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Longest continuously erupting large igneous province driven by plume-ridge interaction

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ABSTRACT

Large igneous provinces (LIPs) typically form in one short pulse of ~1–5 Ma or several punctuated ~1–5 Ma pulses. Here, our 25 new $^{40}Ar/^{39}Ar$ plateau ages for the main construct of the Kerguelen LIP—the Cretaceous Southern and Central Kerguelen Plateau, Elan Bank, and Broken Ridge—show continuous volcanic activity from ca. 122 to 90 Ma, a long lifespan of >32 Ma. This suggests that the Kerguelen LIP records the longest, continuous high-magma-flux emplacement interval of any LIP. Distinct from both short-lived and multiple-pulsed LIPs, we propose that Kerguelen is a different type of LIP that formed through long-term interactions between a mantle plume and mid-ocean ridge, which is enabled by multiple ridge jumps, slow spreading, and migration of the ridge. Such processes allow the transport of magma products away from the eruption center and result in long-lived, continuous magmatic activity.

INTRODUCTION

Large igneous provinces (LIPs) are the result of gigantic intraplate magmatic events with dominantly mafic igneous volumes >10^6 km^3 (Richards et al., 1989). In contrast to igneous generation processes at plate boundaries, such as mid-ocean ridges, continental rifts, and subduction zones—which might also produce magma volumes of LIP scale given sufficient time and space—LIPs are typically emplaced in relatively short durations with significantly higher magma production rates (Coffin and Eldholm, 1993; Sheth, 2007). Typically, the bulk volumes of LIPs with the best age controls—continental flood basalts such as the Central Atlantic magmatic province, the Karoo LIP (southern Africa), and the Deccan Traps (India)—are emplaced in a single main pulse of ~1–5 Ma (Marzoli et al., 2018; Jourdan et al., 2007; Sprain et al., 2019). However, some LIPs (e.g., the Kerguelen LIP, the Caribbean LIP, and the High Arctic LIP) diverge from this scenario, and their main portion of magmatism lasted for relatively long intervals of >20 Ma (Coffin et al., 2002; Dockman et al., 2018). It is suggested that these long-lived LIPs were emplaced in several magmatic pulses of 1–5 Ma (e.g., Bryan and Ernst, 2008). For example, it has been proposed that the High Arctic LIP was emplaced from ca. 128 to 77 Ma, with three short-duration pulses at ca. 122 Ma, 95 Ma, and 81 Ma (Dockman et al., 2018); the Caribbean LIP appears to have mainly formed in two pulses at ca. 89 Ma and ca. 76 Ma (Dürkefälden et al., 2019).

However, knowledge about the durations and eruption episodicities of long-lived LIPs is meagre due to a paucity of reliable, high-precision geochronology data. This is especially the case for the main, Cretaceous portion of the Kerguelen LIP. Based on a few age data, the Kerguelen LIP was believed to have formed by punctuated magmatic events (Neal et al., 2019) over an interval of ~25 Ma (Coffin et al., 2002; Duncan, 2002).

AGES OF THE KERGUELEN LIP

The Kerguelen LIP is the second most-voluminous LIP known of the Phanerozoic and consists of the Southern Kerguelen Plateau (SKP), Central Kerguelen Plateau (CKP), Elan Bank, and Broken Ridge. These features, Ninetyeast Ridge, the Northern Kerguelen Plateau, and some smaller magmatic provinces on circum–eastern Gondwana continents are all believed to be related to the Kerguelen plume (Coffin et al., 2002; Olierook et al., 2017) and belong to the Greater Kerguelen LIP (Olierook et al., 2017). The Cretaceous portion of the Kerguelen LIP characterized by high magma flux, which includes igneous rocks of the SKP, CKP, Elan Bank, and once-contiguous Broken Ridge, covers an area of ~1.5×10^6 km^2, with estimated igneous volumes of ~17.4×10^6 km^3 (Fig. 1; Coffin et al., 2002).

