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# Extreme temporal homogeneity of helium isotopes at Piton de la Fournaise, Réunion Island

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**OCEAN island basalts (OIBs) have strontium, neodymium and lead isotopic compositions that are different from those of mid-ocean-ridge basalts, (MORBs), reflecting long-term differences in the chemical characteristics of the respective mantle source reservoirs. The high $^3He/^4He$ ratios at some islands such as Hawaii and Iceland[1–7] indicate that these basalts come from sources that are less degassed than the source of MORB. Many islands exhibit considerable variability in Sr, Nd and Pb isotopes[8–10], but detailed studies of temporal variations in helium isotopes have been restricted to Hawaiian volcanoes—at Mauna Loa, for example, significant variations in $^3He/^4He$ have been found for the past 30,000 years[11]. Here we report on $^3He/^4He$ ratios from Piton de la Fournaise volcano on Réunion Island. No variations are found over the long time of 360,000 years, indicating a remarkable uniformity of $^3He/^4He$ for the (large) mantle source region over this timescale. The He–Sr–Pb systematics at this island may reflect the simultaneous contribution of both recycled materials (perhaps subducted crust) and primitive components to the Réunion source.**

Réunion Island (21° 7′ S, 55° 32′ E) is the present location of the hotspot trace that trends northeast through Mauritius Island, along the Mascarene Plateau toward the Deccan Traps in India (Fig. 1)[12]. The total distance of ~5,000 km makes this hotspot chain comparable in length to the Hawaiian Island chain. Such hotspot traces are believed to result from the interaction of a relatively fixed, hot rising plume in the Earth's mantle with the moving lithosphere[13]. Réunion Island is located within the Dupal anomaly, which is a broad, nearly globe-encircling band centred around 30° S[14,15]. Many islands in this band, including Réunion[16–19], have characteristically high $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ ratios, reflecting ancient chemical fractionations of U/Pb, Th/U and Rb/Sr. Dupal islands are sometimes thought to contain subducted crust or lithosphere as a mantle component[20–23], or to be produced by ancient mantle metasomatism[23,24].

Réunion Island has two volcanoes; the extinct volcano Piton des Neiges comprises about two-thirds of the island to the northwest, and the presently active Piton de la Fournaise is located in the southeast. Piton des Neiges forms the basement on which Piton de la Fournaise began to grow sometime before ~350,000 yr ago[25]. The Piton de la Fournaise eruptions are well documented both historically and chemically and consist of picrites and lavas that are transitional between alkali basalts and tholeiites[18,19,26,27]. We have measured $^3He/^4He$ and $^{87}Sr/^{86}Sr$ ratios in historic and prehistoric lavas from Piton de la Fournaise. Helium trapped in inclusions was extracted by *in vacuo* crushing of olivine phenocrysts separated by hand-picking under a microscope. Recent lavas studied come from historical eruptions in 1708, 1776 and 1800 AD, and eight others since 1931, including the picritic eruptions of 1931, 1961 and 1977. Prehistoric lavas studied include a basalt dated by $^{14}C$ on charcoal (455 AD), four basalts dated by U–Th disequilibrium (<7,000, 15,000, 97,000 and 106,000 years old) and two picrites dated by K–Ar (327,000 and 360,000 years old)[25].

He isotopes were measured on a mass spectrometer designed and built at the University of California (Santa Barbara) by J. L. The instrument is a 90° curvature, 21-cm radius, statically operated, double-collector mass spectrometer. The sensitivity for He is $>10^{-4}$ A torr$^{-1}$, and the absolute detection limit is $<10^4$ atoms of $^3He$. The inlet system uses a low-temperature (40 K) charcoal trap for separation of He from other rare gases. The precision for He isotopic ratio determinations is very close to the limit based on ion counting statistics for the weak $^3He$ beam. The total system blank is $\sim 1 \times 10^{-10}$ cm$^3$ STP $^4He$. Blanks were always run before samples. A secondary standard of Yellowstone Park gas was always run after samples, with standard size similar to the size of the sample just analysed. This gas has been routinely calibrated against marine air at UCSB and has a $^3He/^4He$ ratio of $16.49 \pm 0.04$ ($2\sigma$) $R_A$ ($R_A$ is the atmospheric ratio of $1.39 \times 10^{-6}$)[28]. This procedure allows very small samples to be analysed and a precise check of sample isotopic ratios in the size range of the analysis.

