Late Cretaceous India–Madagascar fit and timing of break-up related magmatism

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ABSTRACT

A U–Pb zircon age of 91.2 ± 0.2 Myr from western India (St. Mary islands) confidently links India with the Late Cretaceous magmatic province in Madagascar (≈ 84–92 Ma), and the U–Pb age is within analytical error of the U–Pb age of the Analalava gabbro pluton (91.6 ± 0.3 Myr) in northeastern Madagascar. Palaeomagnetic data from India and Madagascar allow us to postulate a new India–Madagascar fit (Euler latitude = 14.24°, longitude = 38.8° and rotation angle = –69.2°). This fit is applicable to the Late Cretaceous, directly prior to and during the early phase of Madagascar–India separation. In our Late Cretaceous reconstruction, south-west India runs roughly subparallel with the first known break-up related magnetic anomaly (A34); it maintains a close connection between Madagascar and India, but places India slightly rotated compared to the eastern margin of Madagascar and more northerly compared with some reconstructions. St. Mary magmatism is linked to the initial break-up between India and Madagascar, and magmatism probably resulted from rift-related extensional processes initially induced by the Marion hotspot underlying southern Madagascar during the Late Cretaceous.

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Introduction

Many plate reconstructions propose a close link between Madagascar and Greater India from Late Precambrian to Cretaceous times, and separation is estimated to have started during or shortly after a period of Late Cretaceous basic and felsic magmatism that is well-known from Madagascar (83.6–91.6 Ma; Storey *et al.*, 1995; Torsvik *et al.*, 1998). During this Late Cretaceous break-up event, the western margin of India presumably rifted off the eastern margin of Madagascar; however, equivalent Cretaceous volcanism is not well documented from western India. Possible exceptions include mafic dykes in mainland south-west India (Radhakrishna *et al.*, 1994, 1999), and the acid volcanic rocks of the St. Mary islands (Fig. 1; Valsangkar *et al.*, 1981).

The St. Mary islands form a chain of small islands trending NW–SE over a distance of about 6 km off the western coast of central India, near the coastal village of Malpe (Fig. 1). The islands consist entirely of flat-lying, undeformed felsic volcanic rocks, including dacites and rhyodacites (Naganna, 1966; Valsangkar *et al.*, 1981; Subbarao

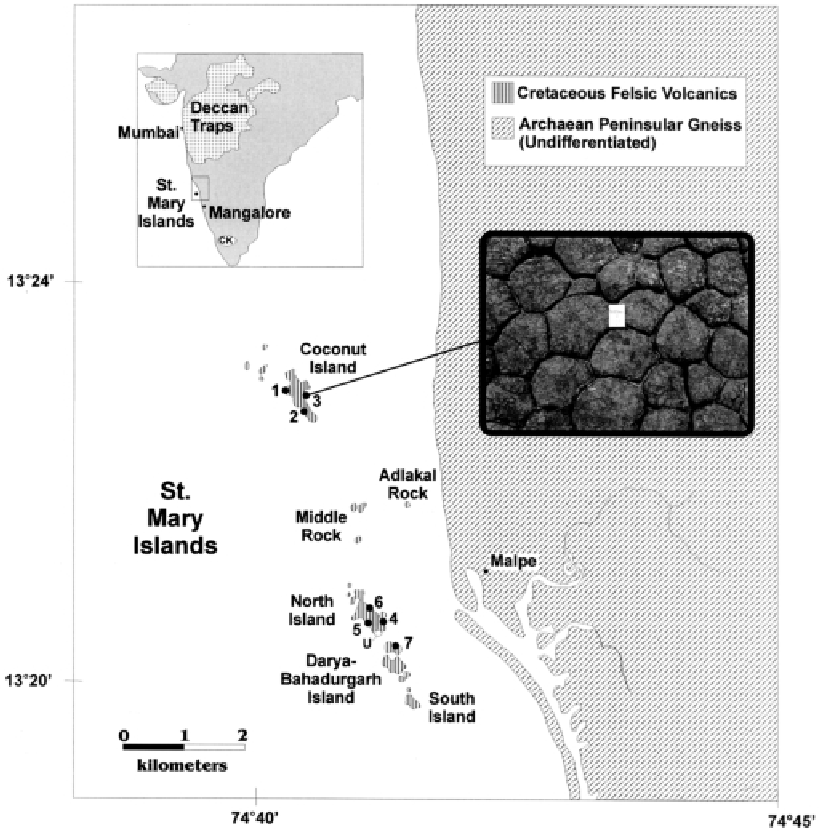

Fig. 1 Geological sketch map of the St. Mary Islands showing sampling sites for palaeomagnetic (1–7) and U–Pb isotopic (U) analyses reported in this paper. Inset map: India showing the main extent of Deccan-related magmatism. Inset picture: Typical columnar jointing observed at the Coconut Island (notebook for scale is 9 × 6 cm). GPS locations are listed in Table 1.

