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Limited latitudinal mantle plume motion for the Louisville hotspot

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Hotspots that form above upwelling plumes of hot material from the deep mantle typically leave narrow trails of volcanic seamounts as a tectonic plate moves over their location. These seamount trails are excellent recorders of Earth's deep processes and allow us to untangle ancient mantle plume motions. During ascent it is likely that mantle plumes are pushed away from their vertical upwelling trajectories by mantle convection forces. It has been proposed that a large-scale lateral displacement, termed the mantle wind, existed in the Pacific between about 80 and 50 million years ago, and shifted the Hawaiian mantle plume southwards by about 15° of latitude. Here we use ^{40}Ar/^{39}Ar age dating and palaeomagnetic inclination data from four seamounts associated with the Louisville hotspot in the South Pacific Ocean to show that this hotspot has been relatively stable in terms of its location. Specifically, the Louisville hotspot—the southern hemisphere counterpart of Hawai'i—has remained within 3–5° of its present-day latitude of about 51° S between 70 and 50 million years ago. Although we cannot exclude a more significant southward motion before that time, we suggest that the Louisville and Hawaiian hotspots are moving independently, and not as part of a large-scale mantle wind in the Pacific.

Our understanding of the Earth's convectional processes is limited to mantle tomography, seismology, numerical modelling of mantle flow and the study of hotspot trails. Lavas sampled from the volcanic islands and seamounts in hotspot trails are the only tangible products of mantle processes occurring somewhere between the upper mantle and the core–mantle boundary[1]. Such hotspot volcanoes are thought to form where mantle plumes rise up from these great depths and intersect the moving tectonic plates[2,3]. Deep-seated, stationary plumes have been traditionally used as a fixed reference frame against which past motions of tectonic plates were measured[4]. However, we now recognize that the Hawaiian plume shifted approximately 15° south between about 80 and 50 Myr ago[5], which represents a plume motion up to half the speed of plate motion. This southward shift could be the result of a pronounced mantle wind at mid-mantle depths[5] or the temporary capture of this plume by a mid-ocean spreading centre[6]. A major outstanding question is whether other hotspots in the Pacific experienced similar large amounts of plume motion.

If all Pacific mantle plumes exhibit motions similar to that of the Hawaiian plume, hotspots might still provide a valuable reference frame against which plate motions can be measured. However, if each hotspot is characterized by its own amount and a unique direction of mantle plume motion, inter-hotspot motion between individual mantle plumes could be substantial and it would be more likely that mantle plume motions are regionally controlled, for example, by different configurations of large-scale deep mantle upwellings and downwellings. In the last scenario, understanding the motion of each individual hotspot would be required to keep the deep Earth hotspot reference frame viable.

Here we report new ^{40}Ar/^{39}Ar ages and palaeomagnetic data from four Louisville seamounts in the South Pacific drilled during Integrated Ocean Drilling Project (IODP) Expedition 330 (ref. 7). Here we show that Rigil Guyot (70 Myr old) yields an average palaeolatitude of 47.0° S (+10.5°/ − 5.6° at the 95% confidence level, $n = 28$) that is compatible with the present-day location of the Louisville hotspot at ∼51° S. Palaeolatitude estimates for Burton (64 Myr old) and Hadar Guyot (50 Myr old) also are statistically indistinguishable from 51° S but these youngest two guyots are unlikely to have adequately sampled secular palaeomagnetic variation. Canopus Guyot, an older 74-Myr-old seamount, has a lower palaeolatitude around 43.9° S ($n = 9$) and may hint at the possibility of an earlier episode of southward plume motion. Whereas the shallower inclinations from the oldest seamount allow significant plume motion, our results from particularly Rigil Guyot, with the deepest 522 m basement penetration at Site U1374, are indicative of a limited 3–5° latitudinal mantle plume motion since 70 Myr ago. This is in sharp contrast to the ∼10° southern shift for Hawai'i[5] during the same time period and provides strong evidence for independent mantle plume motions.

Age progression between 80 and 50 Myr ago

IODP Expedition 330 sampled volcanic basement at five drill sites on four guyots along the old end of the 4,300-km-long Louisville seamount trail (Fig. 1). The primary objective of this expedition was to determine whether the Hawaiian and Louisville hotspots moved coherently over geological time[8,9] or whether these hotspots show significant inter-hotspot motions as predicted by mantle flow model calculations[10–13]. Although the flat guyot tops indicate that these volcanoes formerly had subaerial summits, most recovered material represents (shallow) submarine volcanism during the main constructional phase of each volcano[7]. Volcanic basement at these sites comprises a range of volcanic and volcaniclastic materials, including massive lava flows, peperites, pillow lavas, small lava pods, subvertical dike intrusions, and predominantly hyaloclastite and volcaniclastic deposits.

