Correlations between silicic volcanic rocks of the St Mary’s Islands (southwestern India) and eastern Madagascar: implications for Late Cretaceous India–Madagascar reconstructions

LEONE MELLUSO1*, HETU C. SHETH2, JOHN J. MAHONEY3, VINCENZO MORRA1, CHIARA M. PETRONE4,5 & MICHAEL STOREY6

1Dipartimento di Scienze della Terra, Università di Napoli Federico II, 80134 Napoli, Italy
2Department of Earth Sciences, Indian Institute of Technology, Powai 400076, Mumbai, India
3School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, HI 96822, USA
4Istituto di Geoscienze e Georisorse CNR, University of Firenze, 50121 Firenze, Italy
5Present address: Department of Earth Sciences, University of Cambridge, Cambridge CB2 3EQ, UK
6QUAD-Lab, Roskilde University Centre, Roskilde, 4000 Denmark
*Corresponding author (e-mail: melluso@unina.it)

Abstract: The St Mary’s Islands (southwestern India) expose silicic volcanic and sub-volcanic rocks (rhyolites and granophyric dacites) emplaced contemporaneously with the Cretaceous igneous province of Madagascar, roughly 88–90 Ma ago. The St Mary’s Islands rocks have phenocrysts of plagioclase, clinopyroxene, orthopyroxene and opaque oxide, moderate enrichment in the incompatible elements (e.g. Zr = 550–720 ppm, Nb = 43–53 ppm, La/Yb = 6.9–7.2), relatively low initial 87Sr/86Sr (0.7052–0.7055) and near-chondritic initial 143Nd/144Nd (0.51248–0.51249). They have mineral chemical, whole-rock chemical and isotopic compositions very close to those of rhyolites exposed between Vatomandry–Ilaka and Mananjary in eastern Madagascar, and are distinctly different from rhyolites from other sectors of the Madagascan province. We therefore postulate that the St Mary’s and the Vatomandry–Ilaka–Mananjary silicic rock outcrops were adjacent before the Late Cretaceous rifting that split Madagascar from India. If so, they provide a valuable tool to check and aid traditional Cretaceous India–Madagascar reconstructions based on palaeomagnetism, matching Precambrian geological features, and geometric fitting of continental shelves.

Supplementary material: Mineral analyses, mass-balance calculations and locality information are available at http://www.geolsoc.org.uk/SUP18332.

Correlation between magmatic units of flood basalt provinces emplaced on conjugate continental margins is a fascinating topic for detailed work. Examples of Phanerozoic provinces where far-separated units have been correlated include the Paraná and Etendeka (Milner et al. 1995; Peate et al. 1999; Marsh et al. 2001), the Karoo province and the Ferrar–Kirkpatrick basalts–Tasmanian dolerites (Hergt et al. 1991; Encarnación et al. 1996; Riley et al. 2006), the Deccan Traps and Seychelles dykes (Devey & Stephens 1991, 1992), eruptive units in Ethiopia and Yemen (Ukstins Peate et al. 2005), the North Atlantic Tertiary Province (Larsen et al. 1999; Storey et al. 2007) and outcrops of the Central Atlantic Magmatic Province in Europe, the Americas and Africa (Marzoli et al. 1999). Such correlations have been made in some cases by matching distinctive eruptive units, and in other cases by matching stratigraphic packages of compositionally similar lavas, or simply by matching ages of volcanic units. A close chemical match-up of volcanic units can also be made by tephrostratigraphy (Ukstins Peate et al. 2003).

The silicic volcanic and sub-volcanic rocks of the St Mary’s Islands, off the SW coast of India (Figs 1 and 2a; Naganna 1966; Hegde & Gosavi 2007), were thought to be unrelated to the c. 65 Ma Deccan Traps to the north ever since Valsangkar et al. (1981) reported that they had distinctly older K–Ar ages (80–97 Ma). These older ages were later confirmed when Pande et al. (2001) obtained 40Ar–39Ar plateau and isochron mean ages for St Mary’s Islands samples of 85.4 ± 0.8 Ma (2σ) and 85.6 ± 0.9 Ma (2σ), respectively (relative to monitor MMhb-1 age of 523.1 ± 2.6 Ma, 2σ; Renne et al. 1998). At about the same time, Torsvik et al. (2000) reported a 206Pb–238U zircon age of 91.2 ± 0.2 Ma (2σ) for a dacite flow. The two sets of ages are notably different relative to analytical errors.

