Archaean zircons in Miocene oceanic hotspot rocks establish ancient continental crust beneath Mauritius

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A fragment of continental crust has been postulated to underlie the young plume-related lavas of the Indian Ocean island of Mauritius based on the recovery of Proterozoic zircons from basaltic beach sands. Here we document the first U–Pb zircon ages recovered directly from 5.7 Ma Mauritian trachytic rocks. We identified concordant Archaean xenocrystic zircons ranging in age between 2.5 and 3.0 Ga within a trachyte plug that crosscuts Older Series plume-related basalts of Mauritius. Our results demonstrate the existence of ancient continental crust beneath Mauritius; based on the entire spectrum of U–Pb ages for old Mauritian zircons, we demonstrate that this ancient crust is of central-east Madagascar affinity, which is presently located ~700 km west of Mauritius. This makes possible a detailed reconstruction of Mauritius and other Mauritian continental fragments, which once formed part of the ancient nucleus of Madagascar and southern India.

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Evidence is accumulating that old continental crust may occur beneath some young ocean-island volcanoes, contributing contaminating components to their chemical and isotopic compositions. For example, the Sr, Pb and Nd isotopic compositions of basalts to rhyolites in the Óræfajökull volcano of southeastern Iceland were modelled to have incorporated 2–6% of Precambrian continental crust. This, combined with inversion of gravity anomaly data that indicate unusually thick crust of >30 km, has been used to infer that the Jan Mayen Microcontinent extends southwestward to underlie southeast Iceland. Similarly, a fragment of continental crust was suggested to underlie the young plume-related lavas of the Indian Ocean island of Mauritius, on the basis of gravity inversion modelling (crustal thickness) and the recovery of Proterozoic (660–1,971 Ma) zircons from basaltic beach sands. The island of Mauritius (2,040 km²) is the second youngest member of a hotspot track extending from the active plume site of Réunion, through the Mascarene Plateau, the Laccadive-Chagos Ridge and into the 65.5 Ma Deccan Large Igneous Province. Three phases of Mauritian basaltic volcanism have been named the Older (9.0–4.7 Ma), Intermediate (3.5–1.66 Ma) and Younger (1.0–0.03 Ma) Series. Minor volumes of trachytic rocks occur as intrusive masses or plugs <300 m across and are associated with Older Series basalts, as confirmed by U–Pb zircon thermal ionization mass spectrometry dating, which yielded at one location an age of 6.849 ± 0.012 Ma (ref. 7). Mauritian trachytes are variably altered from probable primary phonolitic magmas, forming a prominent Daly Gap when plotted with coeval basalts; this suggests formation either by extreme fractional crystallization from the basalts or by direct partial melting of...
metasomatized mantle. Isotopic compositions of the trachytes show relatively constant $\varepsilon_{\text{Nd}}$ of $+4.03 \pm 0.15$, with highly variable $\text{ISr}$ of $0.70408–0.71034$, interpreted as reflecting small amounts (0.4–3.5%) of contamination by Precambrian continental crust, successfully modelled using as a proxy $\sim 750$ Ma granitoid composition from the Seychelles. It has been noted that other compositions, including older Proterozoic or even Archaean components, can also be plausibly modelled. It is from such a Mauritian trachyte that a population of zircons was extracted and analyzed for this paper. A subset of these zircons yields Archaean U–Pb ages, confirming the existence of a fragment of Precambrian continental crust beneath Mauritius, and we propose here that Mauritius and other Mauritian continental fragments are dominantly underlain by Archaean continental crust, and that these originally formed part of the ancient nucleus of Madagascar and India.

Figure 2 | Scanning electron microscope images of three Archaean zircon grains. These three grains were recovered from the MAU-8 trachyte sample. Backscattered electron (BSE) images (a–c) of the three grains taken after completing all U–Th–Pb isotopic analyses. Cathodoluminescence (CL) images (d–f) taken prior to acquiring our SIMS data. The indicated analysis numbers correspond to those in Supplementary Data 1. The indicated ages are the radiogenic $^{207}\text{Pb}/^{206}\text{Pb}$ ages for the corresponding craters.
Results

