Widespread Neogene volcanism on Central Kerguelen Plateau, Southern Indian Ocean

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**ABSTRACT**

We report new age determinations and compositions for rocks from 18 dredge hauls collected from eight submarine areas across Central Kerguelen Plateau (CKP). Sea knolls and volcanic fields with multiple small cones were targeted over a \(\sim 125,000 \text{ km}^2\) region that includes Heard and McDonald Islands. Large early Miocene (22–16 Ma) sea knolls rise from the western margin of the CKP and are part of a NNW–SSE line of volcanic centres that lie between Iles Kerguelen and Heard and McDonald Islands. These are probably related to hotspot activity now underlying the Heard Island area. We see evidence of much younger activity (5 Ma to present) in volcanic fields to the north of, and up to 300 km NE of, Heard Island. Compositions include basanite, basalt and trachybasalt, which are broadly similar to plateau lava flows from nearby Ocean Drilling Program Site 1138, lower Miocene lavas at Iles Kerguelen, dredged rocks from the early Miocene sea knolls, and Big Ben lavas from Heard Island. Geochemical data indicate decreasing fractions of mantle source melting with time. We propose that a broad region of the CKP became volcanically active in Neogene time owing to incubation of plume material at the base of the relatively stationary overlying plateau. The presence of pre-existing crustal faults gave access for melts from the Heard mantle plume to rise to the surface.

**INTRODUCTION**

The Kerguelen Plateau (with the once contiguous Broken Ridge) encompasses \(\sim 1.8 \times 10^6 \text{ km}^2\) of seafloor in the southern Indian Ocean (Figure 1). This large igneous province (LIP) is the second largest on Earth (Coffin & Eldholm, 1994) and, together with Ninetyeast Ridge, was created by the Kerguelen/Heard hotspot from Early Cretaceous until the present (Coffin et al., 2002; Duncan, 2002) as the Indian Ocean evolved through a series of plate reorganisations (e.g., Gibbons, Whittaker, & Muller, 2013; Royer et al., 1992). We use the term ‘hotspot’ to mean an elevated upper mantle thermal anomaly, although alternative interpretations exist (e.g., Green & Falloon, 2015).

The Central Kerguelen Plateau (CKP), bounded by the younger Northern and older Southern Kerguelen Plateau provinces (Coffin et al., 2002), covers an area of \(\sim 4.1 \times 10^5 \text{ km}^2\), and until ca 43 Ma (Houtz, Hayes, & Markl, 1977) abutted the 4.4 \(\times 10^5 \text{ km}^2\) Broken Ridge (now on the Australian plate at \(\sim 30^\circ\)S). Basalt cored at Ocean Drilling Program (ODP) Site 1138, that is interpreted as the top of the igneous foundation of the CKP, has yielded an \(^{40}\text{Ar}–^{39}\text{Ar}\) age of 100.4 ± 0.7 Ma and is slightly older than two ages of 95.1 ± 0.8 Ma (ODP Site 1141) and 94.5 ± 0.6 Ma (ODP Site 1142) from Broken Ridge (Coffin et al., 2002; Duncan, 2002). The CKP and Broken Ridge thus constitute the mid-Cretaceous component of the time-transgressive, ca 130–0 Ma Kerguelen/Broken Ridge LIP. Drilling at ODP Site 1138, the closest sampling of the plateau lava flows beneath the study area (Figure 1) recovered 144 m of cobbles of flow-banded dacite overlying volcaniclastic deposits and tholeiitic to transitional basaltic lava flows, that are interpreted as subaerial to shallow water eruptions through remnants of continental crust (Frey, Coffin, Wallace, & Weis, 2003). The CKP (Figure 2) is structurally complex and includes elements of post-emplacement volcanism, rifting, strike-slip and normal faulting, and sedimentary basin formation (e.g., Coffin, Davies & Haxby, 1986; Houtz et al., 1977; Munsch & Schlich, 1987; Munsch, Rotstein, Schlich, & Coffin, 1993). Post-emplacement volcanism is most obvious on the volcanically active Heard and McDonald Islands, but satellite altimetry (Coffin et al., 1986), seismic reflection data (Ramsay et al., 1986), and single-beam echo sounding (Beaman & O’Brien, 2011; Coffin & Leser, 2012) have revealed more than 200 sea knolls and smaller volcanic features on the seafloor of the CKP. Until the present study, basalt ages, petrology and geochemistry have been reported from only one of these features, the unnamed large sea knoll (‘Kerimis’ expedition) closest to Iles Kerguelen (Figure 2) (Weis et al., 2002). These rocks are largely alkali basalts with dominantly olivine, and lesser clinopyroxene phenocrysts. A significant finding was picritic basalts with 30–35 vol% olivine, although high-MgO rocks are...
also reported from îles Kerguelen (Doucet, Scoates, Weis, & Giret, 2005). Overall, the major- and trace-element compositions are very similar to those of Upper Miocene alkali basalts and basanites of the southeast province of îles Kerguelen (Weis, Frey, Leyrit, & Gautier, 1993).