Western India and eastern Madagascar were contiguous until the middle part of the Late Cretaceous (e.g. Katz & Premoli 1979). It has also long been known that widespread Cretaceous volcanism occurred in Madagascar (Lacroix 1923; Besairie 1964). However, knowledge of this volcanism was poor until the 1990s. There have been many publications since, reporting age data (92–84 Ma, 40Ar–39Ar, the ages generally decreasing from north to south) and compositional ranges of the Madagascan rocks (Mahoney et al. 1991, 2008; Storey et al. 1995, 1997; Melluso et al. 1997, 2001, 2002, 2003, 2005; Torsvik et al. 1998). Here, we attempt to place the St Mary’s Islands rocks of southwestern India in the context of the Cretaceous volcanism in Madagascar through the use of geochemical and petrological ‘fingerprinting’, together with plate reconstructions of the relative pre-break-up positions of Madagascar and India.
Fig. 1. Sketch maps of the St Mary’s Islands (SW India; a, b) and Madagascar (c). The location of the samples reported in Table 1 is also shown.
Fig. 2. (a) Columnar jointing in the Coconut Island outcrop, St Mary’s Islands (SW India). (b) Outcrop of altered rhyolites between Vatomandry and Ilaka (Madagascar). These rhyolites were emplaced as porphyritic lavas, sometimes with columnar jointing. The complete lack of both flow banding and orientation of the highly altered feldspar phenocrysts should be noted; this feature excludes a former pyroclastic origin of these rocks. (c) Mafic inclusion in SM1B; cross-polarized light (note clinopyroxene and magnetite included in plagioclase). (d) Granophyric intergrowths in sample SM3b; cross-polarized light. (e) Sample SM2B, cluster of orthopyroxene, clinopyroxene, plagioclase and oxides; cross-polarized light. (f) Vitrophyre MAN90-84, Mananjary: cluster of plagioclase, clinopyroxene, orthopyroxene and oxides in a glassy, partially devitrified matrix; plane-polarized light. The long side of each photomicrograph is c. 2 mm.
et al. (1998), and the continent–ocean transition is very narrow (Storey et al.) igneous material (e.g. Saunders et al.) seaward-dipping seismic reflectors, usually believed to be geophysical data available, the eastern part of Madagascar lacks also intruded by dolerite dykes, although the exact stratigraphic lavas successions, as is often the case in flood basalt provinces Madagascar 1959). They are usually found at the top of mafic outcrops between Vatomandry and Ilaka are roughly 30 km Mananjary form large, subhorizontal lava fields; among them, basement. The rhyolite outcrops from Vatomandry–Ilaka and igneous material, and can dykes M721a (rhyolite) and M722 (dacite) by inductively igneous material, are usually considered shallow-level intrusions, although no contacts are exposed. The country rock exposed in the Malpe area on the mainland is thick laterite, developed from Precambrian gneiss. The geological setting of the Madagascar flood basalt province has been described previously (e.g. Besairie 1964; Nicollet 1984; Storey et al. 1995, 1997; Melluso et al. 2005, and references therein). Lavas, dykes, other igneous intrusions and deeply altered pyroclastic rocks cover much of the eastern and western coasts and parts of the hinterland (Fig. 1c). In many areas the lavas lie directly on the Precambrian basement. Silicic rocks have been found throughout the province, although they are a volumetrically minor component (see Besairie 1964; Melluso et al. 2001, 2005; Fig. 1c). Many outcrops of rhyolitic rocks are known along the eastern coast, and rhyolites are abundant in the Androy complex at the southern end of the island (Mahoney et al. 2008) (Fig. 1c). The rhyolitic rocks are mostly dykes and lavas, intruded into or erupted on the coastal Precambrian basement. The rhyolite outcrops from Vatomandry–Ilaka and Mananjary form large, subhorizontal lava fields; among them, outcrops between Vatomandry and Ilaka are roughly 30 km × 10 km and probably 130–140 m thick (Geological Survey of Madagascar 1959). They are usually found at the top of mafic lava successions, as is often the case in flood basalts (e.g. Peate 1997; Sheth & Melluso 2008), and in some cases are also intruded by dolerite dykes, although the exact stratigraphic relationships are commonly obliterated by heavy lateritization or hidden by vegetation. The extent of the Cretaceous volcanic rocks on the continental shelves of Madagascar is largely unknown. From the limited geophysical data available, the eastern part of Madagascar lacks seaward-dipping seismic reflectors, usually believed to be igneous material (e.g. Saunders et al. 1997; Gladczenko et al. 1998), and the continent–ocean transition is very narrow (Storey et al. 1995; Chand & Subrahmanyan 2003).