$^{40}Ar/^{39}Ar$ geochronology studies have previously been conducted on basalts from eight Ocean Drilling Program (ODP) sites on the main portion of the Kerguelen LIP (Coffin et al., 2002; Duncan, 2002). However, most published age data do not meet established criteria for statistical robustness (i.e., the calculated "ages" are based on discordant results). We rigorously filtered available age data based on statistical concordance and stringent criteria to ensure that only robust and true plateau ages that include >70% of the total ^{39}Ar released are included. Our filtering yields only four statistically reliable plagioclase $^{40}Ar/^{39}Ar$ plateau ages from three sites for the entire Cretaceous Kerguelen LIP, including 121.0 ± 2.1 Ma and 120.8 ± 2.1 Ma (ODP Site 1136), 113.45 ± 0.83 Ma (ODP Site 750), and 108.9 ± 1.3 Ma (ODP Site 1137), recalculated here using the decay constants recommended by Renne et al. (2011). All uncertainties herein are quoted at 2σ and include all sources of

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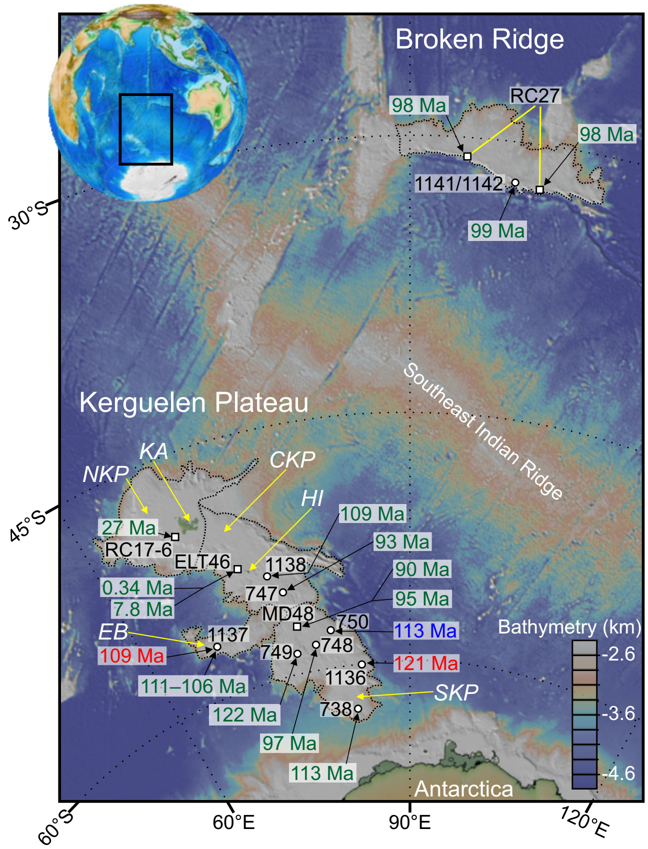

Figure 1. Bathymetric map showing location of the Kerguelen large igneous province. White circles and squares indicate Ocean Drilling Program drill sites and dredge sites, respectively. Age data are from this study (green), Duncan (2002) (red), and Coffin et al. (2002) (blue). CKP—Central Kerguelen Plateau; EB—Elan Bank; HI—Heard Island; KA—Kerguelen Archipelago; NKP—Northern Kerguelen Plateau; SKP—Southern Kerguelen Plateau.

uncertainty (Renne et al., 2010; Tables S1–S2 in the Supplemental Material[1]). Note that $^{40}Ar/^{39}Ar$ plateau ages from groundmass samples (Table S1) are excluded from such a database because they do not necessarily provide reliable crystallization ages, as demonstrated by a growing body of literature (Hofmann et al., 2000; Jourdan et al., 2007; Renne et al., 2015; Merle et al., 2019). We therefore use groundmass plateau (with >70% ^{39}Ar) and mineral mini-plateau (with 50%–70% ^{39}Ar) ages only if they are corroborated by a mineral-separate plateau age from the same sample or formation.