U–Pb systematics. A single trachyte sample (MAU-8; location given in inset to Fig. 1) was selected for zircon separation based on available sample mass (~1 kg) and Zr concentration (1,165 μg g⁻¹); extreme care was taken during sample processing to avoid any risk of contamination. Thirteen zircon grains were recovered, from which we report 68 individual point analyses acquired using the Cameca 1280-HR SIMS (secondary ion mass spectrometer) instrument at GFZ Potsdam; details of the sample processing and analytical methods are provided in the Methods section. Three zircon grains show uniquely mid- to late-Archaean U–Pb systematics, with no evidence for Phanerozoic components. Cathodoluminescence (CL) and backscattered electron (BSE) images (Fig. 2) show that these three crystals contain internal structures such as metamict cores, partially resorbed idiomorphic banding and numerous mineral inclusions. We conducted 20 individual U–Th–Pb spot analyses on these grains, where the concordant or near-concordant ²⁰⁶Pb/²³⁸U ages range from 3,030 ± 5 Ma to 2,552 ± 11 Ma (Fig. 3 and Supplementary Data 1). We interpret these data as indicating the crystallization ages of a complex Archaean xenocrystic component; no overgrowths of young zircon are evident in any of the three Archaean grains, despite great efforts to identify such rims. The mineral inclusions in these ancient zircons include quartz, K-feldspar and monazite, as determined by EDS measurements; this assemblage would be consistent with crystallization from granitic or syenitic melts of fertile metasomatized mantle. Inclusions in Precambrian granitoids from Fennoscandia 16. In contrast, oxygen isotope data for 29 spot analyses of the Miocene age zircons gives a mean δ¹⁸OSMOW value of 4.59 ± 0.20‰ (1 s.d.) (Supplementary Data 2). These values are lower than the average δ¹⁸OSMOW of mantle zircons 15, although grains with δ¹⁸OSMOW > 8.5‰ have been reported in Precambrian granitoids from Fennoscandia 16. In contrast, oxygen isotope data for 29 spot analyses of the Miocene age zircons gives a mean δ¹⁸OSMOW value of 4.59 ± 0.20‰ (1 s.d.) (Supplementary Data 2). These values are lower than the average δ¹⁸OSMOW of mantle zircons (5.3 ± 0.3‰; ref. 15), but are within the range of zircons recovered from some kimberlites (δ¹⁸OSMOW = 3.4–4.7‰; ref. 17). This would be consistent with an origin for Mauritian trachytes as low-degree partial melts of fertile metasomatized mantle 7.

Comparison of U–Pb ages with adjacent continents. Can the spectrum of U–Pb ages for old Mauritian zircons be correlated with exposed Precambrian terranes in nearby continental entities? We considered major continental masses like India, as well as large (e.g., Madagascar, 587 × 10⁵ km²) and smaller (e.g., Seychelles, 459 km²) continental fragments as potential correlates of the sub-Mauritius continental crust. Granitoid rocks of the Seychelles 18 range from ~700–800 Ma, with the vast majority of ages ~750 Ma (ref. 19); no Archaean components have been identified there. The Dharwar Craton of southern India (Fig. 1) consists of a nucleus of Palaeoarchaean to Neoarchaean (3.4–2.5 Ga) migmatisitic orthogneisses 20, dominantly granitoid gneisses 21. Palaeo- and Mesoproterozoic rocks are present south of the Dharwar Craton in India 21. Neoproterozoic igneous or Palaeo- and Mesoproterozoic rocks are present south of the Seychelles 22,23. The best match to the age spectrum of Precambrian zircons recovered from Mauritius occurs in east-

Oxygen isotopes. In order to further characterize the sources of the zircons, we undertook spot analyses of oxygen isotopes by SIMS for some of the grains (Supplementary Data 2). For the Archaean zircons, the results yield δ¹⁸OSMOW values between 5.5–6.0‰ (Grain 3) and 9.7–9.9‰ (Grain 8). The lower value is comparable to the average δ¹⁸OSMOW value of 5.5 ± 0.4‰ for Archaean zircons in tonalite–trondjhemite–granodiorite rocks in the Superior Province of Canada 14. The higher values are outside the range of typical δ¹⁸OSMOW for magmatic zircons 15, although grains with δ¹⁸OSMOW > 8.5‰ have been reported in Precambrian granitoids from Fennoscandia 16. In contrast, oxygen isotope data for 29 spot analyses of the Miocene age zircons gives a mean δ¹⁸OSMOW value of 4.59 ± 0.20‰ (1 s.d.) (Supplementary Data 2). These values are lower than the average δ¹⁸OSMOW of mantle zircons (5.3 ± 0.3‰; ref. 15), but are within the range of zircons recovered from some kimberlites (δ¹⁸OSMOW = 3.4–4.7‰; ref. 17). This would be consistent with an origin for Mauritian trachytes as low-degree partial melts of fertile metasomatized mantle 7.

Figure 3 | Concordia plot. Includes all 20 data points from the three Archaean zircons found in the MAU-8 trachyte sample. The ellipses indicate the 1 s.d. analytical uncertainties for each of the SIMS determinations. Also shown as red symbols are the TIMS wet chemical results reported by Torsvik et al. 2 for eight Proterozoic zircons recovered from Mauritian basaltic beach sands. Not shown are the 48 SIMS determinations on the 10 Miocene zircons, here indicated with the arrow. Tick marks on the Concordia curve are in Ma. TIMS, Thermal Ionization Mass Spectrometry.