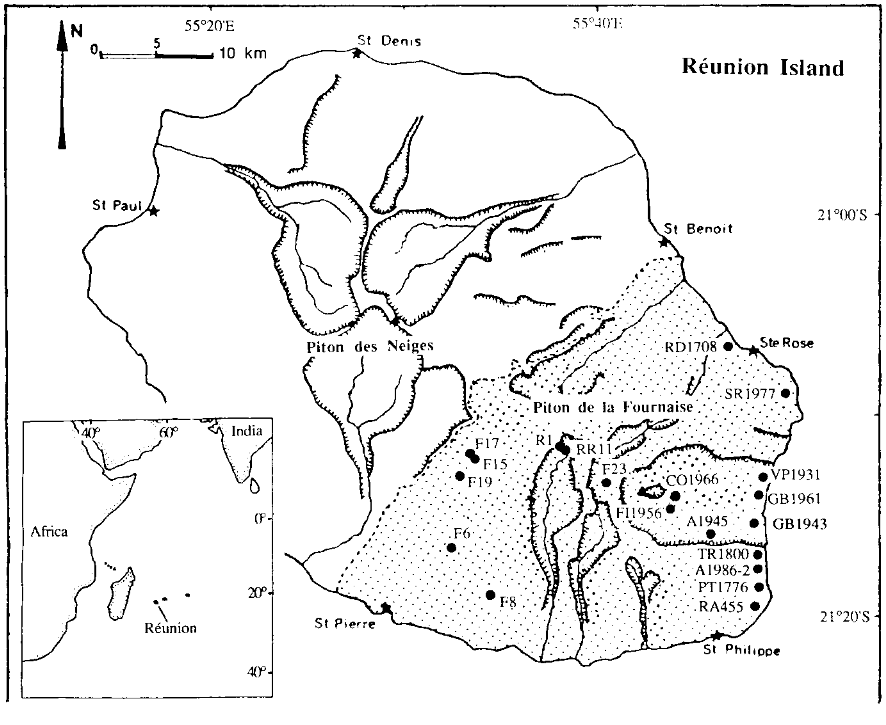

FIG. 1 Sample locations from Piton de la Fournaise, Réunion Island. Inset shows the island location in the Indian Ocean (after ref. 26).

TABLE 1 He and Sr isotopes in basalts and picrites from Piton de la Fournaise

| Sample | Age (years) | Weight (mg) | [He] ($10^{-9}$ cm$^3$ STP g$^{-1}$) | $^3He/^4He$ ($R/R_A$) | $2\sigma_{mean}$ | $\frac{He/Ne}{He/Ne_{air}}$ | $^{87}Sr/^{86}Sr$ |
|---|---|---|---|---|---|---|---|
| Historical samples | | | | | | | |
| RD1708 | 282 | 197.7 | 4.17 | 13.36 | 0.66 | 18.3 | 0.70424 |
| PT1776 | 214 | 451.3 | 3.91 | 12.67 | 0.48 | 35.4 | 0.70419 |
| TR1800 | 190 | 210.8 | 9.37 | 12.89 | 0.36 | 48.0 | 0.70410 |
| VP1931† | 59 | 363.1 | 3.28 | 13.64 | 0.62 | 20.1 | 0.70413 |
| replicate | | 611.1 | 6.17 | 12.96 | 0.28 | 65.6 | |
| GB1943 | 47 | 135.4 | 7.06 | 12.90 | 0.68 | 19.2 | 0.70410 |
| A1945 | 45 | 307.6 | 8.14 | 12.85 | 0.38 | 53.2 | 0.70413 |
| FI1956 | 34 | 174.3 | 18.1 | 12.92 | 0.34 | 67.6 | 0.70424 |
| GB1961† | 29 | 496.7 | 3.78 | 12.82 | 0.42 | 29.8 | 0.70421 |
| replicate | | 430.2 | 8.46 | 12.69 | 0.30 | 74.9 | |
| CO1966 | 24 | 179.3 | 7.96 | 12.97 | 0.52 | 36.5 | 0.70419 |
| SR1977† | 13 | 464.8 | 5.41 | 12.80 | 0.40 | 46.8 | 0.70424 |
| replicate | | 442.9 | 15.5 | 13.06 | 0.22 | 120 | |
| A1986-2 | 4 | 133.0 | 13.2 | 12.69 | 0.36 | 51.1 | 0.70423 |
| Dated samples | | | | | | | |
| F6*† | 360,000 ± 10,000 | 349.4 | 3.52 | 13.17 | 0.58 | 27.2 | 0.70415 |
| F8*† | 327,000 ± 20,000 | 360.0 | 8.37 | 12.78 | 0.36 | 54.4 | 0.70422 |
| R1 | 106,000 ± 16,000 | 417.0 | 1.58 | 12.87 | 0.99 | 7.6 | 0.70406 |
| RR11 | 97,000 ± 14,000 | 463.3 | 32.2 | 12.70 | 0.17 | 243 | 0.70425 |
| F15 | ~15,000 | 419.1 | 11.2 | 13.05 | 0.30 | 73.1 | |
| F17 | 15,000 ± 5,000 | 263.0 | 46.8 | 13.17 | 0.18 | 236 | 0.70425 |
| F19 | <7,000 | 178.4 | 9.08 | 12.63 | 0.46 | 34.4 | 0.70425 |
| F23 | prehistoric | 237.0 | 78.0 | 13.08 | 0.17 | 383 | 0.70426 |
| RA455 | 1,535 | 284.0 | 30.9 | 13.00 | 0.20 | 173 | 0.70416 |