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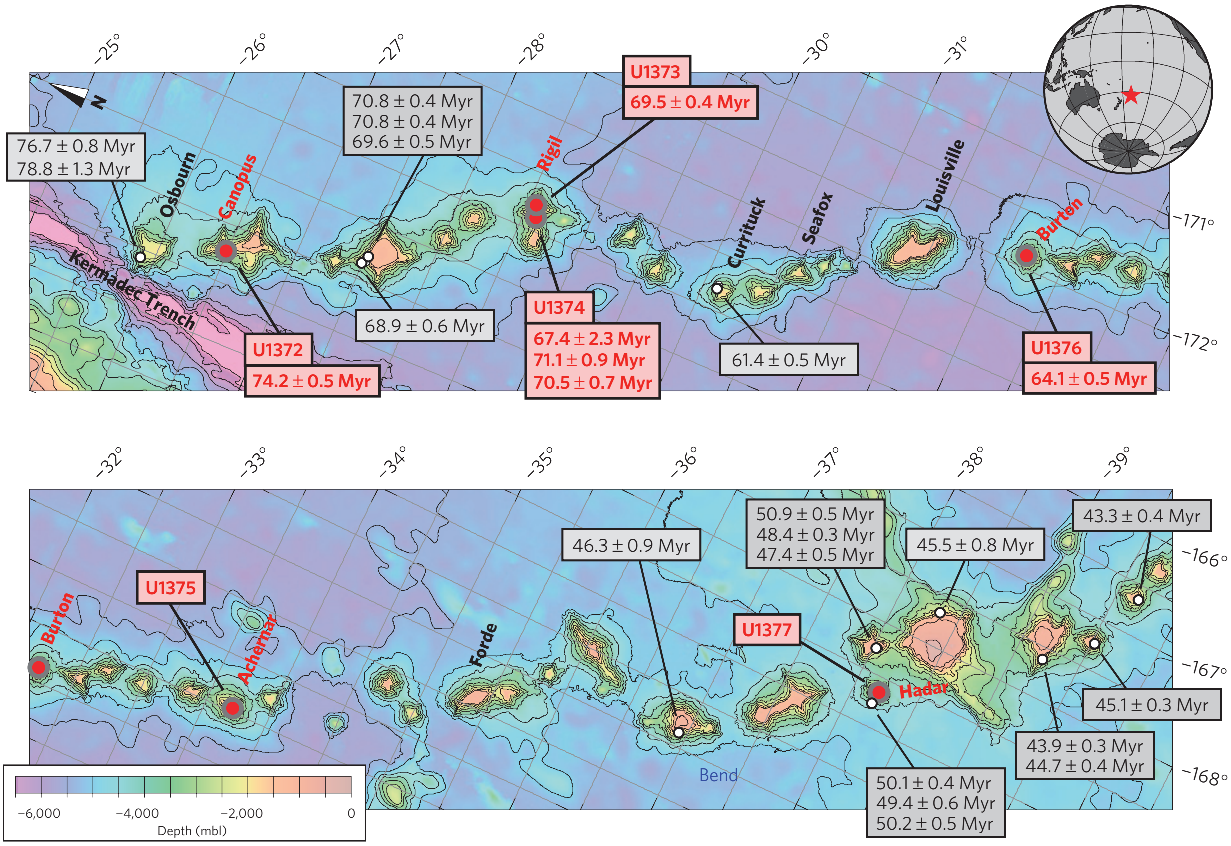

Figure 1 | Louisville seamount trail location maps with IODP Expedition 330 drill sites and new $^{40}Ar/^{39}Ar$ ages. These oblique Mercator bathymetric maps combine SIMRAD EM120 multibeam data collected during the AMAT02 site survey expedition onboard the R/V *Roger Revelle* with the global predicted bathymetry (v8.2) from ref. 26. Measured $^{40}Ar/^{39}Ar$ ages (2σ uncertainties) are from this study (red font) and previous work[11,14] (white circles and black font). Contours are plotted every 500 m. IODP Expedition 330 drill sites are indicated by red circles.