Analytical techniques
Major and trace element contents were determined on agate-ground powders of the St Mary’s Islands rocks and the Madagascan dykes M721a (rhyolite) and M722 (dacite) by inductively coupled plasma optical emission spectrometry and inductively coupled plasma mass spectrometry (ICP-MS) at ACTLABS, Ancaster, Ontario (Table 1). The other chemical analyses of the Madagascan silicic rocks were obtained by X-ray fluorescence spectrometry (XRF) and instrumental neutron activation analysis (INAA), described by Storey et al. (1997). These data are part of a larger XRF dataset for the silicic rocks cropping out along the whole eastern coast of Madagascar (J. J. Mahoney et al., unpubl. data, Fig. 3).

Mineral chemical data were obtained at Istituto di Geologia Ambientale e Geoingegneria, CNR, Rome, utilizing a Cameca SX50 instrument equipped with a wavelength-dispersive spectrometer. Silicates and oxides were used as standards, and the augite Kakanui was used as a monitor of accuracy. A subset of the analyses has been obtained utilizing an energy-dispersive microprobe system linked to a JEOL JSM5310 system operating at 50 kV and 50 μA at CISAG, University of Napoli.

Strontium and Nd isotope analyses were performed at the Department of Earth Sciences, University of Firenze and at the School of Ocean and Earth Science and Technology, University of Hawaii. At Firenze, around 20 mg of sample powder was dissolved in a HF–HNO₃–HCl mixture. Strontium and Nd fractions were separated following standard chromatographic techniques using AG50×8 and Ln–HDEHP resins with HCl as eluent, as described by Avanzinelli et al. (2005). Mass spectrometric analyses were performed by thermal ionization mass spectrometry on a Thermo Finnigan Triton-Ti® system equipped with nine movable Faraday cups. The ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios were measured dynamically in a triple jump routine, except for ¹⁴³Nd/¹⁴⁴Nd of samples M721 and M722, which was measured in static mode. Sample preparation and analysis at Hawaii followed Mahoney et al. (1991) and employed a VG Sector multicollector mass spectrometer for the measurements.

Petrography, mineral chemistry and whole-rock geochemistry of St Mary’s Islands rocks
The St Mary’s Islands rocks are porphyritic rhyolites (SM1B, Coconut Island; SM2B, North Island) and dacites (sample SM3B, Daryabahadurgarh Island). Samples SM1B and SM2B have been dated by Pande et al. (2001) using the ⁴⁰Ar–³⁹Ar incremental heating method. The rocks are quartz normative (23.8–27.5%) and are not peraluminous, as shown by the ubiquitous presence of clinopyroxene. In the total alkali–silica (TAS) diagram, the analyses plot in the same general space as data for the rhyolites, dacites and trachytes of eastern Madagascar (Fig. 3). The dominant phenocrysts in the St Mary’s rocks are zoned plagioclase and lesser amounts of clinopyroxene, orthopyroxene, magnetite and ilmenite (Fig. 2d and e). The groundmass is fine-grained (sample SM1B) or granophyric (sample SM2B and, particularly, granophyre SM3B) and consists of the same minerals, as well as alkali feldspar and quartz. Biotite has been found as a rim on magnetite. Apatite and zircon are accessory phases. Clusters of gabbroic or doleritic appearance (‘mafic inclusions’) occur in the Coconut Island rhyolite (Fig. 2c). They are made up of intergrowths of plagioclase, clinopyroxene and oxides, and could represent mingled magma batches or fragments of basaltic rock incorporated at depth.

