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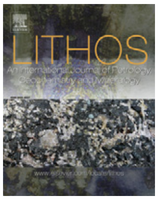

Seychelles alkaline suite records the culmination of Deccan Traps continental flood volcanism

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ABSTRACT

Silhouette and North Islands in the Seychelles represent an alkaline plutonic–volcanic complex, dated at 63 to 63.5 Ma by U–Pb zircon and ^{40}Ar/^{39}Ar methods. This magmatism coincides with the final stages of the cataclysmic Deccan Traps continental flood volcanism in India (67 to 63 Ma), and thus a causal link has been suggested. Recent reconstructions have placed the Seychelles islands adjacent to the Laxmi Ridge and at the western margin of the Réunion mantle plume at the time of formation of the complex. Here we present geochemical evidence in support of the notion that the Seychelles alkaline magmatism was initiated by the peripheral activity of the Réunion mantle plume and is thus part of the Deccan magmatic event. Positive ε_{Nd} (0.59 to 3.76) and ε_{Hf} (0.82 to 6.79) and initial Sr of 0.703507 to 0.705643 at 65 Ma indicate derivation of the Seychelles alkaline magmas from a Réunion-like mantle source with an additional minor enriched component, suggesting entrainment of sub-continental lithospheric mantle. The similarity in trace element composition between the Seychelles suite and Deccan alkaline felsic and mafic rocks provides additional evidence for a common mantle source for the Seychelles and Deccan magmatism. Furthermore, we demonstrate the role of fractional crystallisation in the evolution of the alkaline suite. Modelling using major elements suggests that fractional crystallisation and varying degrees of accumulation of olivine, plagioclase, ilmenite, clinopyroxene, alkali feldspar and apatite can describe the spectrum of rock types, from gabbro, through syenite, to granite.

1. Introduction

The Deccan Traps continental flood basalts record the peak of activity of one of the largest magmatic events in Earth's history, when more than 2 000 000 km^3 of lava erupted onto the Indian sub-continent, the majority in a period of less than 1 million years, with catastrophic consequences for life on Earth (Chenet et al., 2007; Courtillot and Renne, 2003). This event, which has been attributed to the impingement of the Réunion mantle plume, culminated in the final phase of rupture of the Gondwana supercontinent, the separation of the Seychelles from India (Collier et al., 2008; Mahoney et al., 2002). This poses the question: to what extent was the Seychelles affected by the plume before rifting moved it out of range?

The Seychelles microcontinent represents a fragment of Rodinian (Neoproterozoic) continental crust and the majority of the Seychelles islands thus consist of ~750 Ma granite (Ashwal et al., 2002; Torsvik et al., 2001). However, Silhouette Island and North Island (Fig. 1) are exceptions, comprising alkaline felsic rocks with ages recently constrained to between 63 and 63.5 Ma (Ganerød et al., 2011), contemporaneous with the Deccan Traps volcanism (Collier et al., 2008). Furthermore, the latest reconstructions have shown that the Seychelles was situated west of India and in the vicinity of the Réunion plume at this time (Ganerød et al., 2011). It remains to be shown that the Seychelles alkaline magmas were indeed produced by the plume and that it is part of the Deccan magmatic event. Ultimately, this has implications for the original extent of the Deccan Traps Large Igneous Province (LIP) and therefore has relevance for global tectonic, magmatic and climatic events near the Cretaceous–Tertiary boundary.

2. Background

The tectonic evolution of the Seychelles microcontinent is well documented in the studies of Plummer and Belle (1995), Subrahmanya (2001), Collier et al. (2008), Ganerød et al. (2011) and Armitage et al. (2011). During the later stages of Gondwana breakup, after 83.6 Ma (Torsvik et al., 2000), the Seychelles–India continental block separated from Madagascar via the Mascarene Ridge and migrated northward (Collier et al., 2008; Devey and Stephens, 1992; Torsvik et al., 2001). In so doing, it passed over the surface expression of the Réunion plume and plume impingement on the lithosphere induced extensive