Six new $^{40}Ar/^{39}Ar$ incremental heating ages (Fig. 1) were measured on basaltic groundmass samples, and in one case on a mineral separate of plagioclase, from the deepest *in situ* volcanic units at four drill sites. All analyses (see Supplementary Information) confirm the general age-progressive trend along the Louisville seamount trail as established in previous studies[11,14,15] (Fig. 2). Site U1372 on Canopus Guyot is the oldest seamount drilled during IODP Expedition 330 and has an age of 74.2 ± 0.5 Myr. Sites U1373 and U1374 on Rigil Guyot were drilled only ~10 km apart on top of the same seamount and have ages of respectively 69.5 ± 0.4 Myr and 70.7 ± 0.6 Myr ($n = 2$, combining the two oldest samples). Site U1376 on Burton Guyot has an age of 64.1 ± 0.5 Myr and previously dated dredge samples from Hadar Guyot[14] indicate an average age of 50.0 ± 0.3 Myr ($n = 3$) for Site U1377 (Fig. 2). The 64.1 Myr age for Burton Guyot, however, is a minimum age for the formation of this volcano as the core sample is from a dike intrusion close to the base of the drill hole.

These ages from IODP Expedition 330 are significantly older than predicted by absolute plate motion (APM) models that assume fixed hotspots (lower dashed line[4] in Fig. 2). They yield a better fit, particularly for Sites U1376 and U1377, with a suite of alternative global mantle flow models that incorporate the independent motions of four primary hotspots, including Hawai'i and Louisville in the Pacific (upper blue line[10,11] in Fig. 2). Before 45 Myr ago the predictions from this new class of APM models strongly deviate from models assuming fixed hotspots, requiring a significant amount of inter-hotspot motion between Hawai'i and Louisville at this time[14]. The minimum $^{40}Ar/^{39}Ar$ age for Site

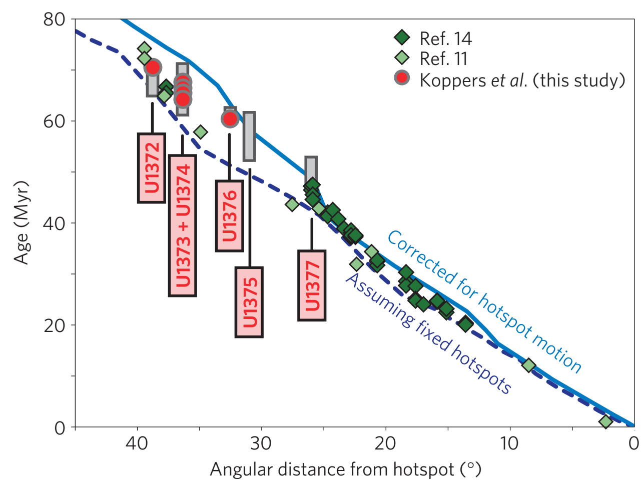

Figure 2 | Louisville seamount ages compared to Pacific Plate APM models. In this age versus distance plot, $^{40}Ar/^{39}Ar$ plateau ages (2σ uncertainties) are compared to APM models either assuming fixed hotspots (WK08G; ref. 4) or incorporating hotspot motion (S04G; refs 10,11). Distances are great circle angular distances (in degrees) with respect to present-day hotspot location at 52.4° S, 137.2° W (ref. 4) and following the seamount trail shape. Minimum palaeontological estimates for the basement ages (grey rectangles) are based on macrofossils (for example, ammonites), planktonic foraminiferas observed in consolidated volcanic breccias and condensed limestones, and calcareous nannofossils in pelagic oozes and chalk.

