direction to the mantle wind in the Pacific<sup>82</sup> (in the direction of the Pacific plate motion, towards the northwest) for over 80 Myr.

### Loa component and fine-scale structure of LLSVP

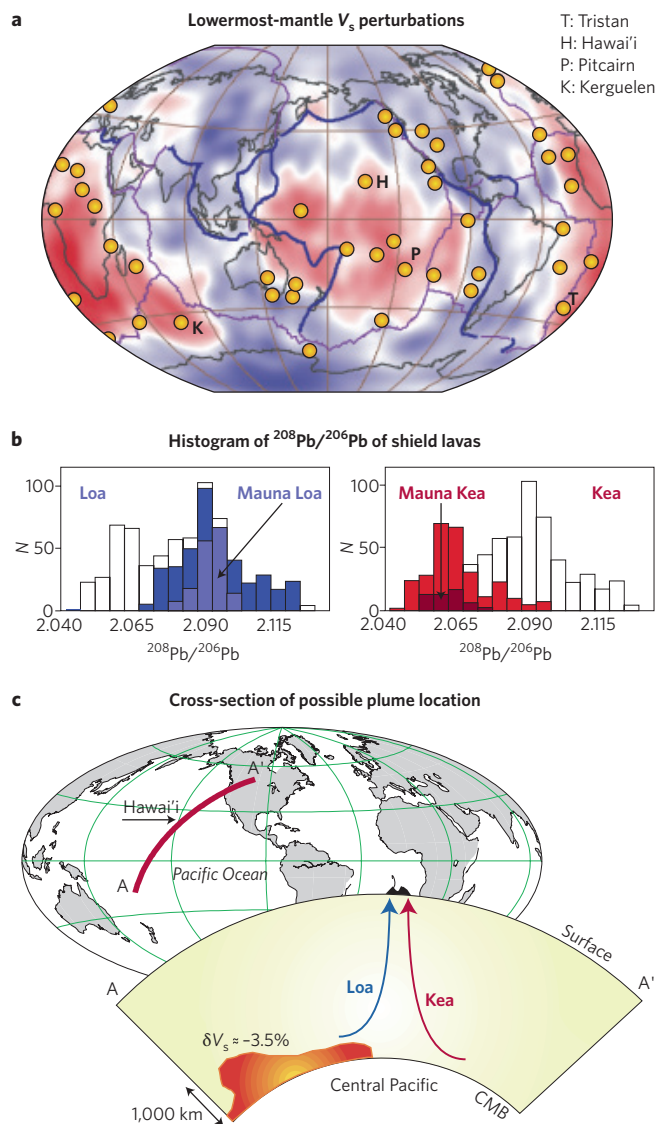
The greater isotopic and geochemical variability of the Loa volcanoes is a remarkable feature that, in principle, requires that the source of the Loa side of the plume is compositionally heterogeneous over many length scales, consistent with recent seismological studies<sup>63,83,84</sup>. A plausible source for some of this additional heterogeneity is a thin (5–50 km) ultra-low-seismic-velocity zone (ULVZ) lens, where P- and S-wave velocities are reduced by up to 10% and 30%, respectively<sup>60,85</sup>, concentrated near the edge of the LLSVP pile<sup>66,85,86</sup> beneath the Loa side of Hawai'i. These structures have recently been modelled as regions of dense<sup>87,88</sup> partial melt, presumably enriched in incompatible elements, which is variably stirred, depending on the competition between compaction and melt drainage and melt retention as a result of coupling to overlying mantle flow<sup>87,89</sup>.

Our model assumes that the Loa- and Kea-trend compositions and the heterogeneity spectrum for Hawaiian basalts are preserved through the melt extraction process. We assume that there is negligible mechanical mixing of melts between the melting region and the surface. In Iceland, where the mantle plume coincides with the Mid-Atlantic Ridge, mixing has been proposed to explain the spectrum of Pb isotope variability in olivine-hosted melt inclusions, at the 100- to 500- $\mu\text{m}$  scale<sup>90</sup>. The existence of individual Pb–Pb arrays for each Hawaiian volcano indicates that mixing occurs at the scale of the plume conduit, 10–50 km (refs 34, 45). Most recent melt extraction models<sup>91</sup> suggest that compaction draws melts together over length scales of at most a few kilometres or a few per cent of the width of the melting region<sup>29</sup>. Thus, whereas this effect may smooth out the spatial variability within each trend as it is expressed at the surface, it is unlikely to affect the qualitative differences between the Loa and Kea endmembers as reflected by the existence of the two parallel chains of volcanoes with distinct geochemical signatures for at least 5 Myr.