We report 47 new $^{40}Ar/^{39}Ar$ analytical results of fresh handpicked plagioclase, sanidine (cf. Fig. S2), glass, pyroxene, and groundmass separates from basaltic samples from eight ODP sites and four dredge sites on the main Kerguelen LIP, from which we obtained 25 plateau ages. The analytical methods and results are given in the Supplemental Material. Our new robust geochronology data, together with published data for ODP Sites 750, 1136, and 1137, cover all nine ODP sites that penetrated volcanic basement and three dredge sites on the SKP, CKP, Elan Bank, and Broken Ridge (Figs. 1 and 2), and thus provide more spatial and temporal control for the progression of volcanism that created the majority of the Kerguelen LIP.

Mineral-separate $^{40}Ar/^{39}Ar$ plateau ages of basalts from the main Kerguelen LIP range from 122.2 ± 2.0 Ma to 89.93 ± 0.97 Ma (Figs. 1 and 2; Fig. S4, Table S3), and specifically from 122.2 ± 2.0 Ma to 89.93 ± 0.97 Ma for the SKP, from 111.3 ± 1.1 Ma to 106.09 ± 0.97 Ma for Elan Bank, from 108.6 ± 2.2 Ma to 92.8 ± 1.5 Ma for the CKP, and from 99.13 ± 0.45 Ma to 97.7 ± 1.8 Ma for Broken Ridge. The ages show that volcanism progressed from building a large portion of the SKP first, and then to Elan Bank, the CKP, and Broken Ridge (Fig. 1). Three additional samples from dredge sites close to the Kerguelen Archipelago and Heard Island yielded Cenozoic ages ranging from ca. 27 to 0.34 Ma (Fig. 1; Fig. S4; Table S3), which are unrelated to the main construct of the Kerguelen LIP and are not further discussed.

DURATION AND EPISODICITY OF THE KERGUELEN LIP

Our data reveal a ~32 Ma span for the formation of the main construct of the Kerguelen LIP (Fig. 3), longer than published previously (Coffin et al., 2002). We note that samples currently available for the Kerguelen volcanic rocks are from the topmost tens of meters of the basaltic basement (Fig. S1), while wide-angle seismic data revealed an average thickness of ~5.3 km for the basaltic layer (Operto and Charvis, 1996). This raises the possibility that the duration of Kerguelen Plateau construction may have been even longer than the ~32 Ma inferred by our data. Such a long duration of emplacement is atypical for LIPs.

Other Phanerozoic LIPs (e.g., Caribbean LIP, High Arctic LIP) were emplaced over relatively long durations of >5 Ma, but these appear to have been emplaced in multiple 1–5 Ma pulses, according to the data currently available (Bryan and Ernst, 2008; Dockman et al., 2018). Our new mineral-separate $^{40}Ar/^{39}Ar$ ages reveal that the volcanic activity constructing the main portion of the Kerguelen LIP (Fig. 1) was rather *continuous* from before ca. 122 Ma to 90 Ma (Fig. 3). Therefore, the Kerguelen LIP is a potentially unique case of a LIP characterized by continuous, high-volume magmatic flux over 30 Ma and a total volcanic activity lasting >120 Ma.

FORMATION OF THE LONG-LIVED KERGUELEN LIP

Short-lived, single-pulsed LIPs are typically attributed to plume-head eruptions (Richards et al., 1989). Long-lived, multiple-pulsed LIPs require alternatives to the classic, single plume-head model, e.g., involvement of multiple mantle plumes, a single plume dismembered by strong mantle shear flow (Coffin et al., 2002), or secondary instabilities induced by the entrainment of a dense eclogite-derived material at the base of the mantle by thermal plumes (Lin and van Keken, 2005). Our new age data suggest that the prolonged and continuous high magma flux associated with the construction of the Kerguelen LIP may be unique for Phanerozoic LIPs (Figs. 2 and 3) and thus requires a unique model for its behavior over time.

Plate reconstructions model the Kerguelen plume beneath the eastern Indian plate before the breakup of India and Antarctica (Gibbons et al., 2013; Whittaker et al., 2013; Fig. 4A), producing small volumes of igneous rocks in the Tethyan Himalaya (Figs. 4E and 4I). More distal from the plume, the volumetrically minor Bunbury Basalt in southwestern Australia is believed to have been generated by melting of the asthenospheric and enriched lithospheric mantle, perhaps aided by an elevated geotherm from the Kerguelen plume starting at ca. 137 Ma (Olierook et al., 2019a, 2017; Fig. 4E). Following rifting and breakup, seafloor spreading initiated between India and Antarctica, while ultraslow motion continued between the Australian and Antarctic plates. With continued opening of the Indian Ocean, the spreading ridges slowly migrated northward relative to Antarctica and approached the Kerguelen plume (Fig. 4B; Whittaker et al., 2015).