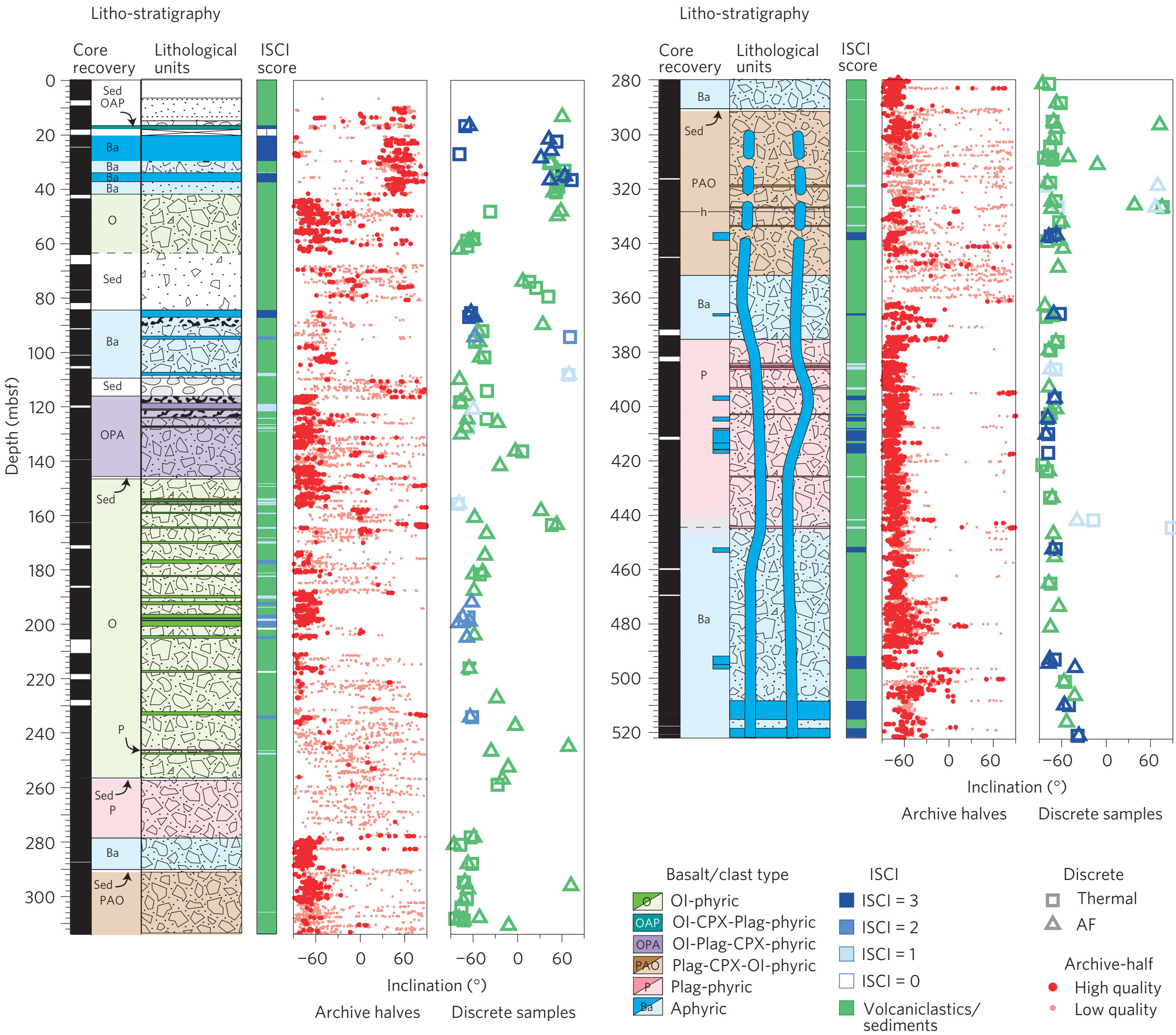

Figure 3 | Downhole stratigraphic and inclination plots for IODP Site U1374 on Rigil Guyot. The blue–green bar is colour-coded according to the *in situ* confidence index (ISCI) and shows the extent of lava flows (blue) versus volcaniclastic breccias, hyaloclastites and sediments (green). Lava flows have solid colours in the stratigraphic column whereas volcaniclastics are pastel-coloured on the basis of modal composition (see legend). Archive-half core inclinations (red circles) represent automated principal component fits every 2-cm interval, with darker points indicating lower misfits. Discrete sample inclinations were determined using thermal (squares) or AF (triangles) demagnetization, with blue and green colours corresponding to ISCI values.

U1376 of 64.1 Myr confirms the much older Louisville age (by a difference of ~12 Myr) that is predicted by these alternative models, providing key evidence for a significant amount of inter-hotspot motion between these hotspots. It also shows that using fixed-hotspot APM models to approximate Pacific Plate motions is problematic, especially before 45 Myr ago. Data from Sites U1372, U1373 and U1374 fall below the moving hotspot APM curve and therefore show that the newer models have not yet fully resolved the inter-hotspot motions. Our new $^{40}Ar/^{39}Ar$ ages support the geodynamic models[10,16] in which the Hawaiian hotspot experiences significant latitudinal drift and the Louisville hotspot relatively little. However, the protracted (>3 Myr) volcanism at some Louisville volcanoes[14] and the fact that available ages do not increase monotonically along the seamount trail (Figs 1 and 2) limit inferences about Louisville–Hawaiian inter-hotspot motion from age information alone.

Palaeolatitude history of the Louisville hotspot

Palaeomagnetic data from IODP Expedition 330 provide the most direct evidence that the Louisville hotspot experienced little latitudinal motion when the Hawaiian hotspot exhibited rapid southward drift. Stepwise demagnetization of nearly 500 discrete samples provides the most accurate inclination data, although best-fit directions determined by an automated fitting technique (see Supplementary Information) from more than 22,000 2-cm intervals on archive-half cores provide a more comprehensive record. Although directions from pass-through measurements are subject to several potential complications[17], the highest quality archive-half inclinations (representing 40% of the data) yield results generally consistent with those from discrete samples and provide data for flow units where no discrete samples are available.