### Comparisons with other ocean islands

The geochemistry of the Loa-trend volcanoes (higher Th/U, as indicated by their higher  $^{208}\text{Pb}^*/^{206}\text{Pb}^*$ , lower  $\epsilon_{\text{Nd}}$  and higher  $^{87}\text{Sr}/^{86}\text{Sr}$  compared with Kea-trend volcanoes) indicates the presence of an enriched component, most prevalent in Lāna'i and Kō'olau volcanoes<sup>27,48</sup>. These geochemical characteristics require a source more enriched in incompatible elements for Loa-trend volcanoes than for those on the Kea trend, and these features could correspond to the ULVZ, which is chemically distinct and probably partially molten<sup>85,92</sup>.

There continues to be debate about the shape, origin and composition of the LLSVP and ULVZ<sup>60,66</sup>, as well as on the role of core–mantle interaction<sup>93</sup> in the generation of heterogeneities in the Earth's mantle. Several authors argue for contribution from the core, on the basis of coupled enrichments in  $^{186}\text{Os}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$  in plume-derived materials when compared with upper-mantle materials<sup>93</sup>. Assessing the geometry, physical structure and extent of ULVZ is still a challenge because of poor tomographic resolution at the CMB and the basic trade-off between velocity reduction and spatial size in forward models relying on seismic ray theory<sup>66</sup>. Materials that could be present in the lowermost mantle include partially molten residues of early Earth differentiation (4.5 billion years ago), subducted



**Figure 5 | Deep mantle velocity anomalies and hotspot locations.** **a**, Global map showing the lowermost-mantle  $V_s$  perturbations from tomographic model TXBW<sup>105</sup> (adapted from ref. 66). Continents, thin black outline; Pacific 'Ring of Fire', thick blue line; circles, hotspot locations<sup>106</sup>. Red and blue colours indicate lower and higher velocities than global average, respectively. The peak-to-peak value for this model is 5.5. Hawai'i and Pitcairn (Pacific Ocean), Kerguelen (Indian Ocean) and Tristan (Atlantic Ocean) have EM-I-type geochemical signatures. **b**, Histogram of  $^{208}\text{Pb}/^{206}\text{Pb}$  (used to minimize analytical noise on  $^{204}\text{Pb}$ ) for Hawaiian shield lavas. **c**, Cross-section through the Hawaiian mantle plume down to the CMB, showing a schematic representation of the low-velocity structures beneath the central Pacific (after ref. 107, modified after ref. 66). Hawaiian Island surface locations and relative position of the Loa and Kea trends in the mantle plume are indicated.

slabs (heterogeneous mixture of sediments, altered oceanic crust and upper mantle), and metal from the outer core (see discussion in ref. 7)<sup>11,12,18,19,83</sup>. Recent  $^{142}\text{Nd}/^{144}\text{Nd}$  studies of deeply sourced mantle plumes, including Hawai'i, present no evidence for the interaction with an early-enriched reservoir (EER) in the source of these basalts<sup>94</sup>.

Loa-trend geochemical characteristics have persisted for at least ~5 million years<sup>54,59</sup>. This period had the highest magma production rate for the Hawaiian mantle plume (Fig. 1a, inset)<sup>95</sup>. The overall

variability among the Loa volcanoes is time-dependent and seems to be larger in the older volcanoes (West Ka'ena, Kō'olau) than in recent ones (Lō'ihi) (Fig. 4a and b). The appearance of the Loa component is probably related to the sampling of the relatively dense, partially melted material in the anomalous velocity lenses at the CMB by the Hawaiian mantle plume and could coincide with elevated magma production rates<sup>48</sup>.