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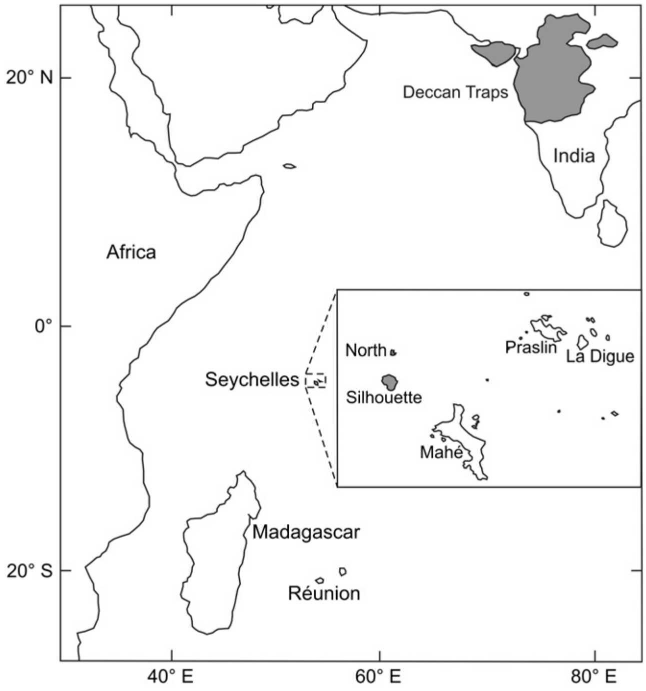

Fig. 1. The location of Silhouette and North Islands with respect to the main Seychelles islands and within the Indian Ocean (after Dickin et al., 1986; Plummer, 1995). The present position of the Deccan plume is below Réunion Island.

magmatic activity, including what is now the Deccan Traps, and also initiated the rifting of the Seychelles away from India (Armitage et al., 2011; Collier et al., 2008; Courtillot et al., 1986; Lightfoot and Hawkesworth, 1988; Mahoney et al., 2002; Plummer and Belle, 1995; Sen, 1995; Todal and Edholm, 1998). This rifting began in the Gop Rift, between India and the Seychelles–Laxmi block, between 70 and 65 Ma (Armitage et al., 2011; Collier et al., 2008; Ganerød et al., 2011), but from 63.4 Ma the spreading centre shifted southward to the Carlsberg Ridge, separating the Seychelles and Laxmi continental fragments (Armitage et al., 2011; Collier et al., 2008; Ganerød et al., 2011).

Accordingly, Collier et al. (2008) identified three main phases of activity in the Deccan-Réunion magmatic event, as follows: An early, ‘pre-Deccan’ phase of plume-related activity (78–67 Ma) relates to extension in the Gop Rift and is manifested in the Bibai basalts of Pakistan, alkaline intrusive rocks in north-western India, the Praslin (Seychelles) tholeiitic dykes and offshore mafic volcanic rocks on the southwest of the Seychelles plateau. This was followed by the main Deccan event (67–63 Ma), which produced massive outpourings of tholeiitic basalt on the western margin of the Indian sub-continent. After the Seychelles began to rift away from India, a third ‘post-Deccan’ pulse of magmatism (63–58 Ma) produced offshore mafic volcanic and intrusive rocks on the northern margin of the Seychelles plateau and alkaline volcanism in India.

Recent work by Ganerød et al. (2011) has provided precise geochronological and palaeomagnetic constraints on the timing of the Silhouette–North Island magmatism, summarised here. Dating by $^{40}Ar/^{39}Ar$ step heating and U–Pb in zircons yielded weighted mean ages of 63.1 ± 0.34 Ma and 63.27 ± 0.05 Ma (2σ errors), respectively, for all the North Island lithologies (syenite, microsyenite and gabbro). U–Pb dating for Silhouette Island lithologies gave a weighted mean age of 63.54 ± 0.06 Ma, while $^{40}Ar/^{39}Ar$ dates for these lithologies encompass a larger range, from 66.8 ± 0.8 (trachyte), through syenite and microsyenite, to 61.3 ± 0.57 (syenite). The U–Pb data indicate that in general the Silhouette Island igneous units are older by 0.27 ± 0.08 Ma than those on North Island. Whereas the previous range in K–Ar mineral and Rb–Sr isochron ages for Silhouette and North Islands by Dickin et al. (1986) had uncertainties too great for adequate correlation, these new ages clearly constrain this magmatism to the end of the main Deccan event. Ganerød et al. (2011) go on to show, via refined plate reconstructions, that the Seychelles microcontinent was still located adjacent to the Laxmi Ridge and above the deep mantle Plume Generation Zone of Burke et al. (2008) at this time.