Owing to the high abundance of volcaniclastic material recovered at all sites, estimating the palaeolatitude for the

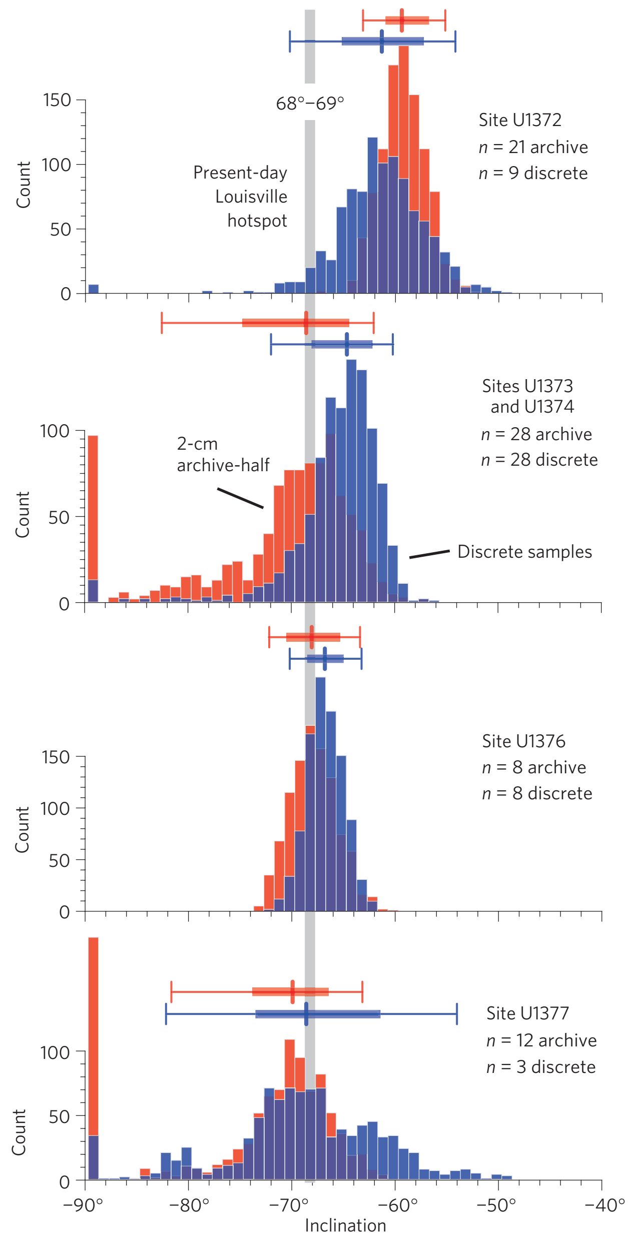

Figure 4 | Bootstrap inclination distributions for individual Louisville seamounts drilled by IODP Expedition 330. Distributions for both 2-cm archive-half (red) and discrete sample (blue) flow means are shown, each representing the bootstrap results of 1,000 resamplings with replacement and incorporating within-flow dispersions, using only units with ISCI = 3 or 2. Inclination averages and 1σ (filled rectangles) and 2σ uncertainties (lines) exclude pseudosamples where inclination-only[20] averaging failed to converge (yielding inclinations of −90° that are excluded in the uncertainties of our average palaeolatitude estimates). The vertical grey line indicates the expected geocentric axial dipole inclination for the present-day hotspot location (50.9–52.4° S; refs 4,17,21,25).

Louisville seamounts is less straightforward than for sites in the Hawaiian–Emperor seamount trail[5,18,19]. We developed an objective, although qualitative, index (the *in situ* confidence index, ISCI; see Supplementary Information) to determine whether individual units were probably *in situ*, ranging from ISCI = 3 for units that are definitely *in situ* to ISCI = 0 for those that are probably not. Volcaniclastic units were assigned an ISCI value of 'not applicable' because it is uncertain whether clasts in these volcanic sediments have retained their orientation since eruption. In this study we use results only from the most reliable lava flow units and dikes (ISCI = 3 or 2).