Other surface hotspot locations can be correlated with lateral shear-wave (S-wave) velocity gradients in the deep mantle<sup>61,96</sup>. Kerguelen, another EM-I oceanic island with a strong enriched signature (Fig. 1b) in the Indian Ocean<sup>97</sup>, is located on the eastern end of the tall steep-sided LLSVP African anomaly<sup>98</sup> (Fig. 5a). Tristan and Pitcairn are two other islands with EM-I signature (Fig. 1b)<sup>18</sup>. When projected onto the CMB, Tristan is located on the western border of the LLSVP African anomaly, whereas Pitcairn straddles a boundary zone in the Pacific LLSVP. We infer that these deep velocity anomalies at the CMB are the repositories for enriched components in the mantle and are brought to the surface by strong mantle plumes. Above the Pacific LLSVP, Pitcairn and Hawai'i carry an enriched signature that is slightly less pronounced and distinct from the one carried by Kerguelen and Tristan, the 'DUPAL anomaly'<sup>99,100</sup>, above the African LLSVP (Fig. 1b). These differences in EM-I compositions correspond to differences in the sources of these islands and indicate that the material constituting the LLSVP at the base of the CMB is different in the Pacific and African anomalies.

### Longevity of Loa component and Pacific LLSVP

To explore more fully the implications of our proposal that the Hawaiian mantle plume provides a long-lived probe of the composition and structure of its CMB source region, and that the LLSVP and ULVZ are repositories of enriched mantle components related either to the early differentiation of the Earth<sup>14,15</sup> or to the presence of subducted material<sup>11,12,18</sup>, we need to go further back in time. High-precision isotopic studies of Hawai'i volcanoes have only been undertaken for lavas erupted during the last 5 Myr and for the Emperor Seamounts (85–42 Myr ago). Thus, our study of the Hawai'i volcanoes provides only a recent snapshot of the situation. There seem to be distinct differences between the Emperor (85 to 42 Myr ago) and Hawaiian (41 Myr ago to present) parts of the Hawaiian–Emperor Chain. In particular, Emperor-chain basalts have Kea-only compositions and were erupted at an approximately constant rate<sup>48,95,101</sup>. In contrast the 5-million-year record of volcanism at Hawai'i is characterized by this remarkable Kea–Loa compositional asymmetry and a magma production rate that has increased greatly over time (Fig. 1a, inset)<sup>95</sup>.

The appearance of the Loa composition may coincide with an increase in magma supply that is evident in the larger size of the Hawaiian volcanoes over the past 5 million years. Alternatively, Loa composition may extend back to the prominent bend in the Hawaiian–Emperor Chain. This dichotomy in isotopic composition and increase in eruption rate could ultimately be linked to changes in the thickness, thermal structure<sup>23</sup> and dynamics of the LLSVP part of the plume source region in the deep mantle.

In principle, the Hawaiian–Emperor hotspot track in the Pacific Ocean with 85 million years of activity (and the Kerguelen hotspot track in the Indian Ocean with an even longer 115 million years of activity) can provide unique insights into our proposed relationship between basalt composition and deep mantle structure. To fingerprint the changes in the source composition over the eruption time series recorded by the Hawaiian chain and to assess when the Loa component appeared will require additional high-precision isotopic work on the remaining 3,400 km of the chain to the northwest of the island of Kaua'i. The timing of the segregation of the LLSVP in the lower mantle and the conditions of its sampling by the Hawaiian mantle plume are two issues that cannot yet be solved. Additional

complementary high-resolution seismological studies of this part of the CMB region will be crucial to make links between the evolving composition of the source region and its structure and constitution. Resolving these fundamental issues will require increased collaboration among disciplines studying the Earth's deep interior.