Plagioclase ranges in composition from An₅₆–₄₁, found in the core of a crystal in a mafic inclusion, to An₁₆ in the rim of a phenocryst of sample SM1B. Secondary albite rims have been found, as was Na-rich alkali feldspar (Or₂₀Ab₇₆). Augite (Ca₃₈–₄₀Mg₄₁–₄₃Fe₁₈–₂₀; Mg-number = 0.6₈–₀.₇₀, where Mg-number = atomic Mg/ (Mg + Fe)), and orthopyroxene (Ca₃₄Mg₆₆–₆₂Fe₃₅–₃₇; Mg-number = 0.₆₂–₀.₆₄) are the two pyroxenes of the St Mary’s Islands rocks (Fig. 4a). The TiO₂ concentration in the augite phenocrysts is relatively low (0.₄–₀.₉ wt%). Equilibration temperatures based on two-pyroxene geothermometry (Lindsley 1983) are around 1000°C. The mafic inclusion has more calcic plagioclase (An₅₈–₄₁) than the phenocrysts of the lavas (An₄₁–₃₅). The augites of the mafic inclusion (Ca₃₈–₄₁Mg₅₀–₄₃Fe₁₇–₁₉) have slightly more...
Table 1. Whole rock major oxides (wt%) and trace elements (ppm) of the St Mary’s Islands rocks (SW India) and silicic rocks of the eastern coast of Madagascar

| Location: Daryabah-
<table>
<thead>
<tr>
<th>North Island</th>
<th>South Island</th>
<th>Sambava sector, Madagascar</th>
<th>Sambava-Vohemar road</th>
<th>Mananjary sector, Madagascar</th>
<th>Mananjary–Ilaka road</th>
<th>Vatovandry South Fenoarivo</th>
<th>W-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type: Lava</td>
<td>Lava</td>
<td>Lava</td>
<td>Dyke</td>
<td>Dyke</td>
<td>Dyke</td>
<td>Lava</td>
<td></td>
</tr>
<tr>
<td>Type: Dyke</td>
<td>Lava</td>
<td>Lava</td>
<td>Dyke</td>
<td>Dyke</td>
<td>Dyke</td>
<td>Lava</td>
<td></td>
</tr>
<tr>
<td>Type: Dyke</td>
<td>Lava</td>
<td>Lava</td>
<td>Dyke</td>
<td>Lava</td>
<td>Lava</td>
<td>Lava</td>
<td></td>
</tr>
</tbody>
</table>
| LOI, loss on ignition. Eu/Eu* = Eun/(Smn × Gdn).5.1 Trace elements determined by ICP-MS. 2Sc, Co, Cs, La to U determined by INAA, others by XRF. LATE CRETACEOUS RHYOLITIC ROCKS OF INDIA AND MADAGASCAR 287.
variable Mg-number (0.67–0.73) than the values found in the phenocrysts of the lavas, and have also slightly higher TiO$_2$ (0.9–2.2 wt%). Ti-magnetite and ilmenite have been found coexisting. Their very narrow ranges of calculated equilibration temperatures and oxygen fugacities are 733–756°C and 10$^{-13.2}$–10$^{-12.4}$ bars $f$O$_2$, respectively (using Lepage 2003, and references therein), suggesting subsolidus re-equilibration. The data plot above the nickel–nickel oxide (NNO) synthetic buffer, indicating a more oxidized environment than inferred from the range of values for northern Madagascan rocks, which cluster around the quartz–fayalite–magnetite (QFM) synthetic buffer (Melluso et al. 2001, 2005, 2006). Biotite rimming magnetite has high Mg-number (0.70). It is moderately Ti-rich (TiO$_2$ 3.4 wt%). Overall, the range of these mineral compositions is similar to that found by Valsangkar (1980) and Subbarao et al. (1993) for the St Mary’s Islands rocks.