The onset of massive volcanism at the SKP commencing before ca. 122 Ma was triggered

[1]Supplemental Material. Methods, supplemental data, Figures S1–S8, and Tables S1–S5. Please visit https://doi.org/10.1130/GEOL.S.12964847 to access the supplemental material, and contact editing@geosociety.org with any questions.

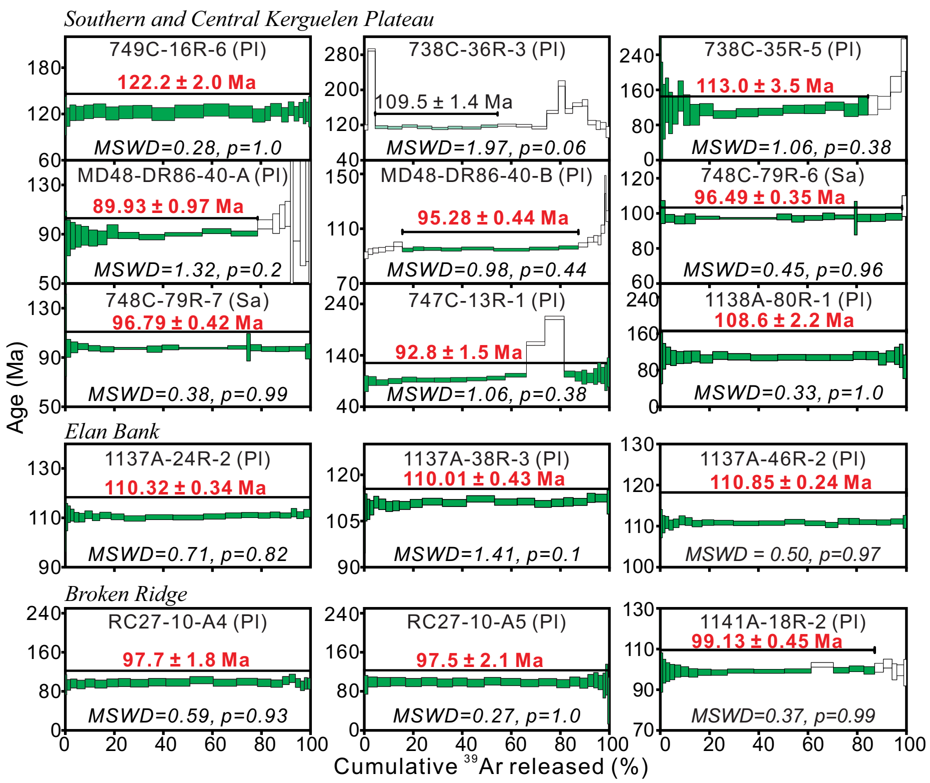

Figure 2. Selected $^{40}Ar/^{39}Ar$ plateaus and mini-plateaus. Steps included in plateau (with >70% ^{39}Ar) and mini-plateau (with 50%–70% ^{39}Ar) are shaded green and turquoise, respectively. Pl—plagioclase; Sa—sanidine; MSWD—mean squared weighted deviation. Plateau ages are indicated in red and bold text. Additional $^{40}Ar/^{39}Ar$ spectra are provided in Figures S4–S6 (see footnote 1). Age uncertainties (2σ) include all sources of uncertainty.