## References

- Davies, G. F. Role of the lithosphere in mantle convection. *J. Geophys. Res.* **93**, 10451–10466 (1988).
- Sleep, N. Hotspots and mantle plumes: Some phenomenology. *J. Geophys. Res.* **95**, 6715–6736 (1990).
- Richards, M. A., Duncan, R. A. & Courtillot, V. E. Flood basalts and hot-spot tracks: Plume heads and tails. *Science* **246**, 103–107 (1989).
- Montelli, R., Nolet, G., Dahlen, F. A. & Masters, G. A catalogue of deep mantle plumes: New results from finite-frequency tomography. *Geochem. Geophys. Geosyst.* **7**, Q11007 (2006).
- Morgan, W. J. Convection plumes in the lower mantle. *Nature* **230**, 42–43 (1971).
- Jellinek, A. & Manga, M. Links between long-lived hot spots, mantle plumes, D<sup>+</sup> and plate tectonics. *Rev. Geophys.* **42**, RG3002 (2004).
- DePaolo, D. J. & Weis, D. in *Continental Scientific Drilling: A Decade of Progress, and Challenges for the Future* (eds Harms, U., Koeberl, C. & Zöback, M. D.), Springer, pp. 259–288 (2007).
- Tatsumoto, M. Isotopic composition of lead in oceanic basalt and its implication to mantle evolution. *Earth Planet. Sci. Lett.* **38**, 63–87 (1978).
- Zindler, A. & Hart, S. Chemical geodynamics. *Annu. Rev. Earth Planet. Sci.* **14**, 493–571 (1986).
- Sun, S. & McDonough, W. Chemical and isotopic systematics of oceanic basalts: Implications for mantle composition and processes, in *Magmatism in the Ocean Basins* (eds Saunders, A. D. & Norry, M. J.) *Geol. Soc. London Spec. Publ.* **42**, 313–345 (1989).
- Hofmann, A. W. in *The Mantle and the Core* (ed. Carlson, R. W.), *Treatise of Geochemistry* Vol. 2 (eds Holland H. D. & Turekian K. K.), 61–101 (Elsevier–Pergamon, 2003).
- White, W. Oceanic island basalts and mantle plumes: the geochemical perspective. *Annu. Rev. Earth Planet. Sci.* **38**, 133–160 (2010).
- White, W. M. Sources of oceanic basalts — radiogenic isotopic evidence. *Geology* **13**, 115–118 (1985).
- Labrosse, S., Hernlund, J. W. & Coltice, N. A crystallizing dense magma ocean at the base of the Earth's mantle. *Nature* **450**, 866–869 (2007).
- Carlson, R. W., Boyet, M. Composition of the Earth's interior: the importance of early events. *Phil. Trans. R. Soc. A* **366**, 4077–4103 (2008).
- van Keken, P., Hauri, E. H. & Ballentine, C. J. Mantle mixing: The generation, preservation, and destruction of chemical heterogeneity. *Annu. Rev. Earth Planet. Sci.* **30**, 493–525 (2002).
- Albarède, F. & van der Hilst, R. Zoned mantle convection. *Phil. Trans. R. Soc. A* **360**, 2569–2592 (2002).
- Willbold, M. & Stracke, A. Trace element composition of mantle end-members: Implications for recycling of oceanic and upper and lower continental crust. *Geochem. Geophys. Geosyst.* **7**, Q04004 (2006).
- Willbold, M. & Stracke, A. Formation of enriched mantle components by recycling of upper and lower continental crust. *Chem. Geol.* **276**, 188–197 (2010).
- Wilson, J. T. Evidence from islands on the spreading of the ocean floor. *Can. J. Phys.* **41**, 863–868 (1963).
- Ribe, N. & Christensen, U. The dynamical origin of Hawaiian volcanism. *Earth Planet. Sci. Lett.* **171**, 517–531 (1999).
- Wolfe, C. J. *et al.* Mantle shear-wave velocity structure beneath the Hawaiian hot spot. *Science* **326**, 1388–1390 (2009).
- Lenardic, A. & Jellinek, A. M. Tails of two plume types in one mantle. *Geology* **37**, 127–130 (2009).