Th/U ratios. U and Th concentrations of all measured individual spots in the zircon grains are given in Supplementary Data 1. For the three Archaean grains, Th/U ratios show distinct values, with Grains 3 and 5 yielding Th/U between 0.05 and 0.47, which is typical of variably metamorphosed and/or recrystallized igneous rocks 9,10. In contrast, Grain 8 is very depleted in Th, with typical of variably metamorphosed and/or recrystallized igneous rocks 9,10. In contrast, Grain 8 is very depleted in Th, with

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central Madagascar, where Palaeoarchaean to Mesoarchaean (3.4–3.1 Ga, Antongil–Masora domain) gneisses have been correlated with lithostratigraphic units in the Dharwar Craton, and juvenile Neoarchaean rocks of the Antananarivo domain can be correlated with similar belts in the Eastern Dharwar\(^24,25\). In addition, gabbroic, syenitic and granitic rocks of Neoproterozoic age (0.85–0.70 Ga) are well represented in Madagascar as the Imorona–Itsindro Suite\(^24,25\), which has been suggested to represent the products of an Andean-type continental arc\(^26,27\).

The entire Precambrian zircon age spectrum found in young Mauritian volcanic rocks could have been derived from a \(\sim 2,000 \text{km}^2\) area in east-central Madagascar, as illustrated in Fig. 5 (inset map).

**Discussion**

Microcontinental fragments are a natural consequence of plate–plume interaction\(^1,2,28\), an obvious example is the Seychelles, where evidence from surface exposures\(^19\) and seismic studies\(^29,30\) support the existence of a partly emergent \(4–4.5 \times 10^4 \text{km}^2\) fragment of continental crust with a thickness of \(\sim 33 \text{km}\). Less clear examples include the Laxmi Ridge (Fig. 6), which has been interpreted as a sliver of thinned continental crust\(^31,32\), or

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**Figure 4 | Backscattered electron images of the 10 Miocene age zircons recovered from the MAU-8 sample.** Analysis numbers in BSE images (a–j) correspond to those given in Supplementary Data 1. The indicated ages are the radiogenic \(^{206}\text{Pb}/^{238}\text{U}\) ages for the corresponding crater.

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composed entirely of underplated oceanic crust. In the Indian Ocean, contiguous continental crust of thickness >25–30 km beneath the Seychelles and northern Mascarenes, and extending south-westwards towards Mauritius (Fig. 6) has been predicted, but admittedly crustal thickness determinations from gravity inversion alone cannot distinguish thinned continental crust from anomalously thick oceanic crust. For Mauritius, receiver function data were used to infer a Moho depth of ~21 km; those authors favoured entirely oceanic crust thickened by magmatic underplating, although they could not rule out the presence of “embedded” continental crust relics. Clearly, geophysical data, in isolation, yield equivocal interpretations of oceanic crustal structures and compositions, but if used in conjunction with geochemical and/or isotopic data (e.g., ref. 7), or with recovered mineral grains that demand the presence of deep continental rocks (this study), the results are more secure.

Our findings confirm the existence of continental crust beneath Mauritius and document, for the first time, the presence of Archaean zircons as xenocrysts in young volcanic rocks from ocean basin settings. Archaean zircons (~3,000 Ma) were reported in young lavas and beach sands from the Galapagos, but so far only mentioned in a conference abstract. Younger zircons (~330 and ~1,600 Ma) have previously been described from Mid-Atlantic Ridge gabbros, and Proterozoic (~1,800 Ma) and Mesozoic zircons (126–242 Ma) have been found in young Icelandic basalts. Proterozoic zircons (2,430, 1,279, 807 Ma) were recovered in an early Paleogene (64 Ma) trachyte from Silhouette Island, Seychelles, a result that is noteworthy that hardly any volcanism related to the early break-up is found in western margin of India (except the 91.2 Ma St Mary Islands), while most of Madagascar was covered with flood basalts. This suggests that Madagascar and western India were separated at that time by at least ~200 km (Fig. 1), a region occupied by Mauritia. The bulk of this continental separation probably existed back in Precambrian times, although Late Jurassic (Tithonian) volcanism in the Seychelles, North Madagascar and Southern India may have been related to a failed rift system that contributed to continental extension between Madagascar and India. Cretaceous pre-breakup strike-slip faulting occurred immediately to the east of Madagascar (blue stippled line in Fig. 1), followed by the opening of the Mascarene Basin, when India, together with Mauritia and the Seychelles/Laxmi Ridge, broke away from Madagascar. Mauritia was subsequently fragmented into a ribbon-like configuration by a series of mid-ocean ridge jumps, triggered by the proximity of the Marion, and thereafter the Réunion plume. Subsequent volcanism blanketed most of the
Mauritian continental fragments, and in the case of Mauritius, the ancient materials were sampled by plume-related volcanic rocks.