Historical sample identification numbers refer to year (AD) of eruption. Sample localities for historic eruptions are described in ref. 19. F6 and F8 are from near le Tampon, R1 and RR11 from near Nez de Boeuf, F15, F17 and F19 from Plaine des Cafres (Piton Hyacinthe) and F23 from Piton Chisny (Fig. 1). All He results are for olivine mineral separates. Reproducibility of air-standard He sizes is better than 3% ($2\sigma$); sample He contents vary much more owing to the variability in abundance of inclusions. All Ne contents were less than twice the blank value and He/Ne ratios should therefore be considered minimum values. Sr isotope results are for whole rocks ($2\sigma < 0.00004$). Sr isotope analyses of historical samples and RA455 were performed at the Centre de Recherches Petrographiques et Geochimiques, some of which were previously reported[19]; Sr analyses of dated samples were performed at the Centre de Recherches Volcanologiques. U-Th ages are from Condomines and Bachelery (manuscript in preparation).

* K-Ar ages[25].

† Picrite.

Our He results (Table 1) confirm the earlier observations that Réunion Island is a high $^3He/^4He$ hotspot[29-33]. In addition, the temporal and spatial homogeneity of $^3He/^4He$ is remarkable. There has been no discernible change on any timescale between ~1 year and 360,000 years at Piton de la Fournaise (Fig. 2). The He isotope compositions of the picrites are indistinguishable from the basalts. The mean $^3He/^4He$ ratio for all samples is $\sim 12.9 \pm 0.4$ ($2\sigma$) $R_A$; that is, the variation in $^3He/^4He$ is only 3% ($n = 20$). This is in marked contrast to the temporal variability in $^3He/^4He$ found at Hawaiian volcanoes[11].

The constant He isotopic ratios contrast with the petrological and trace-element data, which indicate that the historical picrites are produced by disruption of pre-existing, genetically unrelated olivine-rich cumulates, apparently by pulses of basaltic magmas on a timescale of about 17 years[19]. Also, the formation of Dolomieu caldera in 1930, which represented a large change in magma composition[19], was not accompanied by a change in $^3He/^4He$. The minor variability in He and Sr isotopic ratios ($^{87}Sr/^{86}Sr = 0.70406$-$0.70425$; Table 1) indicates that the source region has remained homogeneous during the entire sub-aerial history, and that melting conditions have remained uniform. We can estimate the scale of source homogeneity by assuming that the volumetric production rate of 0.08 km$^3$ yr$^{-1}$ since 1931[26] is grossly representative of the sub-aerial history, and that 7% partial melting of the mantle source is applicable[19]. The characteristic length scale for He isotope homogeneity in the mantle source is then $\sim(0.08 \times 360{,}000/0.07)^{1/3}$, or >70 km. Constant $^3He/^4He$ ratios also suggest short transport times of magma from the source region ($<10^4$ years) and the absence of a long-lived storage reservoir at depth, consistent with inferences based on U-Th disequilibria[34]. The homogeneity of Sr isotopes is circumstantial evidence that the homogeneity of helium is not due to domination by metasomatic fluids, and also makes it unlikely that external components from the asthenosphere or lithosphere have been added on the way to the surface. Helium is therefore a genuine tracer that is transferred on melting from the source rock to the melt. The $^3He/^4He$ record at Piton de la Fournaise is best explained as the result of a well mixed source region, rather than as a mixture of distinct fluid and/or magmatic components, which we would expect to show temporal variability.