The current locus of the hotspot, active since at least ca 130 Ma (Coffin et al., 2002), is debatable, since young volcanic activity has occurred at îles Kerguelen (Ballestracci & Nougier, 1984) as well as on the Heard and McDonald Islands (Patrick & Smellie, 2013), separated by ~500 km (Figure 1). Heard Island is dominated by Big Ben, a roughly circular active volcanic mas-sif that attains an elevation of 2745 m, and nearby McDonald Island, which is also active. Duncan, Quilty, Barling, and Fox (2016) have documented a volcanic history at Heard Island that extends back to 22 Ma. Seismic tomography (e.g., Montelli et al., 2004; Zhao, 2004) cannot currently resolve whether the CKP is underlain by a single or multiple plumes. Plate motion modelling, assuming a relatively stationary mantle plume, achieves an optimum fit of predicted track to Kerguelen Plateau and Ninetyeast Ridge geometry and ages with a hotspot beneath Heard Island (Steinberger, 2000). However, in the hotspot reference frame, the Antarctic plate containing the entire Kerguelen Plateau has been relatively stationary for most of Cenozoic time (e.g., Seton et al., 2012), which may contribute to a broad region of plume uplift and magmatic influence. We obtained sample material from bottom trawl dredging, which was a component of benthic fisheries surveys by FV Southern Champion voyages SC26 (April–May 2003) and SC50 (June 2008; Welsford, Ewing, Constable, Hibberd & Kilpatrick, 2014). The recovered material consists almost entirely of fresh subangular to subrounded volcanic pebbles, with occasional rare cobble-sized pieces. The material also includes rare pieces of subaerial tuff, volcaniclastic sediments, marine nano/foram ooze, as well as very rare fresh plutonic rocks, which have a similar size range to the volcanic rocks. One additional sample was recovered from Pike Bank by a fishing vessel and delivered to Professor Patrick Quilty at the University of Tasmania; this sample has no precise depth information and is referred to in this paper as ‘Captain’s Sample.’

The recently surveyed region of the CKP has been subdivided based on morphological characteristics (Meyer, Constable, & Williams, 1999). Our samples come from the following local areas. Aurora, Coral and Pike Banks, all at the western margin of the plateau, are sea knolls that rise steeply from deep water (Figure 2). Summit water depths in these areas range from 170 to 300 m below sea-level. The banks have relatively large and flat tops, and feature outcrop pinnacles, boulders and a covering of sand. Biological productivity is locally very high owing to upwelling of nutrient-rich waters as the Antarctic Circumpolar Current intercepts the banks, and

![Figure 1. Location map for Kerguelen Plateau, southern Indian Ocean, showing major physiographic features, based on Sandwell, Müller, Smith, Garcia, and Francis (2014) gravity data overlain by etopo2 in polar stereographic projection. Broken Ridge can be seen in the black and white insert map, as the large shallow region just to the northeast of the red outlined box.](image-url)
dissolved iron availability (Blain, Sarthou, & Laan, 2008). Another nearby elevated area, apparently constructed on older plateau lavas is Shallow Heard Island–McDonald Island Platform (HIMIP). Shell Bank, at the eastern margin of the plateau, is a 170–350 m-deep, isolated sea knoll with a flat, even top. The bank has steep craggy slopes and rims, indicative of outcropping crustal rock. The southern area of the study region includes the localities of Southeast HIMIP, Deepeast HIMIP and Gunnari Ridge. These areas exhibit broad, flat and even surfaces with the east and west margins generally steep and undulating to craggy slopes. Water depths exceed 500 m. Until now, only one of the at least several hundred post-plateau construction submarine volcanic features distributed over a few hundred thousand square kilometres of the CKP has been sampled. We have undertaken age determinations, petrological and geochemical analyses of dredged samples from this broad area, to document the age range and compositional variability of volcanism. The new data are consistent with a long-lived hotspot beneath the thick CKP crust and presumed thick lithosphere.

Analytical methods
Sample description and classification

We first classified dredged rocks by size and macroscopic character. Samples include basalts, which we interpret as seafloor crust, either angular pieces plucked from plateau, sea knoll and smaller outcrops, or gathered from pavements of rounded cobbles and pebbles, and felsic crystalline rocks such as granite, tonalite and syenite, which are the subject of ongoing studies. Brief petrographic descriptions accompany geochemical data under ‘Rock Compositions’ below.

40Ar–39Ar incremental heating

We first evaluated the dredged rocks in thin-section for suitability for compositional analyses and age determinations. We then prepared the least altered and best crystallised samples for radiometric dating by crushing and sieving to obtain the 0.1–0.5 mm size fraction. We removed obvious altered material (phenocrysts, clay- or carbonate-filled vesicles and veins). All samples were ultrasonically washed in nitric and hydrochloric acid solutions, then deionised water and dried. We monitored the potential impact of Cl on 36Ar production by measuring 38Ar, and found no significant contamination. Finally, we hand-picked the rock fractions to obtain clean groundmass aliquots for analyses.