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et al., 1993), some with spectacularly developed columnar jointing (Fig. 1). The vertical orientation of these columnar joints verifies the absence of post-magmatic structural tilting. The acid volcanic rocks of the St. Mary islands were argued by Naganna (1966) to represent an early phase of the Deccan flood basalt province (≈ 65 Ma), but whole-rock K–Ar ages ranging from 80.3 ± 1.7 Myr to 97.6 ± 2.3 Myr (Valsangkar *et al.*, 1981) suggest that this magmatism might be better correlated with an older event related to India–Madagascar break-up. For this reason, the geochronology and palaeomagnetism of the rocks of the St. Mary islands were re-investigated. Hand-samples for U–Pb dating were collected from a massive dacite flow from North Island, whilst 60 samples for palaeomagnetic analysis were collected from seven sites on three of the larger islands in the St. Mary group (Fig. 1). All samples are fresh and unweathered.

Laboratory experiments

Uranium and Pb isotopic ratios were measured on a VG Sector 54 TIMS at Washington University (St Louis, USA), and the natural remanent magnetization (NRM) was measured using a JR5A magnetometer at the Geological Survey (Trondheim, Norway).

Clear, colourless zircons consisting of short, prismatic crystals were hand picked for isotopic analysis, and care was taken to avoid selecting grains with inclusions and obvious core material to avoid potential inherited components. Three analyses are all concordant (Fig. 2a) at a common ^{206}Pb/^{238}U age of 91.2 ± 0.2 Myr (95% confidence); there is no evidence for inherited components in these analyses. The weighted mean ^{207}Pb/^{206}Pb age is 95.9 ± 5.3 Myr. The ^{206}Pb/^{238}U age of 91.2 ± 0.2 Myr is cited herein as the true eruption age because, unlike the ^{207}Pb/^{206}Pb age, it is relatively insensitive to the composition of initial Pb.

NRM intensity and susceptibility varied between 3 and 14 A/M and 14 and 32 (10^{-3} SI units), respectively (Table 1). NRM directions are dispersed, but after thermal or AF demagnetization, high-unblocking or high-coercivity (HB) directions from each site are well grouped with NW to WNW declinations and intermediate-to-steep negative inclinations (Fig. 2b,c). Well-defined HB components (Table 1) are identified above 40–70 mT, or at temperatures above 300–400 °C. At site 7, the maximum available AF field (160mT) did not fully demagnetize the samples; so the samples were also thermally demagnetized (Fig. 2b). Thermal demagnetization spectra and thermomagnetic analysis suggest low-Ti titanomagnetite (maximum unblocking temperatures at around 570–580 °C and Curie temperatures at ≈ 580 °C) as the bulk remanence carrier, but with a subordinate influence of haematite. Petrographically, the opaque mineralogy of the rocks is dominated by homogeneous, unoxidized magnetite; some grains are composite intergrowths of magnetite and ilmenite. Some specimens contain additional discrete skeletal ilmenite. Samples from Site 7 show very slight haematite alteration of magnetite; this is consistent with the thermal unblocking spectra (Fig. 2b).

Interpretation

The 91.2 ± 0.2 Myr U–Pb zircon age (Fig. 2a) is within the range of existing K/Ar whole-rock ages (80.3 ± 1.7 Myr to 97.6 ± 2.3 Myr; Valsangkar *et al.*, 1981), but it is suggested herein that the U–Pb age most closely represents the true emplacement age of the St. Mary dacite magmatism.

Normal polarity HB site-mean directions from St. Mary islands are well grouped (Fig. 2c) and were probably acquired during the terminal Cretaceous Normal Superchron (≈ 91.2 Ma). All rocks are flat-lying and unmetamorphosed, and the HB directions are taken to be primary. HB directions differ significantly from those of Valsangkar *et al.* (1981), and this difference is related to incomplete magnetic cleaning procedures in the previous study. Low unblocking components are scattered and their origin remains uncertain.