$^3He/^4He$ ratios along mid-ocean ridges are typically between 7-9 $R_A$. The relatively high $^3He/^4He$ ratios at Réunion compared to MORB may indicate some contribution from relatively undegassed mantle, similar to that beneath other hotspots such as Hawaii and Iceland. Réunion is, however, located within the Dupal anomaly. $^3He/^4He$ ratios lower than MORB values are found at Dupal islands such as Tristan da Cunha and Gough[2], consistent with a higher $(U+Th)/^3He$ produced by crustal recycling or by mantle enrichment events. In contrast, the $^3He/^4He$ results for Piton de la Fournaise indicate that some Dupal islands can also have 'primitive' He isotope signatures. Castillo[35] showed that Dupal anomaly maxima are correlated with low seismic velocities in the lower mantle and with the locations of hotspots. If the relatively high $^3He/^4He$ ratios at hotspots such as Hawaii, Iceland and Réunion are evidence for some degree of chemical isolation or layering in the mantle[36-39], then the He-Sr-Pb isotope systematics at Réunion also suggest that recycled materials (perhaps slabs) may penetrate into lower-mantle regions, where they may acquire relatively primitive rare-gas signatures but retain much of their enriched Sr and Pb isotope signatures. In this case, both primitive and recycled components may contribute simultaneously to the genesis of an individual island such as Réunion.

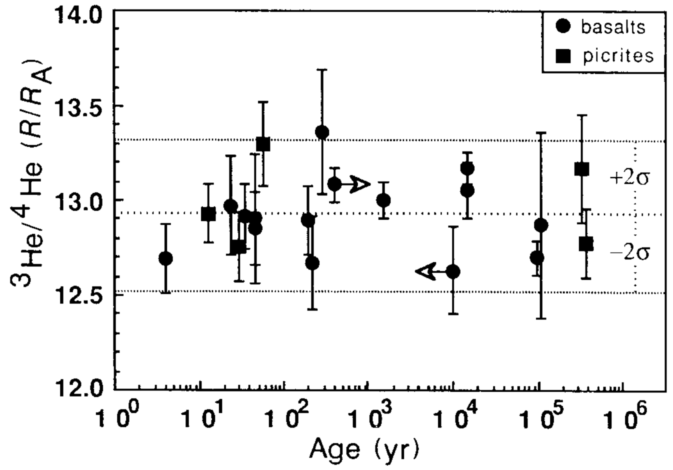

FIG. 2 $^3$He/$^4$He plotted against age for basalts and picrites from Piton de la Fournaise. The two samples with arrows are plotted at their age limits (a prehistoric flow and a sample which is <7,000 yr old). Where replicate analyses were performed the average result is shown. The dashed lines show the mean value of all the data $\pm 2\sigma$. Error bars for individual samples are $\pm 1\sigma_{mean}$.