Speculation that the Silhouette–North Island alkaline complex may have formed as the Seychelles–India plate passed over the Réunion mantle plume is not new (see Courtillot et al., 1986; Devey and Stephens, 1992), and indeed, preliminary geochemical comparisons have been made. Devey and Stephens (1991, 1992) initially proposed that the Silhouette–North Island alkaline rocks and mafic dykes of Praslin, Mahé and Felicité Island in the Seychelles showed a strong resemblance to certain Deccan rocks in terms of geochemistry, petrology and rock relations, and took this as evidence for a common source for these magmas. However, the mafic dykes “of known Cretaceous/Tertiary age” (Devey and Stephens, 1992, 276) from Mahé and Felicité used in comparison have been shown to be Precambrian (Ashwal et al., 2002; Hargraves and Duncan, 1990; Torsvik et al., 2001), while those from Praslin clearly relate to the pre-Deccan phase and their original compositions are obscured by significant contamination (Devey and Stephens, 1991; Dickin et al., 1986). For the alkaline felsic suite, the key comparisons in the study of Devey and Stephens (1992) were made with Deccan alkaline mafic and tholeiitic rocks. There was also a general paucity of geochemical and isotopic data with which to compare. In light of the new, more precise geochronological and palaeomagnetic data of Ganerød et al. (2011), a comprehensive geochemical investigation into the origins of the Silhouette–North Island magmatism and its relation to the Deccan magmatism and the activity of the Réunion Plume is essential, and forms the basis of this contribution.

3. Methodology

Samples were collected from Silhouette Island and North Island on two field expeditions in 1997 and 2008. Major and trace element (Ga, Nb, Zr, Y, Cr, Ni, Co, Sc, Cu, Zn, S) compositions of the 1997 sample set (10 samples prefixed LA and RT) were analysed by X-ray fluorescence (XRF) at the Department of Geology of the University of KwaZulu Natal, South Africa. Additional trace element compositions (Ba, Th, U, V, Pb, Hf, Ta, W, REE) were analysed using inductively coupled plasma emission mass spectrometry (ICP-MS) with a VG elemental Plasmaquad instrument at the Département de Géologie, Musée royal de l'Afrique centrale, Belgium. Details of these analyses and estimates of precision may be found in Ashwal et al. (2002).

Rb, Sr, Lu, Hf, Sm and Nd isotopes and elemental concentrations were analysed at the Research School of Earth Sciences, Australian National University, Canberra. Details of the procedures are given in Nebel and Mezger (2006) and Nebel et al. (2009, 2010). The Lu, Hf, Sm and Nd isotope ratios were analysed with a ThermoFinnigan MC–ICP-MS. Measured ratios of Sm, Nd and Hf were internally corrected for mass fractionation using $^{146}Nd/^{144}Nd = 0.7219$ and $^{179}Hf/^{177}Hf = 0.7325$. All samples are reported relative to the La Jolla ($^{143}Nd/^{144}Nd = 0.511859$ after Lugmair and Carlson, 1978) and JMC-475 ($^{176}Hf/^{177}Hf = 0.282160$ after Blichert-Toft et al., 1997) isotope standards, which yielded values during the analytical session of $^{143}Nd/^{144}Nd = 0.511826 \pm 17$ and $^{176}Hf/^{177}Hf = 0.282152 \pm 8$. Rb isotopes were analysed using the method described in Nebel et al. (2005). Sr was measured on a FinniganMAT 261 in static mode. Instrumental mass fractionation was corrected relative to a value of $^{86}Sr/^{88}Sr = 0.1194$. The NBS-987 standard yielded a value of $^{87}Sr/^{86}Sr = 0.710222 \pm 12$. Procedural blanks are 15 pg, 10 pg, 30 pg, 40 pg, 30 pg and 50 pg for Lu, Hf, Sm, Nd, Rb and Sr, respectively.

The 2008 sample set (14 samples prefixed TOS and TON) was analysed using a ThermoARL (Advant 'XP, model 9800XP) XRF instrument at Set Point Laboratories, Johannesburg, South Africa. Rock