- Richards, M. A. & Griffiths, R. W. Deflection of plumes by mantle shear flow: experimental results and a simple theory. *Geophys. J.* **94**, 367–376 (1988).
- DePaolo, D. J., Bryce, J., Dodson, A., Shuster, D. & Kennedy, B. Isotopic evolution of Mauna Loa and the chemical structure of the Hawaiian plume. *Geochem. Geophys. Geosyst.* **2**, 1044 (2001).
- Kerr, R. & Mériaux, C. Structure and dynamics of sheared mantle plumes. *Geochem. Geophys. Geosyst.* **5**, Q12009 (2004).
- Abouchami, W. *et al.* Lead isotopes reveal bilateral asymmetry and vertical continuity in the Hawaiian mantle plume. *Nature* **434**, 851–856 (2005).
- Ren, Z., Ingle, S., Takahashi, E., Hirano, N. & Hirata, T. The chemical structure of the Hawaiian mantle plume. *Nature* **436**, 837–840 (2005).
- Farnetani, C. G. & Hofmann, A. W. Dynamics and internal structure of the Hawaiian plume. *Earth Planet. Sci. Lett.* **295**, 231–240 (2010).
- Sharp, W. & Renne, P. The <sup>40</sup>Ar/<sup>39</sup>Ar dating of core recovered by the Hawaii Scientific Drilling Project (phase 2), Hilo, Hawaii. *Geochem. Geophys. Geosyst.* **6**, Q04G17 (2005).
- Stolper, E. M., DePaolo, D. J. & Thomas, D. M. Deep drilling into a mantle plume volcano: the Hawaii Scientific Drilling Project. *Scient. Drilling* **7**, 4–14 (2009).
- Clague, D. A., Dalrymple, G. B. The Hawaiian–Emperor volcanic chain Part 1. Geologic evolution. *USGS Prof. Pap.* **1350**, 5–54 (1987).
- Garcia, M. O., Caplan-Auerbach, J., De Carlo, E. H., Kurz, M. D. & Becker, N., Geology, geochemistry and earthquake history of Loihi seamount, Hawaii's youngest volcano. *Chem. Erde* **66**, 81–108 (2006).
- Blichert-Toft, J., Weis, D., Maerschalk, C., Agrani, A. & Albarède, F. Hawaiian hot spot dynamics as inferred from the Hf and Pb isotope evolution of Mauna Kea volcano. *Geochem. Geophys. Geosyst.* **4**, 8704 (2003).
- Eisele, J., Abouchami, W., Galer, S. J. G. & Hofmann, A. W. The 320 kyr Pb isotope evolution of Mauna Kea lavas recorded in the HSDP-2 drill core. *Geochem. Geophys. Geosyst.* **4**, 8710 (2003).
- Kurz, M., Curtice, J., Lott, D. & Solow, A. Rapid helium isotopic variability in Mauna Kea shield lavas from the Hawaiian Scientific Drilling Project. *Geochem. Geophys. Geosyst.* **5**, Q04G14 (2004).
- Rhodes, J. M. & Vollinger, M. J. Composition of basaltic lavas sampled by phase-2 of the Hawaii Scientific Drilling Project: Geochemical stratigraphy and magma types. *Geochem. Geophys. Geosyst.* **5**, Q03G13 (2004).
- Bryce, J., DePaolo, D. J. & Lassiter, J. Geochemical structure of the Hawaiian plume: Sr, Nd, and Os isotopes in the 2.8 km HSDP-2 section of Mauna Kea volcano. *Geochem. Geophys. Geosyst.* **6**, Q09G18 (2005).
- Dana, D. J. *Geology, Report of the United States Exploring Expedition, 1838–1842*, Vol. 10 (C. Sherman, Philadelphia, 1849).
- Jackson, E. D., Shaw, H. R. & Bargar, K. E. Calculated geochronology and stress field orientations along the Hawaiian chain. *Earth Planet. Sci. Lett.* **26**, 145–155 (1975).
- Lassiter, J., DePaolo, D. J. & Tatsumoto, M. Isotopic evolution of Mauna Kea volcano: Results from the initial phase of the Hawaii Scientific Drilling Project. *J. Geophys. Res.* **101**, 11769–11780 (1996).
- Abouchami, W., Galer, S. J. G. & Hofmann, A. W. High precision lead isotope systematics of lavas from the Hawaiian Scientific Drilling Project. *Chem. Geol.* **169**, 187–209 (2000).