We wrapped the prepared samples in Cu-foil and loaded them in evacuated quartz tubes for irradiation in the TRIGA experimental nuclear reactor at Oregon State University (OSU). Samples sat near the central core of the reactor for 6 h.
at 1 MW power, which we monitored with FCS sanidine (28.201 Ma; Kuiper et al., 2008). After cooling, we loaded the irradiated samples into an all-metal, gas extraction line, with a chamber fitted with a BaF window. We heated each sample with a 10 W CO2 continuous power laser, in eight to 38 temperature steps from 400°C to fusion. Gas released at each step passed over several sets of Zr–Al getters before analysis of Ar isotopic composition (masses 36, 37, 38, 39 and 40) using either of two instruments: the first 12 samples with a MAP 215/50 mass spectrometer, fitted with an ion multiplier; the second 13 samples with an ARGUS VI multi-collector mass spectrometer, with four Faraday cups and an ion multiplier; both instruments at OSU.

We calculated sample ages using the ArArCALC software (Koppers, 2002) with the corrected Steiger and Jager (1977) decay constant of $5.53 \pm 0.09 \times 10^{-10} \text{yr}^{-1}$ ($2\sigma$) as reported by Min, Mundil, Renne, and Ludwig (2000). We examined age spectra for contiguous, concordant heating step ages comprising at least 50% of the gas released. Plateau ages are the weighted mean (by inverse variance) of five or more such concordant temperature steps comprising a majority of the total $^{39}\text{Ar}$ released (Figure 3a). Generally, these are simple age spectra with clear middle- and high-temperature plateaus and commonly exhibit Ar-loss at low-temperature steps, or Ar-recoil at low- and high-temperature steps. Isochron ages, calculated from the slope of linear regressions of $^{40}\text{Ar}/^{36}\text{Ar}$ vs $^{39}\text{Ar}/^{36}\text{Ar}$ ('normal', Figure 3a) and $^{36}\text{Ar}/^{40}\text{Ar}$ vs $^{39}\text{Ar}/^{40}\text{Ar}$ ('inverse') step compositions, agree with the plateau ages and initial $^{40}\text{Ar}/^{36}\text{Ar}$ ratios are within error of the atmospheric value (295.5). We calculated the flux gradient factor, $J$, by fitting a second-order polynomial to measured values at seven positions (two measurements each) along the irradiated vials, and interpolating for sample position. Ages are reported with $2\sigma$ analytical errors that include uncertainties in $J$.

Figure 3 (a) $^{40}\text{Ar}–^{39}\text{Ar}$ incremental heating experiment age spectra (left panels) and isochron plots (right panels) for two basalts recovered from the Shallow HIMIP study area.
Compositions

Major-element and trace-element compositions (Table 2) of the same material used in age determinations were determined by X-ray fluorescence methods using a PANalytical Axios Advanced X-Ray Spectrometer at the University of Tasmania using the methods described in Falloon et al. (2007). LOI values range from –0.58 to 2.66 (Table 2). These values correlate strongly with degree of alteration in the samples as observed in petrographic thin-section examination. The majority of samples chosen for dating have <2 wt% LOI and in thin-section are completely fresh or have very minor amounts of alteration, which is confined to patchy zones in the groundmass and minor alteration along fracture planes in olivine. Samples >2 wt% LOI are best described as ‘slightly altered.’ Alteration in these samples is confined to the groundmass, olivine phenocrysts and infilling of amygdales. Although there is petrographic evidence for alteration, this has not significantly changed the primary geochemical characteristics of the lavas. There are no correlations between LOI with age of sample or any geochemical element or index. Thus, we are confident in using the geochemistry of the dated lavas for rock classification as well as in comparing the major- and trace-element data with the lava compositions reported from Iles Kerguelen and other locations on the CKP.

Results

Age determinations

We summarise age determinations of the dredged rocks in Table 1, which includes total fusion, plateau and normal isochron ages, and initial $^{40}$Ar/$^{39}$Ar, each with analytical errors quoted at the 2σ level. MSWD is an F-statistic that compares the variance within step ages with the variance about the plateau age. Values less than about 2 indicate that the step ages that comprise the plateau all come from the same population and that the plateau age is acceptable from a statistical perspective. The selection of heating step ages to include in plateau and isochron ages is somewhat subjective (e.g.,

Figure 3 (b) $^{40}$Ar–$^{39}$Ar age spectra for representative samples from the eight survey areas, CKP.
McDougall & Harrison, 1988), although we are guided by the desire to include as many concordant steps as possible without exceeding statistically significant MSWD values. Representative paired age spectra and isochron plots for two samples from Southeast HIMIP are shown in Figure 3a. Most sample ages are easily interpreted from plots such as these. An additional plot, K/Ca vs cumulative $^{39}$Ar released (Supplementary Papers), comes from measurements of $^{39}$Ar/$^{37}$Ar and is useful in deciphering the composition of phase(s) contributing to the release of Ar with increasing temperature in the whole rock heating experiments. Complete analytical data for all samples are provided in Supplementary Papers. We discuss age data for each of the eight regions (with example age spectra shown in Figure 3b).