The most reliable Cretaceous to early Tertiary palaeomagnetic data from India come from the Deccan (≈ 65 Ma) and Rajmahal (≈ 118 Ma) volcanic provinces of west- and south-central India, respectively (Vandamme *et al.*, 1991; Torsvik *et al.*, 1998). The palaeomagnetic pole from St. Mary (Table 1) is statistically different from the mean Deccan pole, but overlaps with Rajmahal (Fig. 2d). Thus, on both palaeomagnetic and isotopic grounds the St. Mary pole is clearly different than the Deccan poles. Therefore, St. Mary magmatism is linked to the initial break-up between India and Madagascar.

Discussion and conclusion

High quality palaeomagnetic data from the St. Mary dacites indicate a local palaeolatitude of S39.3$^{+9.1}$/$_{-7.5}$ at 91.2 ± 0.2 Myr. This first well-dated Late Cretaceous pole for India allows us to produce the first reliable, palaeomagnetically based reconstruction for Madagascar and Greater India. There exist many published Madagascar–India fits in the literature (e.g. Lawver and Scotese, 1987; Royer and Sandwell, 1989; Müller *et al.*, 1993). These are based on 'coastline' fitting, magnetic anomalies, hotspot tracks, correlation of Precambrian tectonic belts in Madagascar and India/Sri Lanka, or a combination of these approaches. No Cretaceous palaeomagnetic fit of India and Madagascar exists because reliable palaeomagnetic poles of equivalent age from both locations have been unavailable. Temporally equivalent palaeomagnetic data exist for Madagascar (Torsvik *et al.*, 1998) and the St. Mary Islands (India), and allow us now to compare datasets. A test of all published fits for India–Madagascar produces an unsatisfactory fit of the Late Cretaceous poles (12–20° angular great-circle misfit). Therefore, a new Euler pole (lat. = 14.24°, long. = 38.8° and rotation angle = –69.2°) is calculated for India–Madagascar that matches the new poles from Madagascar and India and maintains a close connection between Madagascar and SW India (Fig. 3). Compared with existing fits, Greater India is slightly 'rotated' away from the eastern margin of Madagascar and also somewhat more northerly compared with some reconstructions. The new fit places the SW India margin parallel to the transform segment of 'future' magnetic anomaly A34 (ends at 83 Ma; Cande and Kent, 1995), the first known break-up related anomaly. Palaeolongitude is undetermined from the palaeomagnetic data, thus a wider palaeo-east–west separation between Madagascar and India (Mascarene Basin) is a possibility. The slightly rotated western margin of India (compare palaeomagnetic and hotspot reconstruction in Fig. 3) could also be an artefact of local rotation of the St Mary islands; thus, this Late Cretac-