- Clague, D. A. Hawaiian alkaline volcanism. *Geol. Soc. London Spec. Pub.* **30**, 227–252 (1987).
- Ren, Z.-Y., Tomoyuki, S., Masako, Y., Johnson, K. M. & Takahashi, E. Isotope compositions of submarine Hana Ridge lavas, Haleakala volcano, Hawaii: Implications for source compositions melting process and the structure of the Hawaiian plume. *J. Petrol.* **47**, 255–275 (2006).
- Marske, J. P., Pietruszka, A. J., Weis, D., Garcia, M. O. & Rhodes, J. M. Rapid passage of a small-scale mantle heterogeneity through the melting regions of Kilauea and Mauna Loa Volcanoes. *Earth Planet. Sci. Lett.* **259**, 34–50 (2007).
- Hanano, D., Weis, D., Scoates, J. S., Aciego, S. & DePaolo, D. J. Horizontal and vertical zoning of heterogeneities in the Hawaiian mantle plume from the geochemistry of consecutive postshield volcano pairs: Kohala–Mahukona and Mauna Kea–Hualalai. *Geochem. Geophys. Geosyst.* **11**, Q01004 (2010).
- Xu, G. *et al.* Geochemical characteristics of West Molokai shield- and postshield-stage lavas: Constraints on Hawaiian plume models. *Geochem. Geophys. Geosyst.* **8**, Q08G21 (2007).
- Tanaka, R., Makishima, A. & Nakamura, E. Hawaiian double volcanic chain triggered by an episodic involvement of recycled material: Constraints from temporal Sr–Nd–Hf–Pb isotopic trend of the Loa-type volcanoes. *Earth Planet. Sci. Lett.* **265**, 450–465 (2008).
- Robinson, J. & Eakins, B. Calculated volumes of individual shield volcanoes at the young end of the Hawaiian Ridge. *J. Volcanol. Geotherm. Res.* **151**, 309–317 (2006).
- Garcia, M. O., Hulsebosch, T. P. & Rhodes, J. M. in *Mauna Loa Revealed: Structure, Composition, History, and Hazards* (eds Rhodes, J. M. & Lockwood, J. P.), *Geophys. Monogr. Ser.* **92**. American Geophysical Union, Washington, DC, pp. 219–239 (1995).
- Jicha, B., Rhodes, J. M., Singer, B. S., Vollinger, M. J., Garcia, M. O. <sup>40</sup>Ar/<sup>39</sup>Ar geochronology of submarine Mauna Loa volcano, Hawaii. American Geophysical Union, Fall Meeting, abstract #V43F-2328 (2009).
- Wanless, V. D. *et al.* Submarine radial vents on Mauna Loa Volcano, Hawaii. *Geochem. Geophys. Geosyst.* **7**, Q05001 (2006).
- Rhodes, J. M. & Hart, S. R. in *Mauna Loa Revealed: Structure, Composition, History, and Hazards* (eds Rhodes, J. M. & Lockwood, J. P.), *Geophys. Monogr. Ser.* **92**. 263–288 (American Geophysical Union, 1995).
- Greene, A. R. *et al.* Low-productivity Hawaiian volcanism between Kauai and Oahu. *Geochem. Geophys. Geosyst.* **11**, Q0AC08 (2010).
- Kimura, J., Sisson, T., Nakano, N., Coombs, M. & Lipman, P. Isotope geochemistry of early Kilauea magmas from the submarine Hilina bench: The nature of the Hilina mantle component. *J. Volcanol. Geotherm. Res.* **151**, 51–72 (2006).
- Chen, C., Frey, F. A., Garcia, M. O., Dalrymple, G. & Hart, S. R. The tholeiite to alkalic basalt transition at Haleakala Volcano, Maui, Hawaii. *Contrib. Mineral. Petrol.* **106**, 183–200 (1991).
- Gaffney, A., Nelson, B. & Blichert-Toft, J. Geochemical constraints on the role of oceanic lithosphere in intra-volcano heterogeneity at West Maui, Hawaii. *J. Petrol.* **45**, 1663–1687 (2004).
- Blichert-Toft, J., Frey, F. A. & Albarède, F. Hf isotope evidence for pelagic sediments in the source of Hawaiian basalts. *Science* **285**, 879–882 (1999).