Results from Rigil Guyot provide the best documented inclination record, with 522 m penetration at Site U1374 and an additional 66 m drilled at Site U1373, located ~10 km to the east on the summit plain. Site U1374 has dominantly steep negative inclinations (normal polarity) with several reversed polarity flows in the uppermost 45 m and remarkably consistent inclinations in many volcaniclastic breccias, similar to that of intercalated *in situ* flows or dikes (Fig. 3). A total of 19 *in situ* flow unit means for Site U1374 were determined from discrete samples (seven additional units were not sampled at sea). After correction for deviation of the borehole from vertical (2.2° correction; see Supplementary Information) these yield a mean inclination of −68.7 ± 8.4° using inclination-only averaging[20]. An additional 9 flow units from Site U1373 give a shallower mean inclination of −55.2 ± 10.6°, similar to moderate inclinations recorded at both the top and base of U1374. As lava flows of Site U1373 erupted ~1.0 Myr later than lava flows in the deepest basement units of Site U1374, the shallower inclinations at Site U1373 are more likely to reflect palaeosecular variation rather than Pacific Plate motion or drift of the Louisville hotspot.

We have therefore combined flow units from Sites U1373 and U1374 to calculate an overall mean inclination for Rigil Guyot at ~70 Myr ago. For this and other guyots, we have treated each flow unit as independent, because we were unable to sample all *in situ* flow units at sea and the remaining unsampled units would probably affect identification of inclination groups[18]. More importantly, the presence of intercalated sediments and volcaniclastics suggests that many flow units in fact represent independent samples of the geomagnetic field. Owing to the small number of lava flows, we use a bootstrap resampling to provide the most robust estimate of the mean inclination and its uncertainty for each site (Fig. 4 and Table 1; see Supplementary Information for details). In contrast to earlier studies, we also explicitly incorporate within-flow inclination dispersion (with a median kappa of ~280 for discrete sample flow means). The resulting distributions for 2-cm archive-half measurements and discrete samples from Rigil Guyot are similar and statistically indistinguishable (at the 1σ confidence level) from the geocentric axial dipole inclination (±68°) for the present-day hotspot location at ~51° S.

The resulting palaeolatitude for Rigil Guyot is 47.0° S ± 8.0° ($n = 28$) and its distribution of mean flow inclinations is statistically similar to that expected from global geomagnetic field models at ~51° S (Fig. 5). This result alone suggests that the Louisville hotspot experienced limited latitudinal motion since 70 Myr ago. Therefore, assuming the simplest possible palaeolatitude history, it follows that the younger Louisville volcanoes are likely to have sampled the geomagnetic field at a similar latitude. Even though we sampled only a limited number of flows from the 64- and 50-Myr-old Burton and Hadar guyots, they each are statistically indistinguishable from 51° S at 49.8° S ± 4.8° ($n = 9$) and 52.3° S ± 20.2° ($n = 3$). It is unlikely that the results from either guyot adequately average palaeosecular variation, but nevertheless these results are broadly compatible with the palaeolatitude estimate of Rigil Guyot and, therefore, a limited Louisville hotspot motion, at least since 70 Myr ago.

Together, the inclinations from Sites U1373–U1377 represent a relatively large number of flows, from one dominantly normal polarity and two reversed polarity guyots, which may provide an adequate sampling of geomagnetic palaeosecular variation. To test this, we compare the directional scatter (circular standard deviation, θ_{63}) of the combined data set to two statistical models of the geomagnetic field (CJ98, TK03; refs 22,23) that were designed

Table 1 | Shipboard inclination averages for IODP Expedition 330 drill sites.

Expedition 330 Drill Sites	Average inclinations (negative degrees) 2-cm archives	1σ	2σ	n	Discrete samples	1σ	2σ	n	Palaeolatitude estimates (in ° S latitudes) 2-cm archives	1σ	2σ	n	Discrete samples	1σ	2σ	n
U1372 [N]	−59.6°	−57.3 −61.4	−55.4 −63.5	21	−61.7°	−57.9 −65.3	−54.5 −70.5	9	40.4°S	37.9 42.5	35.9 45.1	21	42.9°S	38.6 47.4	35.0 54.7	9
U1373+U1374 [N+R]	−68.9°	−64.9 −74.9	−62.2 −82.9	28	−65.0°	−62.6 −68.3	−60.4 −72.3	28	52.3°S	46.9 61.6	43.5 76.0	28	47.0°S	44.0 51.5	41.4 57.5	28
U1376 [R]	−68.3°	−65.9 −70.6	−63.6 −72.4	8	−67.1°	−65.3 −68.8	−63.6 −70.6	8	51.5°S	48.2 54.8	45.2 57.6	8	49.8°S	47.4 52.2	45.2 54.8	8
U1377 [R]	−70.2°	−66.8 −74.0	−63.6 −82.0	12	−68.9°	−61.8 −73.9	−54.3 −82.5	3	54.2°S	49.4 60.2	45.2 74.3	12	52.3°S	43.0 60.0	34.8 75.2	3

