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


1VISTA, c/o Geological Survey of Norway, Leif Eirikssons vei 39, N-7491 Trondheim, Norway, 2Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130, USA, 3Department of Geology, Rand Afrikaans University, PO Box 524, Auckland Park, 2006 South Africa, 4Department of Geology, University of Oslo, Sem Sælendes vei 1, PO Box 1047 Blindern, N-0316 Oslo, Norway, 5Geological Survey of India, Operations Karnataka and Goa, Vasudha Bharan, Kamaraswamy, Bangalore 560078, India, 6Geological Survey of India, Marine Wing, PKV Bhandarkars Complex, Mambaguda, Mangalore 575003, India

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.

Terra Nova, 12, 220–224, 2000

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

*Correspondence: E-mail: trond.torsvik@ngu.no; also at: Department of Geology, Lund University, S-222 333, Sweden

Fig. 1 Geological sketch map of the St. Mary Islands showing sampling sites for palaeomagnetic (I–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.
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 JRSA 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 206Pb/238U age of 91.2 ± 0.2 Myr (95% confidence); there is no evidence for inherited components in these analyses. The weighted mean 207Pb/206Pb age is 95.9 ± 5.3 Myr. The 206Pb/207Pb age of 91.2 ± 0.2 Myr is cited herein as the true eruption age, because, unlike the 207Pb/206Pb 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 (10–7 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 dacies indicate a local palaeolatitude of S39.3 ± 9°/–7° 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. Lawyer and Scottese, 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 (Mascaren 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 Cretace
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 3σ95 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 (∼83–118 Ma; Cande and Kent, 1995). In stereoplots, 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 3σ95 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

<table>
<thead>
<tr>
<th>Site</th>
<th>Island</th>
<th>Lat. 'N</th>
<th>Long. 'E</th>
<th>NRM</th>
<th>Sus.</th>
<th>N</th>
<th>α95</th>
<th>Dec°</th>
<th>Inc°</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coconut</td>
<td>13.37</td>
<td>74.67</td>
<td>6.1</td>
<td>17.6</td>
<td>5</td>
<td>3.6</td>
<td>310.8</td>
<td>-57.8</td>
</tr>
<tr>
<td>2</td>
<td>Coconut</td>
<td>13.37</td>
<td>74.67</td>
<td>3.1</td>
<td>14.7</td>
<td>8</td>
<td>4.8</td>
<td>298.4</td>
<td>-57.7</td>
</tr>
<tr>
<td>3</td>
<td>North</td>
<td>13.34</td>
<td>74.69</td>
<td>5.3</td>
<td>21.0</td>
<td>7</td>
<td>4.0</td>
<td>302.7</td>
<td>-54.1</td>
</tr>
<tr>
<td>4</td>
<td>North</td>
<td>13.34</td>
<td>74.69</td>
<td>2.9</td>
<td>14.2</td>
<td>7</td>
<td>7.3</td>
<td>285.8</td>
<td>-68.6</td>
</tr>
<tr>
<td>5</td>
<td>North</td>
<td>13.34</td>
<td>74.69</td>
<td>5.0</td>
<td>18.8</td>
<td>12</td>
<td>2.4</td>
<td>298.6</td>
<td>-41.1</td>
</tr>
<tr>
<td>6</td>
<td>North</td>
<td>13.34</td>
<td>74.69</td>
<td>7.8</td>
<td>14.9</td>
<td>8</td>
<td>5.0</td>
<td>299.6</td>
<td>-62.0</td>
</tr>
<tr>
<td>7</td>
<td>Daya Bahádúrgar</td>
<td>13.34</td>
<td>74.69</td>
<td>14.3</td>
<td>31.6</td>
<td>10</td>
<td>4.4</td>
<td>310.3</td>
<td>-66.5</td>
</tr>
<tr>
<td>Mean sites</td>
<td>13.35</td>
<td>74.68</td>
<td>6.4</td>
<td>19.0</td>
<td>7*</td>
<td>2.5</td>
<td>301.2</td>
<td>-58.5</td>
<td></td>
</tr>
</tbody>
</table>

Palaeomagnetic pole: N14.2°, E297.8° dp/dm = 8.2'111°

Lat./Long., sampling latitude/longitude; NRM, Natural remanent magnetization intensity (A/M); Sus., bulk susceptibility (10^-3 S); N, Number of samples; α95, 95% confidence circle; Dec/Inc, Mean Declination/Inclination; dp/dm, semi-axes 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–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.

This study was supported by the Norwegian Research Council, Geological Survey of Norway, National Research Foundation (South Africa) and the Geological Survey of India (Dr Acharyya, Director General).

References

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 dacies 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 dacies are plume-related, they would be located 1000 km from the Marion hotspot, near the plume edge boundary. However, magma of 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.

Received 7 February 2000; revised version accepted 28 December 2000