59. Garcia, M. O. *et al.* Petrology, geochemistry and geochronology of Kaua'i lavas over 4.5 Myr: implications for the origin of rejuvenated volcanism and the evolution of the Hawaiian plume. *J. Petrol.* **51**, 1507–1540 (2010).
60. Garnero, E. J. & McNamara, A. Structure and dynamics of Earth's lower mantle. *Science* **320**, 626–628 (2008).
61. Thorne, M., Grand, S. & Garnero, E. Geographic correlation between hot spots and deep mantle lateral shear-wave velocity gradients. *Phys. Earth Planet. Inter.* **176**, 47–63 (2004).
62. Burke, K., Steinberger, B., Torsvik, T. H. & Smethurst, M. A. Plume generation zones at the margins of large low shear velocity provinces on the core–mantle boundary. *Earth Planet. Sci. Lett.* **265**, 49–60 (2008).
63. Ritsema, J., van Heijst, H. & Woodhouse, J. Complex shear wave velocity structure imaged beneath Africa and Iceland. *Science* **286**, 1925–1928 (1999).
64. Mégnin, C. & Romanowicz, B. The shear velocity structure of the mantle from the inversion of body, surface, and higher modes waveforms. *Geophys. J. Int.* **143**, 709–728 (2000).
65. To, A., Fukao, Y. & Tsuboi, S. Evidence for a thick and localized ultra low shear velocity zone at the base of the mantle beneath the central Pacific. *Phys. Earth Planet. Inter.* **184**, 119–133 (2011).
66. Garnero, E. Heterogeneity of the lowermost mantle. *Annu. Rev. Earth Planet. Sci.* **28**, 509–537 (2000).
67. Ishii, M. & Tromp, J. Normal-mode and free-air gravity constraints on lateral variations in velocity and density of Earth's mantle. *Science* **285**, 1231–1236 (1999).
68. Tarduno, J. *et al.* The Emperor Seamounts: Southward motion of the Hawaiian hotspot plume in Earth's mantle. *Science* **301**, 1064–1069 (2003).
69. Wolfe, C. J. *et al.* Mantle P-wave velocity structure beneath the Hawaiian hotspot. *Earth Planet. Sci. Lett.* **303**, 267–280 (2011).
70. Richards, M. A. & Griffiths, R. W. Thermal entrainment by deflected mantle plumes. *Nature* **342**, 900–902 (1989).
71. Kerr, R. C. & Lister, J. R. Rise and deflection of mantle plume tails. *Geochem. Geophys. Geosyst.* **9**, Q10004 (2008).
72. Blichert-Toft, J. & Albarède, F. Mixing of isotopic heterogeneities in the Mauna Kea plume conduit. *Earth Planet. Sci. Lett.* **282**, 190–200 (2009).
73. Blake, S. & Campbell, I. The dynamics of magma-mixing during flow in volcanic conduits. *Contrib. Mineral. Petrol.* **94**, 72–81 (1986).
74. Lister, J. Long-wavelength instability of a line plume. *J. Fluid Mechanics* **175**, 413–428 (1987).
75. Cao, Q., der Hilst, van, R., de Hoop, M. & Shim, S. Seismic imaging of transition zone discontinuities suggests hot mantle west of Hawaii. *Science* **332**, 1068–1071 (2011).
76. Olson, P. & Yuen, D. A. Thermochemical plumes and mantle phase transitions. *J. Geophys. Res.* **87**, 3993–4002 (1982).
77. Hirose, K. Phase transitions in pyrolytic mantle around 670-km depth: Implications for upwelling of plumes from the lower mantle. *J. Geophys. Res.* **107**, B42078 (2002).
78. Boschi, L., Becker, T. & Steinberger, B. Mantle plumes: Dynamic models and seismic images. *Geochem. Geophys. Geosyst.* **8**, Q10006 (2007).
79. Bercovici, D. & Mahoney, J. Double flood basalts and plume head separation at the 660 kilometer discontinuity. *Science* **266**, 1367–1369 (1994).
80. Kumagai, I. & Kurita, K. On the fate of mantle plumes at density interfaces. *Earth Planet. Sci. Lett.* **179**, 63–71 (2000).
81. Lister, J. & Kerr, R. C. The propagation of two-dimensional and axisymmetric viscous gravity currents at a fluid interface. *J. Fluid Mechanics* **203**, 215–249 (1989).
82. Steinberger, B., Sutherland, R. & O'Connell, R. J. Prediction of Emperor–Hawaii seamount locations from a revised model of global plate motion and mantle flow. *Nature* **430**, 167–173 (2004).
83. Garnero, E., Lay, T. & McNamara, A. In *Plates, Plumes, and Planetary Processes* (eds Foulger, G. R. & Jurdy, D. M.), *Geol. Soc. Am. Spec. Paper* **430**, 79–101 (2007).
84. Idehara, K. Structural heterogeneity of an ultra-low-velocity zone beneath the Philippine Islands: Implications for core–mantle chemical interactions induced by massive partial melting at the bottom of the mantle. *Phys. Earth Planet. Inter.* **184**, 80–90 (2011).
85. McNamara, A., Garnero, E. & Rost, S. Tracking deep mantle reservoirs with ultra-low velocity zones. *Earth Planet. Sci. Lett.* **299**, 1–9 (2010).