Inclination-only averages[20] are listed for discrete shipboard samples for lava flows and other volcanic cooling units ($n=48$) and for 2-cm archive-half measurements ($n=69$) for units with ISCI = 3 or 2.

to fit a global database of 0–5 Myr lava flows. The directional scatter for discrete samples ($\theta_{63} = 18.3° \pm 7.1°$) and 2-cm archive-half core measurements ($\theta_{63} = 19.2° \pm 7.5°$) estimated using our bootstrap resampling compares favourably to those from the CJ98 ($\theta_{63} = 15.8°$) and TK03 ($\theta_{63} = 19.2°$) models for 51° S. These estimates also are similar to more poorly known estimates for the Late Cretaceous and early Cenozoic[24] and we suggest that the mean inclination from these Louisville guyots (within 1° of that derived from Rigil Guyot alone) provides a reasonable time-averaged inclination.

Although the average palaeolatitudes for Rigil Guyot (47.0° S, 70 Myr old) and the younger Burton (49.8° S, 64 Myr old) and Hadar (52.3° S, 50 Myr old) guyots are similar to the present Louisville hotspot location, Site U1372 on Canopus Guyot (74 Myr old) has a distinctly shallower mean (normal polarity) inclination of −61.7° ($n=9$) corresponding to an estimated average palaeolatitude of 42.9° S. Indeed, the apparent trend of inclinations with age (Fig. 4) is compatible with significant southward motion and linear regression incorporating the palaeolatitude uncertainties yields a southward drift of 11° (±8°) between 74 and 50 Myr ago. We regard this large linear drift as unrepresentative for the 70–50 Myr time interval given our 47.0° S palaeolatitude estimate for Rigil Guyot and because the small number of flows from the youngest two guyots are unlikely to have adequately sampled secular variation. We suggest that the palaeolatitude estimate for Rigil Guyot represents the best estimate of the average hotspot location at 70 Myr ago.

Implications for deep Earth geodynamics

Comparison of the cumulative distribution functions (CDFs) for the Louisville guyots to distributions from the CJ98 and TK03 field models provides a straightforward test of whether the Louisville hotspot experienced drift similar to that of the Hawaiian hotspot (Fig. 5). Flow mean inclinations from discrete samples and 2-cm archive-half measurements from Sites U1373–U1377 plot very close to the CJ98 and TK03 curves for a 51° S latitude, rather than near curves for 46° S, 41° S or 36° S, which would represent Louisville hotspot motions of 5°, 10° or 15° to the south. Similarity to these field model curves can be quantified with a statistical Kolmogorov–Smirnov test (see Supplementary Information for details). We find that, at the 95% confidence level, the distribution of discrete sample inclination means is statistically indistinguishable from the field models for 55–47° S (CJ98) and 53–44° S (TK03) with a highest probability match for latitudes of respectively 50° S ($P = 0.93$) and 49° S ($P = 0.90$). The 2-cm archive-half data typically yield