The St Mary’s Islands rhyolites and dacites have low contents of CaO (1.9–2.9 wt%), MgO (0.6–1.1 wt%), total iron as Fe$_2$O$_3$ (3.3–4.9 wt%), TiO$_2$ (0.8–1.1 wt%) and P$_2$O$_5$ (0.12–0.28 wt%), and relatively high Na$_2$O (4.4–4.7 wt%) and K$_2$O (2.7–3.1 wt%), indicating a moderate degree of chemical variation. The rocks are characterized by relatively high concentrations of incompatible elements such as Zr (585–719 ppm), Nb (43–53 ppm), Y (75–86 ppm), Ba (528–624 ppm) and Rb (64–74 ppm), increasing with decreasing MgO. Vanadium, Sc, Zn and Sr concentrations decrease with MgO (Table 1). The increase in Zr with decreasing MgO precludes significant fractionation of zircon. The St Mary’s Islands rocks have moderately high ratios of light REE (LREE) to heavy REE (HREE) (e.g. La/Yb$_n$ = 6.9–7.2; the subscript $n$ means chondrite normalized; chondrite values of Boynton 1984), and lack negative Eu anomalies (Eu/Eu* = 1.02–1.06, where Eu is the normalized measured value and Eu* is interpolated Eu between normalized Gd and Sm), a remarkable feature for dacites and rhyolites (Table 1). Moderately high La/Nb (1.4–1.5) and Ba/Nb (11.8–15.6) ratios are observed.

Initial (at 88 Ma) $^{87}$Sr/$^{86}$Sr and $^{143}$Nd/$^{144}$Nd range from 0.70539 to 0.70571 and from 0.512481 to 0.512488, respectively (Table 2); $\epsilon_{Nd}$(88 Ma) ranges from −0.8 to −0.9 epsilon units. This small range of variation does not permit significant variable open-system processes within the dacite–rhyolite compositional range. The values plot close to the limit of the Sr–Nd isotopic range of basalts of northern and eastern Madagascar ($^{87}$Sr/$^{86}$Sr 0.70295–0.70681; $\epsilon_{Nd}$ +7.4 to −5.3) (Fig. 5).

The major and trace element variations within the St Mary’s Islands rocks are compatible with 11% crystal fractionation of a dioritic composition, starting from sample SM3B, to obtain SM2B. The relatively high concentrations of elements such as Zr, Nb, Y and Ba, the lack of negative Eu anomalies, the relatively low La/Nb and Ba/Nb, and the relatively low initial $^{87}$Sr/$^{86}$Sr and high $^{143}$Nd/$^{144}$Nd, with $\epsilon_{Nd}$ values close to the chondritic average value, indicate that the St Mary’s Islands rocks are unlikely to be a product of anatexis of typical Precambrian upper or lower continental crust. They may be anatetic melts of previously intruded Cretaceous basalts or, more likely, the result of prolonged crystal fractionation and some crustal contamination of a tholeiitic basalt parental magma.

The eastern Madagascar rhyolites: searching for equivalents of the St Mary’s Islands silicic rocks

It is worth noting that evolved rock located away from the eastern Madagascar coast, such as the western Madagascar (Mailaka), Antampombato and Androy dacites, trachydacites and rhyolites, have very strong petrographic differences from the St Mary’s Islands rocks, which exclude any common petrogenetic evolution. For example, the Mailaka dacites are peraluminous,
and contain cordierite phenocrysts rather than clinopyroxene (Melluso et al. 2001). The few Antampombato rhyolites (Melluso et al. 2005) and some of the uppermost Androy rhyolites are peralkaline, and carry minerals such as ferrosalitic (hedenbergitic) clinopyroxene and sodic amphibole (Mahoney et al. 2008), minerals barely seen in evolved rocks of typical tholeiitic affinity. These rocks have other chemical and isotopic differences with the St Mary’s Islands rocks, not to mention their relatively large geographical distances from the east coast of Madagascar.

The search for equivalents of the St Mary’s Islands rocks in Madagascar should therefore be made along or close to its eastern coast. We distinguish the eastern Madagascar silicic rocks on a geographical basis, following the distinction made by Storey et al. (1997) on the mafic flows and dykes: Sambava (north), Tamatave (centre) and Mananjary (centre–south) (Fig. 1; Table 1).

Some rhyolites and trachytes of eastern Madagascar appear very weakly peralkaline (agpaitic index (AI), i.e. molar (Na + K)/Al, up to 1.05). Considering the systematic presence of plagioclase, the absence of sodic pyroxene or amphibole, and the degree of alteration of the samples, no rhyolites from Tamatave or Mananjary can be considered true peralkaline rocks.