**Pike Bank**

Pike Bank is located to the east of ‘Kerimis’ sea knoll from which Weis et al. (2002) reported dredged rock ages and compositions. It is also part of a roughly E-W-trending curvilinear arc of sea knolls, including Discovery Bank and Shell Bank that cross the CKP. Sample 1180010-2 produced an 18-step plateau comprising 53% of the total gas released, yielding an age of 18.07 ± 0.20 Ma. The corresponding isochron age is compatible, at 17.49 ± 0.93 Ma, with a $^{40}$Ar/$^{36}$Ar intercept within analytical error of atmosphere. A similar plateau age of 17.56 ± 0.19 Ma is derived from all eight steps from sample 1180011-2; isochron age 17.56 ± 0.20 Ma. A third sample from this locality, named ‘Captain’s sample,’ exhibits a 38-step age spectrum strongly affected by recoil. The age spectrum shows decreasing step ages with increasing temperature, and no distinct plateau. Such a pattern is common in fine-grained rocks, in which $^{39}$Ar and $^{37}$Ar are moved within crystal lattices by recoil following neutron capture during irradiation. Relatively K-rich phases (e.g., secondary clay, cryptocrystalline matrix) lose $^{39}$Ar to relatively K-poor phases (e.g., clinopyroxene, olivine). Since the K-rich and K-poor phases...
atmospheric initial Ar from the 40Ar/36Ar intercepts. Hence, the isochron ages are compatible, and there is no evidence for non-atmospheric initial Ar from the 40Ar/36Ar intercepts. The corresponding isochron ages are consistent, so we calculate a total fusion age of 21.09 ± 0.28 Ma, comprising all steps; the corresponding isochron age is 0.290 ± 0.002 Ma from 16 of 31 steps (73% of total gas) derived from sample 154-1; the isochron age (0.285 ± 0.002 Ma) is consistent. This area, then, presents evidence of degas at low and high temperatures, respectively, the age spectrum that develops through incremental heating shows older ages at low temperature steps and younger ages at high temperature steps (Figure 3b). Under the assumption that no radiogenic 40Ar has been lost from the rock, the best estimate of crystallisation age is the sum of all steps, which is equivalent to a total fusion (single step) age. In this case, we calculate a total fusion age of 16.44 ± 0.08 Ma. Hence, we determine activity between 18.1 and 16.4 Ma at Pike Bank.

**Coral Bank**

Coral Bank is a large sea knoll to the SSW of Pike Bank and lies on a separate NE–SW-trending arc of sea knolls that extends towards McDonald Island. We analysed samples from two dredge hauls. Sample 203-1 exhibited a recoil pattern, with step ages decreasing smoothly from 23 to 15 Ma. No significant age plateau can be discerned, so we calculate a total fusion age of 21.09 ± 0.10 Ma as the best estimate of this sample’s age. Two samples from dredge 205 gave convincing and consistent plateau ages, 19.54 ± 0.21 Ma and 19.66 ± 0.13 Ma, both from six of eight step ages. The corresponding isochron ages are compatible, and there is no evidence for non-atmospheric initial Ar from the 40Ar/36Ar intercepts. Hence, we find Coral Bank formed from 21.1 to 19.5 Ma.

**Aurora Bank**

The next large sea knoll to the SE is Aurora Bank. We analysed samples from two dredge hauls from this location. Two samples from dredge 177 gave excellent and consistent plateau ages, 18.51 ± 0.24 Ma and 18.54 ± 0.19 Ma, both from eight of step ages. The corresponding isochron ages are compatible, and the 40Ar/36Ar intercepts are of atmospheric composition. Sample 189-1 provided a clear plateau age at 17.19 ± 0.22 Ma, comprising all steps; the corresponding isochron age is consistent. Thus, Aurora Bank formed from 18.5 to 17.2 Ma.

**Shallow HIMIP**

Shallow HIMIP is immediately ENE of Aurora Bank. Sample 156-3 produced a six-step plateau age of 2.41 ± 0.28 Ma from 82% of the gas released. The isochron age is compatible, and the 40Ar/36Ar intercept is within analytical error of the atmospheric value. Hence, we accept the plateau age as a reliable measure of the crystallisation age of this rock. We analysed two samples from dredge 154. We observe a clear plateau age of 0.290 ± 0.002 Ma from 16 of 31 steps (73% of total gas) derived from sample 154-1; the isochron age (0.285 ± 0.004 Ma) is consistent. This area, then, presents evidence of recently active volcanism. Sample 154-4, however, is much smaller.
### Table 2. Major- and trace-element geochemistry of dredged volcanic rocks from the CKP.