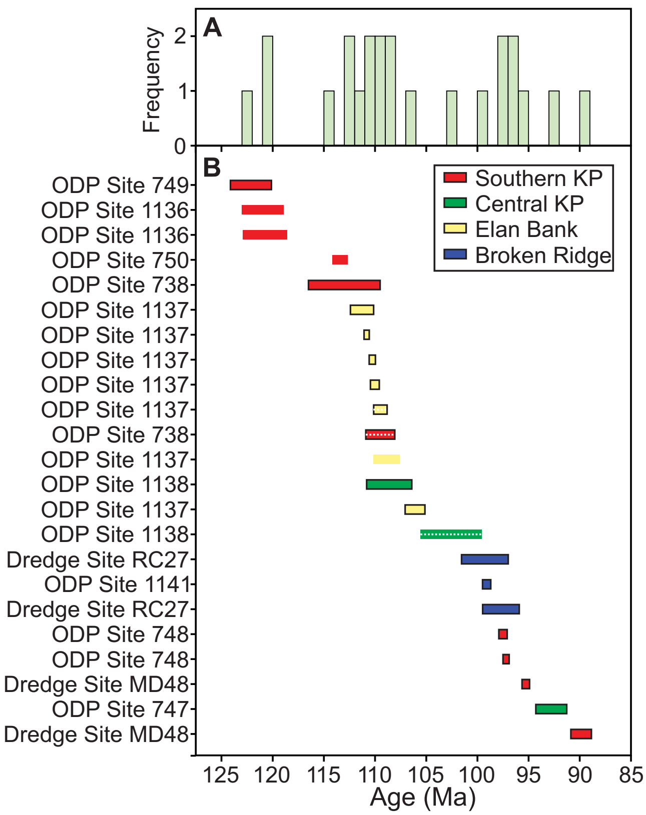

Figure 3. (A) Histogram of ages. (B) Comparison of $^{40}Ar/^{39}Ar$ ages from the main Kerguelen large igneous province. Boxes with outlines are ages from this study. Boxes without outlines are data from Coffin et al. (2002) and Duncan (2002). Boxes with dashed white lines indicate $^{40}Ar/^{39}Ar$ mini-plateau ages (with 50%–70% ^{39}Ar). Width of boxes indicates 2σ uncertainties. For locations of Ocean Drilling Program (ODP) drill sites and dredge sites refer to Figure 1. KP—Kerguelen Plateau.

by the elevated temperature of the Kerguelen plume, which enhanced mantle upwelling at the spreading ridge and led to melting of the asthenosphere and continental lithospheric mantle (dispersed within the Indian Ocean mantle as the breakup of eastern Gondwana; Frey et al., 2002; Fig. 4F). This is supported by the chemical characteristics of the samples from the SKP, Elan Bank, and Broken Ridge, in particular the isotopic compositions, which indicate a mixture of asthenospheric and lithospheric mantle components. The composition of the CKP basalts is dominated by the asthenospheric component, while the Kerguelen plume component is absent (Figs. 4I–4L; Olierook et al., 2017). We note that alternative models have suggested that the Kerguelen plume-head composition could be distinct from that of the plume tail, which can be represented by the composition of the Cenozoic Kerguelen Archipelago and Heard Island basalts and the composition of CKP (ODP Site 1138) basalts, respectively. Therefore, the plume tail could have been a major component in the mantle source of the Cretaceous Kerguelen LIP (Ingle et al., 2003). However, we argue that only asthenospheric and lithospheric components can equally explain the isotopic data (Fig. S7; Olierook et al., 2017).

The required mantle temperatures to yield anomalously thick oceanic crust at the Kerguelen Plateau indicate that the plume must have been proximal. Although moving hotspot reference frames were considered (Doubrovine et al., 2012; O'Neill et al., 2005; Figs. 4A–4D), a fixed hotspot reference frame (Müller et al., 1993; used in cross-section illustrations in Figs. 4E–4H) places the plume closer to the spreading ridges and continental lithosphere fragments of the Kerguelen Plateau (Figs. 4B–4D) and thus better explains enhanced upwelling at the spreading ridge and melting of the continental lithosphere (Figs. 4I–4L). The jumps of the Indian-Antarctic Ridge at ca. 115 Ma (Fig. 4B; Gibbons et al., 2013; Whittaker et al., 2013) and of the Indian-Australian Ridge and Australian-Antarctic Ridge at ca. 108 Ma (Fig. 4D; Whittaker et al., 2013) enabled long-term plume-ridge interaction and form a critical component in sustaining magmatic production of the Kerguelen LIP.