From among the eastern Madagascan silicic rocks, samples MAN90-84, MAN90-28, M722 and TAM92-56a (Table 1) come from the Mananjary and Vatomandry sectors (Fig. 1a). These samples are porphyritic, and some are pitchstones (Fig. 2f). The samples are generally very altered (particularly those cropping out in the Vatomandry–Ilaka area), although a few are relatively fresh. Plagioclase is the main phenocryst phase, and is accompanied by smaller amounts of augite, orthopyroxene, magnetite and ilmenite. Devitrification is widespread, even though relatively fresh glass is sometimes observed (sample MAN90-84 from near Mananjary). Plagioclase phenocrysts in MAN90-84 range from An 49 to An 44. Augite (Ca 36–38Mg 40–43Fe 20–23; Mg-number = 0.64–0.68) and orthopyroxene (Ca 4Mg 59Fe 37; Mg-number = 0.61–0.62) are the two pyroxenes of the Mananjary and Tamatave rhyolites (Fig. 4a). Coexisting Ti-magnetite and ilmenite have calculated equilibration temperatures of 912 ± 8°C and oxygen fugacity of 10/8 ≤ 10/10 bars, again plotting above the NNO synthetic buffer, but displaced to higher temperatures than those of St Mary’s Islands rocks. Two-pyroxene geothermometry (Lindsley 1983) yields values close to 1000°C, almost identical to those of the St Mary’s Islands rocks. The M722 rhyolite (west of Vatomandry) has sodic plagioclase (An 36–29) strongly albitized near the rims, alkali feldspar, and clinopyroxene with a larger...
The element concentrations shown here are from Table 1. Sr, Nd and Sm of MAN samples have been analysed using isotope dilution. For the analyses performed at Firenze, uncertainties in measured isotopic ratios refer to the least significant digits; they are reported as 2 standard errors for within-run precision and 2 standard deviations for external precision on standards. The 87Sr/86Sr value for the NBS987 standard measured during the course of this work was 0.710247 ± 11 (n = 10). The 143Nd/144Nd value for the La Jolla standard was 0.511846 ± 6 (n = 7). The total procedural blank was 211 pg for Sr and <100 pg for Nd, making blank correction negligible. Samples MAN90-28 and MAN90-84 were measured at the University of Hawaii. These data are reported relative to measured 87Sr/86Sr/C6 Jolla standard was 0.511846.

The Nd isotope diagram for the St Mary’s Islands samples (Fig. 1), are 0.70522, and 0.70390. Initial 87Sr/86Sr and 143Nd/144Nd of Vatomandry rhyolite and MAN90-28, and dacite MAN90-51 have patterns matching those of the St Mary’s Islands samples (Fig. 6). In contrast, rhyolites and trachytes of the Sambava area are chemically distinct, in that they have generally higher contents of elements such as Ba, Ti, Th and light lanthanides, and more marked troughs at Sr, Eu and P (Fig. 6).

Initial 87Sr/86Sr and 143Nd/144Nd of Mananjary rhyolites MAN90-28 and MAN90-84 (Fig. 1), are 0.70522, and 0.70390 and 0.512570 and 0.512662 (εNd(NBS88) = +0.8 to +2.6), respectively. Initial 87Sr/86Sr and 143Nd/144Nd of Vatomandry rhyolite and dacite dykes (M721a, M722) range from 0.70552 to 0.70833 and from 0.512399 to 0.512241 (εNd(NBS88) = −2.5 to −5.6), respectively (Table 2). The data are within the observed ranges of the associated basalts of the eastern coast and plot far from the fields of other silicic rocks of the province, particularly the Mailaka dacites (Melluso et al. 2001) and the Androy dacites, trachydacites and rhyolites (Mahaney et al. 2008; Fig. 5).