| Location                  | Sample no. | Plateau Shallow | Aurora Bank | Shell Bank | Coral Bank | Pike Bank | Plateau Southeast | Plateau Deep East | Gunnari Ridge |
|---------------------------|------------|-----------------|-------------|------------|------------|-----------|-------------------|------------------|--------------|
|                           | 156-3      | 154-1           | 154-4       | 189-1      | 177-1      | 177-3     | 253-12           | 253-14           | 274-2        |
|                           |            |                 |             | 274-3      | 274-2      | 205-1     | 205-2            | 203-1            | 203-1        |
|                           | 1180001-2  | 1180001-2       | 1180041-1a  | 1180044-1a | 1180042-1  | 1180004-1a | 1180004-1a       | 1180051-2       | 1180256-2    |
|                           |            |                 |             |            |            |           |                  |                  | 1180256-1    |
| SiO₂                     | 43.74      | 47.79           | 51.70       | 47.85      | 48.00      | 48.00     | 53.23             | 53.23            | 51.77        |
| TiO₂                     | 5.91       | 4.52            | 3.46        | 2.59       | 3.54       | 3.39      | 5.27              | 4.27             | 4.46         |
| Al₂O₃                    | 11.19      | 13.74           | 15.55       | 10.01      | 9.05       | 9.05      | 15.90             | 19.16            | 12.12        |
| FeO                      | 3.46       | 2.59            | 3.15        | 2.59       | 3.15       | 3.09      | 3.15              | 2.61             | 2.92         |
| MnO                      | 0.18       | 0.15            | 0.15        | 0.15       | 0.15       | 0.15      | 0.15              | 0.15             | 0.15         |
| MgO                      | 9.49       | 6.00            | 5.14        | 14.99      | 8.20       | 9.72      | 8.56              | 7.57             | 8.56         |
| CaO                      | 9.69       | 4.95            | 7.89        | 9.13       | 9.06       | 9.04      | 8.57              | 8.57             | 8.57         |
| Na₂O                     | 2.51       | 2.94            | 3.61        | 1.83       | 2.05       | 2.05      | 3.68              | 3.68             | 3.68         |
| K₂O                      | 2.41       | 2.77            | 2.34        | 1.76       | 1.73       | 1.75      | 2.45              | 2.45             | 2.45         |
| P₂O₅                     | 1.10       | 0.99            | 0.71        | 0.41       | 0.45       | 0.53      | 0.58              | 0.58             | 0.58         |
| LOI                      | 1.53       | 1.40            | 1.00        | 2.54       | 0.67       | 0.76      | 1.14              | 1.04             | 1.04         |
| Ni                       | 221.9      | 77.9            | 79.4        | 467.5      | 465.0      | 200.0     | 499.1             | 499.1            | 499.1        |
| Cr                       | 382.4      | 96.5            | 52.3        | 618.6      | 600.4      | 194.5     | 740.0             | 740.0            | 740.0        |
| Sc                       | 26.9       | 21.9            | 21.6        | 21.5       | 24.5       | 23.4      | 27.3              | 27.3             | 27.3         |
| V                        | 288.7      | 280.3           | 241.8       | 204.4      | 219.6      | 253.3     | 256.2             | 256.2            | 256.2        |
| Nb                       | 61.7       | 61.7            | 48.3        | 29.6       | 26.7       | 34.2      | 42.7              | 42.7             | 42.7         |
| Zr                       | 347.9      | 351.6           | 376.6       | 199.1      | 237.2      | 276.5     | 205.7             | 205.7            | 205.7        |
| Y                        | 27.1       | 32.8            | 31.7        | 18.0       | 20.7       | 26.9      | 20.3              | 20.3             | 20.3         |
| Rb                       | 47.8       | 64.5            | 34.5        | 35.8       | 32.9       | 17.4      | 34.6              | 34.6             | 34.6         |
| Ba                       | 679.8      | 625.9           | 544.0       | 436.6      | 379.0      | 418.3     | 525.2             | 525.2            | 525.2        |
| Sr                       | 973.2      | 872.1           | 691.5       | 380.3      | 476.4      | 625.9     | 604.6             | 604.6            | 604.6        |
| La                       | 49.3       | 55.3            | 47.9        | 34.5       | 33.0       | 39.7      | 39.0              | 39.0             | 39.0         |
| Ce                       | 103.4      | 116.4           | 99.4        | 63.4       | 69.8       | 75.2      | 72.9              | 72.9             | 72.9         |
| Nd                       | 57.9       | 60.4            | 51.4        | 32.3       | 36.2       | 41.0      | 36.9              | 36.9             | 36.9         |

Major elements are in wt% resumed to 100% on anhydrous basis with all Fe calculated as FeO (FeOT). LOI denotes loss of ignition (in wt%). Trace elements are in ppm. CS refers to 'Captain’s sample.'
older. The age spectrum shows decreasing step ages with increasing temperature and no distinct plateau—a clear recoil pattern. Under the assumption that no radiogenic $^{40}$Ar has been lost from the rock, the best estimate of crystallisation age is the sum of all steps, which is equivalent to a total fusion (single step) age. In this case, we calculate the total fusion age at $15.51 \pm 0.08$ Ma.

**Shell Bank**

Shell Bank is a shallow area of volcanic centres that lies on the eastern margin of the CKP. We analysed samples from two dredges from this locality. Samples 253-12 and 253-14 produced convincing plateaus, with ages of $1.46 \pm 0.19$ Ma and $0.320 \pm 0.010$ Ma, respectively. Corresponding isochron ages are compatible and indicate atmospheric initial Ar compositions. Sample 274-2 yielded a similarly young and significant plateau, with an age of $0.168 \pm 0.090$ Ma. Hence, we observe an area of relatively young volcanic activity, which is far ($\sim 300$ km) from the vicinity of the previously known active volcanoes in the region—Heard and McDonald Islands. Sample 274-3, however, has a complex age spectrum, with variable but older step ages from low temperatures, decreasing to minimum step ages of about 18 Ma, then climbing to much older step ages from high temperature release. This pattern is typical of rocks containing ‘excess’ $^{40}$Ar, derived from incomplete outgassing of the magma at the time of crystallisation. Hence, using the atmospheric value ($\sim 295.5$) for initial $^{40}$Ar/$^{36}$Ar produces variable and erroneously old step ages. An estimate of the crystallisation age comes from regression of collinear step age compositions in the isochron plot, resulting in a slope equivalent to $15.02 \pm 1.38$ Ma. The initial $^{40}$Ar/$^{36}$Ar composition indicated for these steps is greater than the atmosphere, at $322 \pm 7$. However, the MSWD for this regression is larger than the cutoff for statistical significance, and we conclude that this sample is probably between 18 and 15 Ma. We also note that this sample is compositionally distinct, in being tholeiitic (see Figure 4) and having a much higher Zr/Nb, both compatible with plateau building lava flows rather than central volcanoes (e.g., sea knolls).