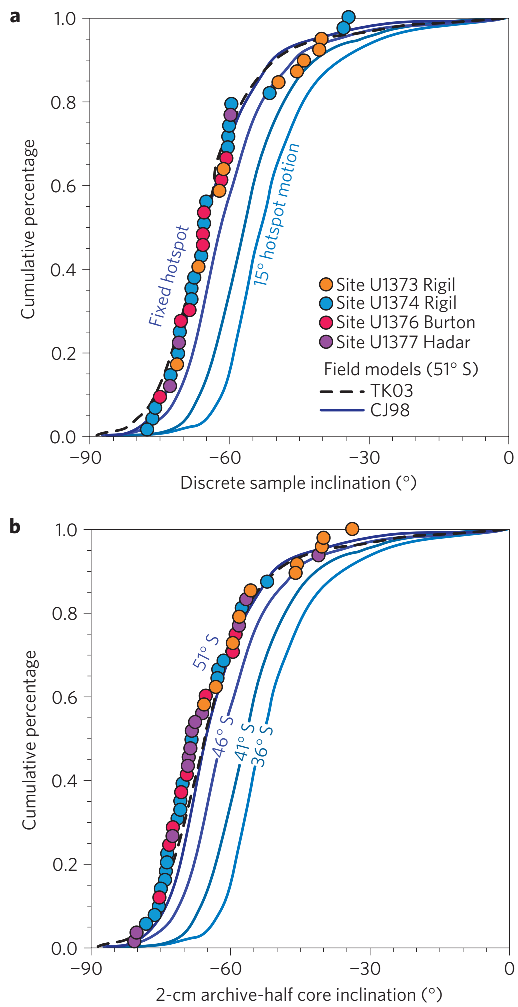

Figure 5 | Comparisons of observed flow mean inclinations for the Louisville hotspot to geomagnetic field model predictions. In both diagrams the CDFs of flow units (ISCI = 3 or 2) from Sites U1373–U1377 are compared to CDFs of 1,000 inclinations drawn from two 0–5 Myr field models (TK03 and CJ98; refs 22,23). Shown for reference are three CDF curves for a range of latitudes representing up to ∼15° of a potential latitudinal shift for the Louisville hotspot. CDFs for discrete sample flow means (**a**) and 2-cm archive-half data (**b**) are most similar to those expected for latitudes at or near the present-day hotspot location (51° S).

best matches with lower probabilities ($P = 0.56$, 0.78) and higher southern latitudes. These field model comparisons confirm that measured inclinations from Sites U1373–U1377 are most compatible with a limited latitudinal hotspot motion between 70 and 50 Myr ago.

Our palaeolatitude and age data thus require significant inter-hotspot motion between the Hawaiian and Louisville hotspots. As we consider only two hotspots, there could theoretically exist a single rotation pole for the upper mantle beneath the Pacific that satisfies both the large southward motion of Hawai'i and little to no motion for the Louisville hotspot from 70 to 50 Myr ago. An exhaustive search (see Supplementary Information) shows, however, that there are no single rotation poles that can explain both plume motion histories by a uniform large-scale movement of the Pacific mantle as a whole between 70 and 50 Myr ago. We surmise that the largest component of this inter-hotspot motion must have been caused by the independent motion of the Hawaiian hotspot. The shape and age progression of the Louisville seamount trail, therefore, provide a better indication of Pacific Plate motion, whereas the sharp Hawaiian–Emperor bend reflects primarily the effect of the strong Hawaiian plume motion.

The limited latitudinal motion for Louisville is similar to predictions from whole-Earth mantle flow modelling, which predict southward motions of 2–2.5° for the Louisville hotspot[10,11] and up to 8° in more extreme cases[12,16] using different modelling assumptions (for example, viscosity models, plume initiation ages and depths). Even though our inclination data indicate only a modest latitudinal motion since 70 Myr ago, they do not rule out a possible significant longitudinal motion of the Louisville hotspot as predicted by these mantle flow models. Our findings suggest that mantle plumes must be moving independently and that these motions are regionally controlled by different configurations of large-scale deep mantle upwellings and downwellings. In the case of the Louisville hotspot, its motion is probably governed by the subduction of the Pacific Plate in the Tonga–Kermadec subduction zone to the west, causing a pronounced return flow in the mantle towards the east and in the direction of the Pacific–Antarctic mid-ocean ridge.

Methods

We have archived the ArArCALC $^{40}Ar/^{39}Ar$ age data files online in the EarthRef.org Digital Archive to be downloaded from http://earthref.org/erda/louisville-exp330-ages-koppers. The archived data files are provided in the standard ArArCALC format (with the AGE extension) and the Microsoft Excel, Adobe Acrobat PDF and Extended Marking Up Language XML formats. The ArArCALC v2.5.1 software can be downloaded from http://earthref.org/ArArCALC/. These data as well as the pertinent inclination data are listed in the Supplementary Information.

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Author contributions

All authors contributed extensively to the work presented in this paper. A.A.P.K., T.Y. and J.G. led and supervised IODP Expedition 330. A.A.P.K. carried out the $^{40}Ar/^{39}Ar$ geochronology analyses. J.S.G. carried out the bootstrap analysis and Kolmogorov–Smirnov statistical tests. J.S.G., N.P. and H.H. were the shipboard palaeomagnetists collecting the inclination measurements. N.P. was responsible for additional post-cruise data quality control. A.A.P.K. and J.S.G. wrote the main paper and the Supplementary Information. All authors co-edited this manuscript. The IODP Expedition 330 Scientific Party includes all other shipboard scientists responsible for core descriptions, igneous petrology and volcanology, geochemistry, palaeontology, sedimentology, downhole logging and physical properties.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to A.A.P.K.

Competing financial interests

The authors declare no competing financial interests.

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CORRIGENDUM

Limited latitudinal mantle plume motion for the Louisville hotspot

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In the print version of this Article originally published, the present address for Toshitsugu Yamazaki was erroneously omitted. It is as follows: Atmosphere and Ocean Research Institute, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8564, Japan. This is correct in the PDF and HTML versions.