Methods

SIMS U–Pb methods. A key objective of this investigation was to establish whether any older components were present within the late Miocene Mauritian trachytic rocks. The selected sample (MAU-8, Fig. 1) was collected in situ from outcrop located at 20.3284° S; 57.7132° E (ref. 7). Approximately 1 kg of material was sent to GFZ Potsdam for sample processing and zircon recovery. Prior to processing, both the sample and the entire crushing facility were carefully cleaned and inspected in order to preclude any risk of cross-contamination from previously processed samples. The MAU-8 sample was fiable, so the initial crushing was accomplished by hand using a metal rolling pin on a steel surface. No crushing or grinding apparatus was used. Repeated crushing and sieving resulted in nearly all of the material being reduced to the < 500 μm grain size fraction. The resulting material was then panned in tap water, both to remove fine-grained dust and to concentrate the heavy mineral fraction. The dried material was passed through a Frantz magnetic separator, followed by concentration using bromoform, and then methyl iodide heavy liquids. The resulting material was washed, and ultimately 13 grains were recovered from basaltic beach sands2. All results for Precambrian zircons recovered from basaltic beach sands2. All results for Precambrian zircons were determined using a Zygo Lot 7100 white light profilometer. These reveal backscattered electron images show the presence of numerous zircon (416.50 Ma (ref. 43), confirming that no significant systematic bias is present in our U–Pb determinations. Common Pb corrections, where needed, were based on the observed 204Pb/206Pb ratio (older grains) or 207Pb/206Pb ratio (younger grains), in conjunction with a recent common Pb composition.

Our initial survey of U–Pb ages identified three grains with Archaean ages. We decided to survey the two larger of these grains (Grains 3 and 8, Fig. 2) in detail, using a small beam diameter. A 100 pA 16O2 primary beam employing a Gaussian beam distribution was focused to a ~2 μm diameter at the sample surface; this lowered beam current resulted in a much lower ion collection rate in order to produce a flat-bottomed sputtering crater, a ~5 × 5 μm raster was applied to the primary beam, and this was compensated for using the dynamic transfer capability of the 1280-HR’s secondary ion optics. All other aspects of the second data acquisition series were the same as those for earlier 2 nA analyses. Measurements of the Temora2 zircon (416.50 Ma age2) and the Phanerozoic zircons from Madagascar (N = 386)25.

SIMS oxygen isotope methods. With the intent of further characterizing the nature of our suite of Mauritian zircons, we undertook additional oxygen isotope determinations by SIMS. Our analytical technique closely followed that described for the Potsdam SIMS laboratory44, using the 91500 calibrant during the initial U–Pb session (3 days spread over a week), yielding an unweighted mean 206Pb/238U age of 421.1 ± 2.8 Ma (1 s.d.), which is in reasonable agreement with the published age of 416.50 Ma (ref. 43), confirming that no significant systematic bias is present in our U–Pb determinations. Common Pb corrections, where needed, were based on the observed 204Pb/206Pb ratio (older grains) or 207Pb/206Pb ratio (younger grains), in conjunction with a recent common Pb composition.

Results of all SIMS spot analyses of zircons in trachyte sample MAU-8 are given in Supplementary Data 1, and are plotted on a conventional Concordia diagram in Fig. 3, along with the thermal ionization mass spectrometry analyses of Precambrian zircons recovered from basaltic beach sands2. All results for Precambrian-zircons from Mauritius are plotted on a histogram in Fig. 5, along with a compilation of Precambrian zircons from Madagascar (N = 386)25.

Imaging methods. Backscattered electron images show the presence of numerous mineral inclusions in 2 of the 3 Archaean grains (Fig. 2), whereas all 10 of the Miocene grains were inclusion-free (Fig. 4). In order to identify the nature of these inclusions, we removed the gold coating by gently rubbing with an ethanol-saturated tissue. The mount was then cleaned in high-purity ethanol for 5 min using an ultrasonic bath. The sample was sputter coated with carbon, followed by EDS analyses using the GFZ Potsdam SEM instrument. From the major element abundances we identified quartz, K-feldspar and monazite.

Data availability. The authors declare that all relevant data are available within the article and its Supplementary Data files. Other pertinent data are available from the authors upon request.
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Author contributions

L.D.A. collected and characterized the samples petrologically and geochemically, and initially recovered the first zircons in the trachytic rocks. M.W. oversaw the SIMS and SEM laboratory experiments, and played the leading role in data reduction and the interpretation of the SIMS isotopic data. T.H.T. provided the plate reconstructions. All authors contributed to the manuscript.

Additional information

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