![Figure 4. Total alkalis (Na$_2$O + K$_2$O) vs SiO$_2$ for rocks from the CKP. In addition to the samples identified in the legend, fields are shown for dredged rocks from sea knolls (green) located between the Iles Kerguelen and Heard Island (Weis et al., 2002), lavas recovered at ODP Site 1138 (purple, Frey et al., 2003), lavas from the northern Kerguelen Plateau (peach, Davies et al., 1989; Mahoney et al., 1995), and lower Miocene lavas from Iles Kerguelen (light blue, Frey, Nicolaysen, Kubit, Weis, & Giret, 2002). Short dashed line marks the boundary between tholeiitic and alkali basalt compositions (Macdonald & Katsura, 1964).](image-url)
**Gunnari Ridge**

Gunnari Ridge lies to the southwest of Shell Bank, on the southeast margin of HIMIP. Two dredges provided datable rocks. Sample 1180256-2 developed an excellent plateau at 0.152 ± 0.003 Ma from 31 steps, while sample 1180256-1 was compatible but less precise (more altered, LOI = 2.5 wt%) at 0.059 ± 0.170 Ma from eight of eight heating steps. Sample 1180180-2 from a second dredge also produced an excellent plateau, with a somewhat older age of 0.482 ± 0.008 Ma. Isochrons for all three samples are compatible with the plateau ages. It appears that Gunnari Ridge is another area of young volcanic activity at significant distance (>150 km) from Heard and McDonald Islands. We note that Sr-dating of biogenic carbonate from volcanics indicates that older basement rocks are also exposed in this area.

**Southeast HIMIP**

Some 50 km to the southwest of Gunnari Ridge lies another raised area of apparent volcanic landforms, Southeast HIMIP. We dated samples from three dredges from this area. Sample 1180042-1 yielded an excellent plateau with age 5.44 ± 0.09 Ma; the isochron age is compatible and similarly precise (Figure 4a). Samples 1180043-1 and 1180044-1 produced good plateaus with ages of 0.436 ± 0.009 Ma (7 of 31 steps) and 1.62 ± 0.01 Ma (16 of 31 steps), respectively, with compatible isochron ages. Thus, we observe an age range of 5.4 to 0.4 Ma for crustal rocks in this area. This is consistent with the 3.6–2.5 Ma age determined by Quilty, Murray-Wallace, and Whitehead (2004) for sedimentary rock containing *Austrochlamys heardensis* (Fleming) recovered from this feature.

**Deepoast HIMIP**

At a distance of about 30–40 km to the southwest lies another raised area of apparent volcanic landforms, Deepeast HIMIP. We dated samples from two dredges from this area. Sample 1180050-1 yielded an excellent plateau with age 2.59 ± 0.01 Ma; the isochron age is compatible and similarly precise. The robust plateau (7 of 8 step ages) from sample 1180051-2 is younger and less precise, at 0.562 ± 0.105 Ma. Hence, ages in this area continue the trend of young volcanic activity along the southeast margin.

**Rock compositions**

Major- and trace-element concentrations, and mineralogy provide a basis for classifying the dredge rocks and comparing them with other Neogene volcanic rocks from Iles Kerguelen and the CKP. A much more complete description of geochemical data, including isotopic and rare earth element compositions, will be reported in a companion paper (T. J. Fallon, pers. comm.). Compositions of the dredged volcanic rocks plotted in the total alkalis vs silica rock classification diagram of Le Maitre et al. (1989) show that the older rocks (20–17 Ma), principally from the large sea knolls, range from basanite, basalt and basaltic trachyandesite, with basalt of both alkali and tholeiitic character being the dominant rock type (Figure 4). In contrast, the younger dated volcanics (5–0 Ma) include several basanites, trachybasalts and trachyandesites and have overall relatively higher total alks compared with the older rocks. The following is a brief petrographic summary of the primary mineralogy of the dated rock samples:

**Early to middle Miocene lavas**

**Basanite**

The sole basanite is the ‘Captain’s Sample.’ It consists of ~15 modal % (this and all subsequent modes are based on visual inspection of petrographic thin-sections or crushed rock fractions under stereo-binocular microscope) of olivine and clinopyroxene phenocrysts set in a devitrified glassy matrix with plagioclase and clinopyroxene microlites.