After the formation of the main Cretaceous Kerguelen LIP, the Kerguelen plume produced the less-voluminous Ninetyeast Ridge hotspot track between ca. 83 Ma and ca. 37 Ma and, starting at ca. 34 Ma, produced the Northern Kerguelen Plateau (Fig. S8; Duncan, 2002).

IMPLICATIONS FOR OCEANIC AND CONTINENTAL LIPS

Oceanic plateaus commonly form close to spreading ridges, e.g., the Shatsky Rise (northwestern Pacific; Sager et al., 2019), Ontong Java Plateau (southwestern Pacific), and Caribbean

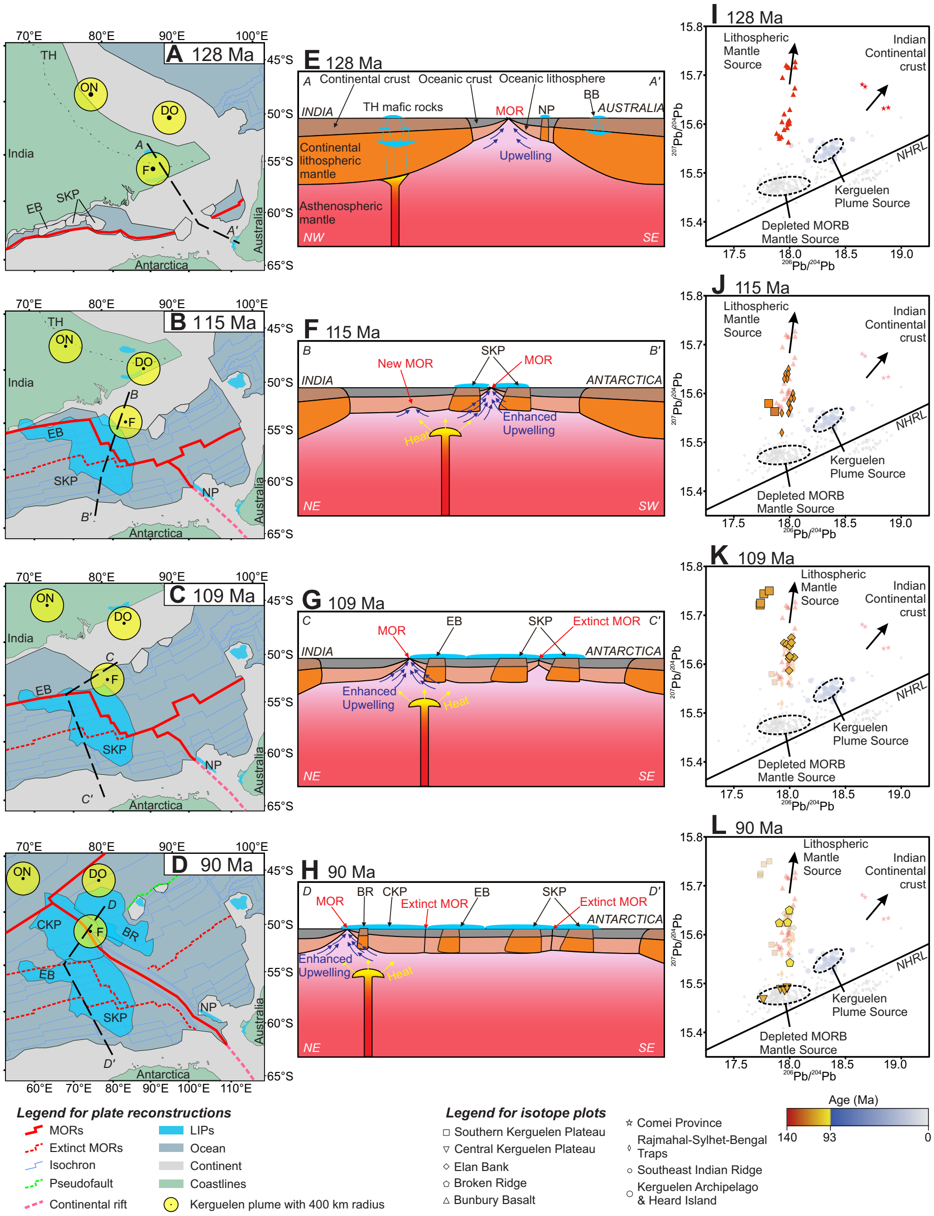

Figure 4. (A–D) Plate reconstructions at 128 Ma, 115 Ma, 109 Ma, and 90 Ma (in fixed Antarctica reference frame); after Gibbons et al. (2013) and Whittaker et al. (2013). Plume locations are: DO—Doubrovine et al. (2012); F—a fixed plume reference frame (Müller et al., 1993); ON—O'Neill et al. (2005). (E–H) Schematic illustrations showing formation of the Kerguelen large igneous province (LIP). Fixed plume location (Müller et al., 1993) was used. (I–L) Isotope data of basalts. In J–L, the Kerguelen large igneous province basalts that were produced in the previous periods are shown in semi-transparent symbols. Isotope data and references are provided in Table S5 (see footnote 1). Data were filtered for loss on ignition (LOI <2%), except for the depleted mid-oceanic ridge basalt (MORB) mantle source, where there are few data with LOI. Data from the Kerguelen Archipelago and Heard Island are shown to indicate the composition of the Kerguelen plume. BB—Bunbury Basalt; BR—Broken Ridge; CKP—Central Kerguelen Plateau; EB—Elan Bank; MOR—mid-ocean ridge; NHRL—Northern Hemisphere Reference Line (Hart, 1984); NP—Naturaliste Plateau; SKP—Southern Kerguelen Plateau; TH—Tethyan Himalaya.

LIP (cf. plate reconstructions of Whittaker et al. [2015]). Studies of the Shatsky Rise (Sager et al., 2019) suggest it formed through plume-ridge interaction at a triple junction that caused thicker-than-normal oceanic crust, rather than via massive LIP volcanism emplaced onto the ocean floor after the formation of oceanic crust. We argue that the Kerguelen Plateau was formed by a similar process of plume-induced excess volcanism at spreading ridges. This is supported by the isotopic data, which revealed dominant asthenospheric and continental lithospheric