Data for the clinopyroxenes of the St Mary’s Islands dacites and rhyolites and of many rhyolites of the eastern coast of Madagascar plot in the same fields, not only on plots of major elements with a narrow range of variation (such as Ca, Mg, and Fe) (Fig. 4a), but also for MnO (up to 2.3 wt%) and Na2O (up to 0.75 wt%) and low TiO2 and Al2O3 at Mg-number (0.70–0.64 (Fig. 4b). The augites are clearly distinct from those of the associated tholeiitic basalts (Fig. 4b) and are different also from pyroxenes of other rhyolites, such as those found in sample M722. On the other hand, the clinopyroxenes of the mafic inclusions of St Mary’s Islands plot within the range of the associated basalt dykes of the eastern coast and the Androy (Fig. 4a–c). In addition, orthopyroxenes of both St Mary’s Islands and eastern Madagascar rhyolites have unusually high MnO content for their Mg-number (1.7–3.2 wt% at Mg-number = 0.64–0.61).

Regardless of the causes of the different minor element composition of clinopyroxene of basalts and rhyolites, there is compelling evidence that the clinopyroxenes of the rhyolites are not inherited phases from the basalts and we believe that their composition is a highly distinctive petrogenetic feature. Thus, similar petrogenetic evolution and extremely similar physicochemical conditions are suggested from clinopyroxene chemical
compositions of many silicic magmas of central–western Madagascar and southwestern India.

Regarding Sr–Nd isotope ratios, the St Mary’s Islands silicic rocks have slightly more radiogenic Sr and less radiogenic Nd isotope ratios than most eastern Madagascan basalts (Storey et al. 1997; Melluso et al. 2002, 2005), but they fall well within the compositional range we have found in the eastern Madagascar (Mananjary–Vatomandry) rhyolites, close to the isotopic composition of sample MAN90-28 (Fig. 5).

Considering all observations, the St Mary’s Islands rocks, although having slightly different petrographic characteristics from the Vatomandry–Ilaka and Mananjary rhyolites, are closely similar in mineral compositions and whole-rock geochemical and isotopic compositions. These similarities cannot be fortuitous, given the differences in these aspects between the St Mary’s Islands rocks and rhyolites elsewhere in eastern Madagascar. Thus, there is possibility of correlation between the St Mary’s Islands rocks and the Vatomandry–Ilaka–Mananjary silicic rocks along the central–southern strip of the Madagascan east coast.

**Palaeogeographical implications**

Having established that the St Mary’s Islands dacites and rhyolites have geochemical equivalents in silicic lavas and dykes cropping out along the central–southern stretch of the east coast of Madagascar, and nowhere else in Madagascar, we use this information to fit India and Madagascar in a pre-drift position before the opening of the Mascarene basin in Late Cretaceous times (Fig. 7). Many palaeogeographical reconstructions of the India–Madagascar pre-drift relative positions are already available in the literature (Fig. 7). They are based on palaeomagnetism, backtracking the landmasses along the fracture zones of the Mascarene basin (Reeves & de Wit 2000), correlating major Precambrian structures (in particular, the Archaean blocks of the western Dharwar craton cropping out in the Antongil Bay and Vatomandry areas; see de Wit 2003; Raval & Veeraswamy 2003), mineralization (Dissanayake & Chandrajith 1999), geometric fits of continental shelves (Yatheesh et al. 2006), and even palaeontological arguments (e.g. Bardhan et al. (2002) estimated a <100 km separation between India and Madagascar during the Turonian, between 93.5 ± 0.8 and 89.3 ± 1 Ma).

Our attempt to correlate rhyolitic units between eastern Madagascar and southwestern India is thus a complementary approach to that taken by other workers. The strong geochemical similarities between the St Mary’s Islands rocks and the Vatomandry–Ilaka–Mananjary rhyolites, the distinct geochemical differences between the St Mary’s Islands rocks and rhyolites elsewhere in eastern Madagascar, the absence of seaward-dipping reflectors along the very narrow continental shelf of eastern Madagascar (Storey et al. 1995), the difficulty of very viscous
silicic flows travelling large distances, as well as the fact that some of our studied units (such as the Daryabahadurgarh granophyre and the Vatomandry rhyolite dykes) are shallow-level intrusions, mean that we are able to tightly constrain the south–central eastern coast of Madagascar and the southwestern coast of India in a Late Cretaceous pre-drift restoration at c. 88 Ma (Fig. 7).