**Basalt**

Basalts include two groups of samples. The first group is ‘alkalic’ (see Figure 4; samples 189-1, 177-1, 177-3, 1180011-2 and 1180010-2). These samples contain ~7–15 modal % olivine + clinopyroxene ± plagioclase ± Ti-magnetite phenocrysts in a glassy interstitial groundmass with plagioclase microlites and clinopyroxene and oxide crystals. Sample 189-1 has a relatively coarser grained groundmass indicative of a more slowly cooled lava flow interior. The second group is ‘tholeiitic’ (see Figure 4; samples 274-3, 203-1 and 205-2). These samples are relatively aphyric lavas (~1–<3 modal % phenocrysts) with glassy interstitial groundmass with plagioclase microlites and clinopyroxene and oxide crystals. They contain rare euhedral plagioclase laths as phenocrysts, as well as subhedral clinopyroxene phenocrysts.

**Basaltic trachyandesites**

Samples 205-1 and 154-4 are basaltic trachyandesites. Sample 205-1 is an aphyric lava with a glassy interstitial groundmass with plagioclase microlites and clinopyroxene and oxide crystals. Sample 154-4 contains ~5 modal % plagioclase + clinopyroxene + Ti-magnetite phenocrysts in a glassy interstitial groundmass, where the plagioclase microlites display a well-developed trachytic texture. The sample also contains rare resorbed olivine phenocrysts.

**Late Miocene–Pleistocene**

**Basanites**

Basanite samples (274-2, 156-3, 253-12, 1180180-2) contain ~8–17 modal % olivine and clinopyroxene phenocrysts in a glassy devitrified matrix with plagioclase and clinopyroxene microlites.

**Trachybasalts**

Trachybasalt samples (154-1, 253-14, 1180051-2, 1180256-2) contain ~3–10 modal % olivine + clinopyroxene ± plagioclase ± Ti-magnetite phenocrysts set in a glassy devitrified matrix with plagioclase and clinopyroxene microlites.
**Basaltic trachyandesites**

Trachyandesites samples (1180043-1a, 1180044-1a, 1180050-1a) are aphyric lavas with a glassy intersertal groundmass with plagioclase microlites and clinopyroxene and oxide crystals. Sample 1180042-1 contains ~3 modal % plagioclase + clinopyroxene + Ti-magnetite phenocrysts in a similar groundmass.

Trace-element concentrations vary with respect to MgO, as would be predicted from crystallisation of predominantly olivine and lesser amounts of clinopyroxene. Discrimination plots (e.g., Zr/Y vs Ti/Y or Nb/Y vs Zr/Y) place the dredged rock compositions firmly in ‘within plate’ tectonic settings (e.g., Fitton, Saunders, Norry, Hardarson, & Taylor, 1997; Irvine & Baragar, 1971). Ratios, such as Ba/Nb and Zr/Nb, fall within fields of nearby Îles Kerguelen and ‘Kerimis’ sea knoll compositions (Weis et al., 2002) and Heard Island lava flows (Laurens Peninsula; Barling, Goldstein, & Nicholls, 1994). We plot Zr/Nb for volcanic products of the Heard hotspot over the last 115 Ma (Figure 5) as a context for the new sample compositions. Clearly, the dredged rocks have compositions that closely resemble the Neogene volcanics erupted from Îles Kerguelen to Heard Island. As noted by Weis et al. (2002), Zr/Nb decreases from the ocean plateau forming event (120–115 Ma), through the long construction of the Ninetyeast Ridge (82–38 Ma), to the early stages of construction of Îles Kerguelen to the Neogene and ongoing volcanic activity (22–0 Ma). Since Zr is slightly more compatible in clinopyroxene during mantle melting than Nb, smaller degrees of partial melting lead to low Zr/Nb, whereas higher degrees of partial melting produce higher Zr/Nb. This simple relationship is apparently consistent with the decreasing rates of magma production from the hotspot through time (Coffin et al., 2002; Scoates et al., 2008; Weis et al., 2002).

**Discussion**

From age determinations and major- and trace-element compositions of dredged samples from eight areas covering much of the CKP, we have learned that Neogene volcanic activity is much more widespread than previously realised. Pike Bank, ‘Kerimis’ sea knoll west of Pike Bank, Coral Bank, Aurora Bank, and the oldest rocks comprising Shallow HIMIP at the western margin of the plateau are clearly part of the province of sea knolls that connect early Miocene activity in Îles Kerguelen with earliest uplift and diabasic intrusions into the limestone that underlies Heard Island (22.0 ± 0.32 Ma; Duncan et al., 2016). Weis et al. (2002) proposed that the ‘Kerimis’ sea knoll, Coral Bank and Aurora Bank reveal the track of the Antarctic plate over the hotspot now beneath Heard Island. As noted earlier, a hotspot location at Heard Island gives the best fit to the geometry and age progression of volcanic activity along the Ninetyeast Ridge (Steinberger, 2000). However, the age distribution along this lineament (Figure 6) does not really support a progression in either direction—measured ages fall in the range 22–16 Ma, with no preferred trend. It is also worth noting that another line of sea knolls, from W to E including ‘Kerimis’ sea knoll, Pike Bank, Discovery Bank and Shell Bank, provide similar Miocene ages.