mantle components, instead of obvious plume components in the mantle source of the Cretaceous Kerguelen Plateau basalts (Figs. 4I–4L). However, in contrast to the Shatsky Rise, the major portion of which formed over a short interval of ~3 Ma (Sager et al., 2019), the Cretaceous Kerguelen Plateau continuously erupted for ≥32 Ma This is due to the jumps of the spreading ridges toward the plume (Figs. 4B–4D) and the slow migration and spreading rates of the Indian-Antarctic and Australian-Antarctic Ridges (Müller et al., 1998; Olierook et al., 2020; Whittaker et al., 2013), which enabled long-term plume-ridge interaction.

Some oceanic plateaus emplaced since ca. 140 Ma may share the plume-ridge interaction model with the Kerguelen LIP (Whittaker et al., 2015). Although continuous long-term magmatic activity has so far not been observed for other oceanic LIPs demonstrating plume-ridge interaction, controls on the timing of magmatism for most oceanic plateaus are extremely sparse (cf. review of Ontong Java LIP geochronology; Olierook et al., 2019b). Most lack robust and precise data that would allow a comprehensive evaluation of their emplacement episodicities. The longevity of oceanic plateaus formed via plume-ridge interaction is probably a continuum, modulated by the presence of ridge jumps and the rate at which spreading ridges migrate away from the plume. To test a continuum theory, more geochronology data for other oceanic plateaus are needed.

Oceanic plateaus such as the Kerguelen Plateau and the Shatsky Rise (Sager et al., 2019) suggest that caution should be exercised for a direct analogy between oceanic and continental LIPs. In the case of a continental flood-basalt province, magma must go through thick and complex continental crust. As massive volumes of basalts accumulate in and above the crust, large volumes of cooled magma gradually clog the magmatic conduits, making further magma output difficult. This might be an important factor leading to the one or several ~1–5 Ma punctuated pulse(s) of continental LIPs. For the Kerguelen LIP, however, ridge jumps and spreading of the mid-ocean ridges created sufficient space for long-term continuous eruption and basalt accumulation at the spreading center.

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