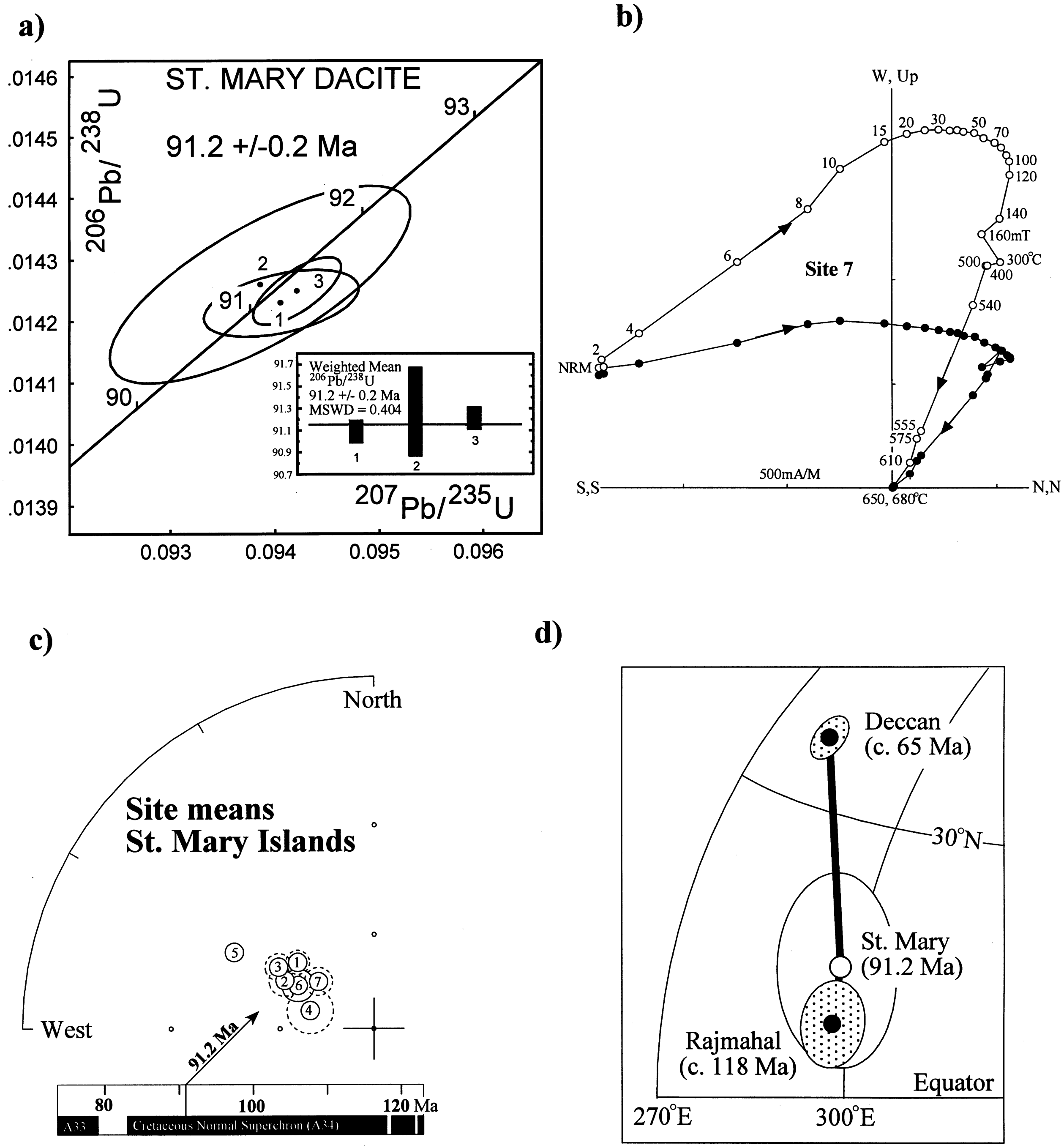

Fig. 2 (a) Concordia diagram showing isotope dilution analyses of zircon (analyses 1–3) of St. Mary island dacite sample. All analyses are concordant within analytical error (shown as 2σ on the figure). (b) Example of AF demagnetization (2–160mT) followed by thermal demagnetization for a site 7 sample. In vector diagram, open (closed) symbols represent points in the vertical (horizontal) plane. (c) St. Mary site-mean HB directions with 3 $\alpha95$ confidence circles (Table 1). All site-means are of normal magnetic polarity and the U–Pb age (91.2 ± 0.2 Myr) suggest that magnetization was acquired within the Cretaceous Normal Superchron ($\approx$ 83–118 Ma; Cande and Kent, 1995). In stereoplot, open symbols denote upward pointing inclinations. (d) St. Mary pole compared with mean poles from the Deccan traps (pole latitude = 36.9°N, longitude = 281.3°E & A95 = 2.4°) and the Rajmahal basalts, eastern India (latitude = 8°N, longitude = 297.8°E & A95 = 4.7°). St Mary pole is plotted with 3 $\alpha95$ confidence circle. Deccan (Vandamme *et al.*, 1991) and Rajmahal (Torsvik *et al.*, 1998) poles plotted with A95 confidence circles.

eous reconstruction should be viewed with these alternatives in mind.

The St. Mary U–Pb age is within analytical error of the U–Pb age of the Analalava gabbro pluton (91.6 ± 0.3 Myr; Fig. 3), that underlies, and prob-

Table 1 Site mean statistics (high unblocking/coercivity components) from the St. Mary Islands

Site	Island	Lat. °N	Long. °E	NRM	Sus.	*N*	α_{95}	Dec°	Inc°
1	Coconut	13.37	74.67	6.1	17.6	5	3.6	310.8	–57.8
2	Coconut	13.37	74.67	3.1	14.7	8	4.8	298.4	–57.7
3	Coconut	13.37	74.67	5.3	21.0	7	4.0	302.7	–54.1
4	North	13.34	74.69	2.9	14.2	7	7.3	285.8	–68.6
5	North	13.34	74.69	5.0	18.8	12	2.4	298.6	–41.1
6	North	13.34	74.69	7.8	14.9	8	5.0	299.6	–62.0
7	Darya Bahädurgahr	13.34	74.69	14.3	31.6	10	4.4	310.3	–66.5
	Mean sites	13.35	74.68	6.4	19.0	**7***	**7.5**	**301.2**	**–58.5**
	Palaeomagnetic pole: N14.2°, E297.8° dp/dm = 8.2°/11.1°								

Lat./Long., sampling latitude/longitude; NRM, Natural remanent magnetization intensity (A/M); Sus., bulk susceptibility (10^{-3} SI); *N*, Number of samples; α_{95}, 95% confidence circle; Dec/Inc, Mean Declination/Inclination; dp/dm, semiaxes of the cone of 95% confidence about the pole.