It has been noted by many researchers that the slow motion of the Antarctic plate would produce only a short hotspot track since the beginning of activity at Îles Kerguelen (ca 30 Ma). This may be the case (and the modelled direction of plate over hotspot motion is consistent with the orientation of the NE–SW-trending sea knoll lineament; Figure 2), but volcanic activity began more or less simultaneously along this lineament at 22–20 Ma, and also at Shell Bank on the eastern margin of the CKP. Such widespread volcanic activity might
otherwise be related to regional extensional tectonics, but seismic stratigraphic images (Munschy & Schlich, 1987; Munschy et al., 1993) indicate that normal and strike-slip faulting began in Cretaceous time, and continued into Paleogene time, culminating in the separation of Kerguelen Plateau and Broken Ridge (46–43 Ma) at the onset of Southeast Indian Ridge spreading. Evidence for extension as a precursor to volcanism is missing. On the other hand, seismic images and drilling at ODP sites 737 and 1138 document a hiatus in sedimentation in the Kerguelen–Heard Basin between 23 and 15 Ma, which Borissova et al. (2002) propose resulted from regional uplift caused by the Heard plume. The volcanic history of Heard Island also exhibits a hiatus between 22 Ma diabase sills intruded into lower Cenozoic limestone and 9 Ma pillow lavas and tuffaceous sediments (Duncan et al., 2016). Presumably, mantle melts at the lithosphere–asthenosphere boundary beneath the plateau used the pre-existing normal and strike-slip faults intermittently as paths to the surface at this time. The slow plate motion means that the hotspot has remained under the NKP and CKP since separation of Broken Ridge and northward drift of the Southeast Indian spreading ridge. Much of the SKP and CKP had been constructed as a LIP at 120–115 Ma, with continuing activity up to 100 Ma (Site 1138). By Eocene–Oligocene time, the plateau had thickened lithosphere that impeded mantle melts from reaching the surface. Hence, melts from the Heard hotspot accumulated beneath the plateau, perhaps underplating and intruding plateau crust, until buoyancy of the plume mantle caused uplift, extension along pre-existing faults and magmatism across a region centred on the plume. The geochemistry of the early Neogene volcanism indicates relatively greater degrees of partial melting at relatively shallower depths compared with younger volcanism. We are faced with having to explain an apparent time gap (Figure 6) between the youngest sea knoll activity (ca 15 Ma) and the oldest late Neogene activity (9–5 Ma). Several possibilities exist: perhaps future sampling of other parts of the CKP will discover submarine features formed within that gap; perhaps plume output is waning or variable, and gaps in its volcanic production are to be expected in overcoming the lithospheric ‘lid’ of the plateau. A significant fraction of melts have reached the surface around the margins of the CKP, where foundering of the plateau edges is ongoing (e.g., M5.4, Okal, 1981; M4.7, Adams & Zhang, 1984, earthquakes along the eastern margin of Labuan Basin). However, from the limited mapping and sampling, it is not clear whether these peripheral fields are unusually active; large areas of the CKP remain unexplored.

The recognition of young and widespread volcanic activity on the CKP raises some exciting research questions. What is the morphology of the volcanic fields built at the margins of the old plateau lava flows? This will require a dedicated multi-beam bathymetric survey of the entire region. Are there active hydrothermal vents in these young features? If so, are the trace-metal-rich vent fluids contributing to biologic primary productivity? The recent eruption of magmas on the plateau surface implies a melt zone under a much larger region than strictly beneath Heard and McDonald Islands. Can this be imaged geophysically, such as through passive seismic and/or magneto-telluric arrays?

**Conclusions**

The CKP has been volcanically active over a broad region for much of Neogene and Quaternary time. New age
determinations and rock compositions for dredged samples from eight widely distributed, shallow submarine areas document several patterns. Large sea knolls rise from the western margin of the plateau as part of a NNW–SSE, curvi-linear array of volcanic centres that lie between Iles Kerguelen and Heard and McDonald Islands. A second line of sea knolls runs E–W across the centre of the CKP. These large volcanic centres formed in the age range 22–16 Ma, and are probably related to hotspot activity continuing today in the Heard and McDonald Islands area. These aligned volcanic centres, however, do not show an age progression. Much younger activity (5 Ma to present) occurs in volcanic fields to the north of, and up to 300 km NE of, Heard Island. While active volcanism at Heard and McDonald Islands is well known, it is probable that several (or all) of the shallow water volcanic fields are now intermittently active. Rocks from the sea knolls and volcanic fields are broadly similar in composition to submarine plateau lava flows, lower Miocene lavas at Iles Kerguelen, and lavas from Heard Island. Geochemical data indicate decreasing mantle source melting with time, from plateau construction to the present volcanic fields. We conclude that a broad region of the CKP became volcanically active in Neogene time owing to incubation of plume material at the base of the relatively stationary overlying plateau. Resulting magmas made their way to the surface along pre-existing crustal weaknesses, including but not exclusively plateau margin normal faults.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplementary Paper

Electronic Annex A. Complete ArArCALC data files for 40\(^{\text{Ar}}\)–39\(^{\text{Ar}}\) incremental heating experiments on dredged rocks from CKP.

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