86. Williams, Q., Revenaugh, J. & Garnero, E. A correlation between ultra-low basal velocities in the mantle and hot spots. *Science* **281**, 546–549 (1998).
87. Rost, S., Garnero, E., Williams, Q. & Manga, M. Seismological constraints on a possible plume root at the core–mantle boundary. *Nature* **435**, 666–669 (2005).
88. Nomura, R. *et al.* Spin crossover and iron-rich silicate melt in the Earth's deep mantle. *Nature* **473**, 199–202 (2011).
89. Hernlund, J. W. & Jellinek, A. M. Dynamics and structure of a stirred partially molten ultralow-velocity zone. *Earth Planet. Sci. Lett.* **296**, 1–8 (2010).
90. MacLennan, J. Lead isotope variability in olivine-hosted melt inclusions from Iceland. *Geochim. Cosmochim. Acta* **72**, 4159–4176 (2008).
91. Hewitt, I. J. Modelling melting rates in upwelling mantle. *Earth Planet. Sci. Lett.* **300**, 264–274 (2010).
92. Williams, Q. & Garnero, E. J. Seismic evidence for partial melt at the base of the mantle. *Science* **273**, 1528–1530 (1996).
93. Brandon, A. D. & Walker, R. J. The debate over core–mantle interaction. *Earth Planet. Sci. Lett.* **232**, 211–225 (2005).
94. Murphy, D. T., Brandon, A. D., Debaille, V., Burgess, R. & Ballentine, C. J. In search of a hidden long-term isolated sub-chondritic <sup>142</sup>Nd/<sup>144</sup>Nd reservoir in the deep mantle: Implications for the Nd isotope systematics of the Earth. *Geochim. Cosmochim. Acta* **74**, 738–750 (2010).
95. Vidal, V. & Bonneville, A. Variations of the Hawaiian hot spot activity revealed by variations in the magma production rate. *J. Geophys. Res.* **109**, B03104 (2004).
96. Huang, S., Hall, P. S. & Jackson, M. G. Geochemical zoning of volcanic chains associated with Pacific hotspots. *Nature Geosci.* <http://dx.doi.org/10.1038/ngeo1263> (2011).
97. Weis, D., Bassias, Y., Gautier, I. & Mennessier, J. Dupal anomaly in existence 115 Ma ago — evidence from isotopic study of the Kerguelen Plateau (South Indian Ocean). *Geochim. Cosmochim. Acta* **53**, 2125–2131 (1989).
98. Ni, S., Tan, E., Gurnis, M. & Helmberger, D. V. Sharp sides to the African super plume. *Science* **296**, 1850–1852 (2002).
99. Hart, S. R. A large-scale isotope anomaly in the Southern Hemisphere mantle. *Nature* **309**, 753–757 (1984).
100. Wen, L. A compositional anomaly at the Earth's core–mantle boundary as an anchor to the relatively slowly moving surface hotspots and as source to the DUPAL anomaly. *Earth Planet. Sci. Lett.* **246**, 138–148 (2006).
101. Regelous, M., Hofmann, A. W., Abouchami, W. & Galer, S. J. G. Geochemistry of lavas from the Emperor Seamounts, and the geochemical evolution of Hawaiian magmatism from 85 to 42 Ma. *J. Petrol.* **44**, 113–140 (2003).
102. US Geological Survey. Bathymetric map of the Hawaiian Islands (2003), available at <http://geopubs.wr.usgs.gov/i-map/12809>.
103. Geochemistry of Rocks of the Oceans and Continents (GEOROC) database, available at <http://georoc.mpch-mainz.gwdg.de/georoc/>.
104. Trusdell, F. A. & Lockwood, J. P. Geologic Maps of the Northeast Flank of, Central-Southeast Flank of, Southern Mauna Loa Volcano, Island of Hawai'i, Hawai'i: US Geological Survey SIM 2932-A, SIM 2932-B, SIM 2932-C respectively, scale 1:50,000 (in the press).
105. Grand, S. P. Mantle shear-wave tomography and the fate of subducted slabs. *Phil. Trans. R. Soc. A* **360**, 2475–2491 (2002).
106. Steinberger, B. Plumes in a convecting mantle: Models and observations for individual hotspots. *J. Geophys. Res.* **105**, 11127–11152 (2000).
107. Bréger, L. & Romanowicz, B. Three-dimensional structure at the base of the mantle beneath the central Pacific. *Science* **282**, 718–720 (1998).

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### Author contributions

D.W. acquired the data, compiled the literature data, conceived the idea for the paper and developed the conceptual model with A.M.J. D.W. wrote the paper, together with A.M.J. and J.S.S. All authors discussed the results and the model, and contributed to the manuscript. M.O.G. and J.M.R. also wrote the proposals, led the expeditions and organized the sampling on Hawai'i and shared their knowledge and data on these islands.

### Additional Information

The authors declare no competing financial interests. Supplementary Information accompanies this paper on [www.nature.com/naturegeoscience](http://www.nature.com/naturegeoscience).