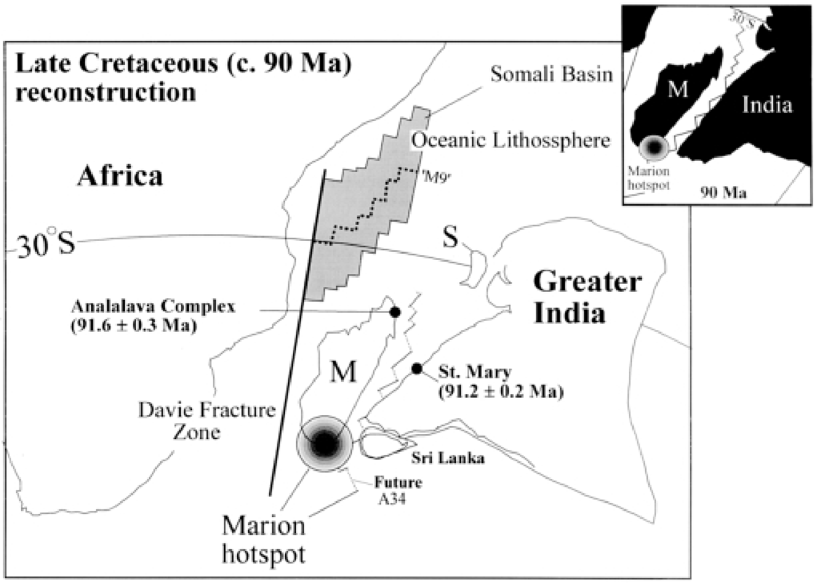

Fig. 3 Late Cretaceous reconstruction for Africa, Madagascar (M), Seychelles (S) and Greater India, reconstructed with a mean Madagascar pole (pole latitude = 68.5°N, longitude = 230.3°E, A95 = 5.5°; age 84–90 Myr; see Torsvik *et al.*, 1998) and St. Mary pole. Africa–Madagascar is fixed; new India–Madagascar fit is 14.24°, 38.8° & –69.2° (this study) and Seychelles–India fit (Lat. = 25.8°, Long. = 330° and rotation angle = 28°) from Torsvik *et al.* (2001). Sri Lanka–India fit after Lawver and Scotese (1987). Reconstruction is 'adjusted' in longitude so that the Marion hotspot underlies southern Madagascar for comparison with the hotspot reconstruction (inset diagram). The extent of late Jurassic and Early Cretaceous oceanic lithosphere in the Somali Basin (M25 to M9), and the first known break-up related magnetic anomaly between Madagascar and India (A34; ≈ 83 Ma) is shown (Coffin and Rabinowitz, 1988; Müller *et al.*, 1997). Inset diagram: Hotspot reconstruction at ≈ 90 Ma (Müller *et al.*, 1993) is closely similar to the palaeomagnetic reconstruction (compare relation of Madagascar with the Marion hotspot), except the 'rotated' and somewhat more northerly placed India. India–Madagascar fit is 22.5°, 23.6° & –53.0° in the Müller *et al.* (1993) hotspot reconstruction which produces an angular great circle misfit of 17° between the St. Mary and the mean Madagascar palaeomagnetic poles.

ably represents the magma chamber for basaltic and rhyolitic volcanics in eastern Madagascar (Torsvik *et al.*, 1998). In the present Late Cretaceous reconstruction, Greater India stretched from ≈ 23°S to 45°S, Madagascar from 34°S to 47°S, and the St. Mary dacites were located 500 km from the Analalava Complex in NE Madagascar (Fig. 3). The Marion hotspot has been argued to be instrumental in the break-up of India and Madagascar (Mahoney *et al.*, 1991; Storey *et al.*, 1995, 1997; Torsvik *et al.*, 1998), with southern Madagascar marking the focal point of the Marion plume in the Late Cretaceous. This scenario agrees well with palaeomagnetic data (Fig. 3). If the St. Mary dacites are plume-related, they would be located 1000 km from the Marion hotspot, near the plume–edge boundary. However, magmatism at St. Mary, as well as the mafic to felsic dykes of eastern Madagascar might also have resulted from rift-related extensional processes initially induced by the Marion hotspot.

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