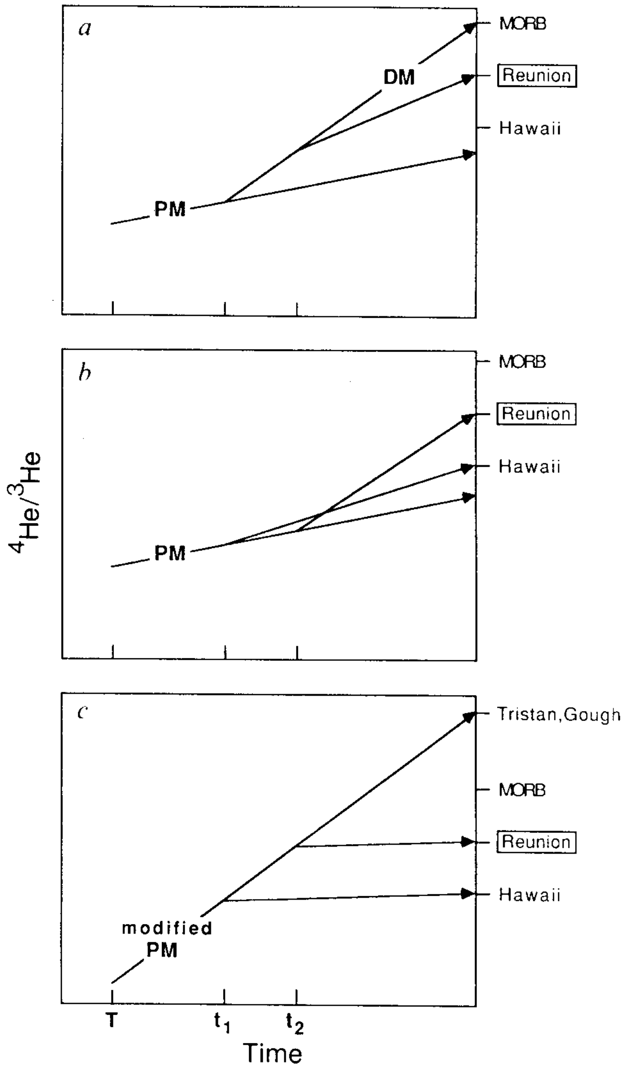

FIG. 3 Simplified evolutionary models for $^4$He/$^3$He in the Réunion mantle source. Lines shown are schematic because of the nonlinear production rate of $^4$He by radioactive decay of $^{238}$U, $^{235}$U and $^{232}$Th. $T$ is the age of the Earth. Relative He isotope compositions for OIBs and MORBs are shown on the right. Melt extraction always leaves a residue with lower Rb/Sr and Th/U. In *a* and *b*, He is assumed to be more incompatible than U and Th during partial melting; in *c* He is less incompatible than U and Th. *a*, Model 1—Réunion source formed at $t_2$, by metasomatic enrichment of depleted mantle (DM) with fluids having high Rb/Sr, Th/U and low (U+Th)/$^3$He. DM was formed as a residue of melt extraction from primitive mantle (PM) at $t_1$. Radiogenic Sr and Pb isotopes at Réunion do not allow the source to be a residue of melt extraction from DM, and the Sr and Nd isotopes in Hawaiian basalts with high $^3$He/$^4$He are not representative of PM. *b*, Model 2—Réunion source formed as a residue of melt extraction from PM. This decreased Rb/Sr and Th/U, but increased (U+Th)/$^3$He relative to PM. The case shown assumes similar Rb/Sr and Th/U fractionations at $t_1$ and $t_2$; because the Hawaiian source has lower $^{87}$Sr/$^{86}$Sr and $^{208}$Pb/$^{204}$Pb it would be 'older' than the Réunion source in this case. The case of larger Rb/Sr and Th/U fractionations at $t_2$ compared to $t_1$ is also possible, in which case the Réunion source would be formed at $t_1$ and the Hawaiian source at $t_2$. In either case the fractionations in (U+Th)/$^3$He and Rb/Sr are not strictly correlated, because Hawaii has higher $^3$He/$^4$He and lower $^{87}$Sr/$^{86}$Sr than Réunion. *c*, Model 3—Réunion source formed as a residue of melt extraction from 'modified PM' at $t_2$. Early outgassing produced PM with high (U+Th)/$^3$He. Subsequent melt extraction produced a residue with lower Rb/Sr, Th/U and (U+Th)/$^3$He. The isotope signature for PM is that of bulk Earth ($^{87}$Sr/$^{86}$Sr = 0.7047 and $^3$He/$^4$He = 5 $R_A$). As DM also lost U and Th throughout its history whereas PM did not, DM evolved to higher $^3$He/$^4$He than 'PM', consistent with MORB values of 7–9 $R_A$. Parent/daughter fractionations are all in the same direction; the magnitudes of the fractionations are also correlated between the Hawaiian and Réunion sources, but not between DM and OIB sources, as DM has the lowest $^{87}$Sr/$^{86}$Sr but intermediate $^3$He/$^4$He.

In addition to the complex mixing described above, other possible explanations for the He-Sr-Pb relations at Réunion include: (1) old enrichment of depleted mantle by fluids having high Rb/Sr, U/Pb, Th/U and low (U+Th)/$^3$He; (2) ancient differentiation from primitive mantle by partial melt extraction; (3) ancient differentiation from a remnant of primitive mantle that was outgassed during an early stage of Earth history. These alternatives are qualitatively outlined in Fig. 3. Model 3 leads to the idea that helium may not be as effectively outgassed as is often assumed. In the absence of fluids, such as in the deep mantle, helium is simply partitioned into the melt phase as an incompatible element. Depending on the mineralogical constitution of the source, He might sometimes be more compatible than U or Th because He solubility in solids is not much less than in melts[40,41]. Under these circumstances partial melting would leave a residue with lower (U+Th)/$^3$He, and with time promote increasingly higher $^3$He/$^4$He ratios in the residual peridotite (harzburgite) compared to more fertile sources. Because melt extraction should also leave a residue with low Rb/Sr and Th/U, the lower $^{87}Sr/^{86}Sr$ and $^{208}Pb/^{204}Pb$ and higher $^{3}He/^{4}He$ ratios at islands such as Hawaii and Iceland could suggest that their mantle sources are residues of earlier differentiation of the same reservoir which later produced the Réunion source.

Collectively, the uniform and relatively high $^{3}He/^{4}He$ ratios coupled with moderately radiogenic Sr and Pb isotopes at Réunion Island can be reconciled with either a simultaneous contribution of recycled and primitive components to the genesis of an individual ocean island volcano, or with metasomatism or ancient differentiation that in some cases produced a decrease in $(U+Th)/^{3}He$ in the mantle. □

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