Our inferred palaeoposition of India and Madagascar is
broadly consistent with reconstructions proposed by Katz & Premoli (1979), Royer & Coffin (1992), Storey et al. (1995), Dissanayake & Chandrajith (1999), Yoshida et al. (1999), Raval & Veeraswamy (2003), Yatheesh et al. (2006), Ali & Aitchison (2008) and Eagles & König (2008). Other proposed fits between Madagascar and India differ in placing India in a more northerly position (Torsvik et al. 1998, 2000; Parson & Evans 2005) or Madagascar in a northerly position (Reeves & de Wit 2000; de Wit 2003; Masters et al. 2006). These reconstructions do not all relate to the same age (c. 88 Ma), and the age is of course an important variable. Indeed, recent studies suggest that India moved northwards before Madagascar in the Early Cretaceous, in response to multiple openings of oceanic basins between India and Antarctica (see Coffin et al. 2002, and references therein), leading to strong sinistral strike-slip movements with Madagascar (Gaina et al. 2007). Later, Madagascar started to move northwards along the same strike-slip fault system (some faults were located in the Mozambique Basin; see Marks & Tikku 2001).

This fault system became the locus of drifting that led to the formation of the Mascarene Basin (Storey et al. 1995, and references therein). Although the relative movements of India and Madagascar may have been simpler than those described by Gaïna et al. (2007) (see Eagles & König 2008), caution should be used in correlating the position of the landmasses in the Late Cretaceous based on the fits of pre-Cretaceous (Precambrian) structures alone. If Madagascar and India moved in opposite senses during the Early Cretaceous (Gaina et al. 2007), the juxtaposed position of St Mary’s Islands and the Vatomandry–Ilaka–Mananjary rhyolites during the later part of the Cretaceous (Radhakhrishna et al. 2007) may have been simpler than those described by Gaina et al. (2007) (see Eagles & König 2008), caution should be used in correlating the position of the landmasses in the Late Cretaceous based on the fits of pre-Cretaceous (Precambrian) structures alone. If Madagascar and India moved in opposite senses during the Early Cretaceous (Gaina et al. 2007), the juxtaposed position of St Mary’s Islands and the Vatomandry–Ilaka–Mananjary rhyolites during the later part of the Cretaceous, realized in this study, constrains their Late Cretaceous positions much better than Precambrian geological features.

Concluding remarks

The rhyolites and dacites of the St Mary’s Islands, southwestern India, have chemical and isotopic characteristics very different from those of typical anatectic melts of Precambrian continental crust, and are better explained as the products of fractional crystallization of tholeiitic basalt melts along with some crustal assimilation. These rhyolites and dacites are analogous to those cropping out extensively in eastern Madagascar. The somewhat anomalous but almost identical mineral chemical and whole-rock chemical and isotopic compositions of the St Mary’s Islands rocks and the Vatomandry–Ilaka–Mananjary rhyolites definitely suggest closely similar magmatic evolution. They also suggest that these lavas, dykes and shallow subvolcanic intrusions must have occupied a common and relatively restricted area before the break-up of India and Madagascar at c. 88 Ma.

Finally, we note that some basic igneous rocks in southern India (mostly dolerite dykes) have a roughly similar age to the St Mary’s Islands rhyolites ( Radhakhrishna et al. 1994, 1999; Kumar et al. 2001). Some of these basic rocks may correlate with basic units in Madagascar (Storey et al. 1995), but more thorough sampling and petrographic, geochemical and age data on the Indian rocks than available at present are needed to evaluate these potential correlations.

We thank K. Pande for company and assistance in the field, and M. Marrazzo for her help with laboratory and microprobe work. M. Lustrino, R. de’ Gennaro and M. Serracino are thanked for their help in obtaining microprobe data. S. Tommasini is particularly thanked for his help in the isotopic work in a period of troubles for the Firenze mass spectrometer. I. Rocco is also thanked for her help with analytical work at SOEST. A. Saunders was essential for the completion of this project, and is thanked for providing data, material and useful comments. This project was supported by Italian MIUR (PRIN grants to 2004 to V.M.). D. Peate provided very useful inputs, and improve an initial version of the manuscript, and discussion with various colleagues at the LIPS–IODP meeting in Coleraine (especially those with M. Coffin and R. Duncan) helped to tighten the contents of early versions. We acknowledge the detailed and constructive reviews of T. Barry and J. Marsh, the thorough reading and editorial comments of D. Peate, and the patience of A. Hills.

References


