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Further geochronological and paleomagnetic constraints on Malani (and pre-Malani) magmatism in NW India



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ABSTRACT

At 750 Ma India was part of a larger fragment of eastern Gondwana blocks that included the Seychelles-Mauritia, Madagascar, Sri Lanka and the Enderby Land-Prydz Bay region of East Antarctica. Subduction of the Mozambique Ocean beneath Seychelles-Mauritia, northern Madagascar and northwestern India formed a lengthy continental arc that remained active during the formation of Gondwana. Paleomagnetic data from the Malani rhyolites and associated dykes provide a robust paleomagnetic pole constraining India's position at this time. The rhyolitic and granitic rocks associated with the Malani Igneous Suite (MIS) have robust age constraints; however, the ages of the mafic dykes were inferred solely on the basis of similarity in paleomagnetic directions to the rhyolitic units. Here we present new geochronological data from the Malani mafic dykes that yield a *minimum age* of 704 Ma. The ²⁰⁷Pb/²⁰⁶Pb ages obtained for the dykes are less-likely to be affected by Pb-loss and yield a more reliable estimate for the age of the mafic dykes of ~750 Ma. We argue that intrusion of these mafic (and minor felsic) dykes represents the final pulse of MIS magmatism.

Many of the granitic rocks in the region are reported as 'unclassified' due to limited geochemical data and/or geochronological ages. Some of these 'unclassified' granites are intruded by the mafic dykes sampled in this study near the town of Bilara. The granites yielded zircon core ages of ~1100 Ma with younger rims averaging ~1020 Ma. We argue that this provides further evidence for a significant orogenic event ~1000 Ma that may relate to the collision of the Marwar block with the Banded Gneiss Complex/Bundelkhand craton in north-central India. Other ~1000 Ma orogenesis is also known along the Central Indian Tectonic Zone (CITZ) and the Eastern Ghats Mobile Belt. Globally, this same time interval is thought to represent the amalgamation of the supercontinent Rodinia and may also have resulted in the closure of the major "Purana" basins in India.

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1. Introduction

The breakup of the Rodinia supercontinent resulted in plate reorganizations that culminated with the assembly of the Gondwana continent during Ediacaran–Cambrian time (Meert and Lieberman, 2008; Meert and Torsvik, 2003). Although a working model for Rodinia was posited by Li et al. (2008), the configuration at any particular interval of Neoproterozoic time (1000–635 Ma) is contentious. Nevertheless, there is a consensus opinion that the supercontinent began to disaggregate around 750 Ma. In the archetypal Rodinia, Peninsular India (Fig. 1a) is placed along the periphery of the supercontinent and usually in an East Gondwana configuration adjacent to the Mawson block of East Antarctica (Fig. 1b). Geological evidence points to a collisional boundary between the Rayner Province of East Antarctica and the Eastern Ghats province of India around 1000 Ma (Meert et al., 2010). It is less clear whether or not the Rayner Province was contiguous with the remaining pieces of East Antarctica (Mawson Block and Dronning Maud land) as depicted in the Geodynamic map of Rodinia (Li et al., 2008). A number of publications consider India as an independent block (i.e. separate from the archetypal East Gondwana) during the Neoproterozoic (Boger et al., 2001; Collins and Pisarevsky, 2005; Fitzsimons, 2000; Meert, 2003; Meert and Van der Voo, 1997; Powell and Pisarevsky, 2002) although others (Yoshida and Upreti, 2006) maintain the integrity of East Gondwana throughout the Neoproterozoic.

There are few paleomagnetic tests of these connections and in the list of three Neoproterozoic poles cited by Li et al. (2008) for India, two poles do not support a connection of India to the rest of East Gondwana at 750 Ma (see Torsvik et al., 2001a,b). The other pole used in the compilation is problematic. The Harohalli pole (Radhakrishna and Mathew, 1996) is listed as 814 ± 34 Ma. A more recent study





TECTONOPHYSICS

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of these alkaline dykes by Pradhan et al. (2008) confirmed the paleomagnetic direction, but U–Pb dating of zircons from the dykes indicated that they were emplaced at ~1200 Ma. Thus, the India connection in Rodinia is poorly constrained by paleomagnetic data; however, geological evidence including widespread 1100–1000 Ma trans-India orogenesis is consistent with global events reflecting supercontinent assembly.

In this paper, we expand on previous paleomagnetic studies of the Malani Igneous Province with a focus on late-stage mafic dykes. As part of that exercise, we also provide age constraints on their emplacement and the duration of Malani magmatism. In addition, we document 1100–1000 Ma ages for an 'un-classified' granite intruded by the Malani mafic dykes.

2. Regional geology of the Malani igneous province

The Malani Igneous Suite lies to the west of the Aravalli–Delhi orogenic belts and the Archean-age Banded Gneissic Complex in the state of Rajasthan, northwestern India (Fig. 1). The MIS is separated from the orogenic belts by the Western Margin Fault (WMF; Fig. 2a). The older tectonic history of the region to the east of the WMF can be broadly confined to an Archean phase (emplacement and metamorphism of the Banded Gneissic Complex), the Aravalli Orogenic cycle (1900–1700 Ma) and culminated with the end of the Delhi Orogenic Cycle around 1000 Ma. The Delhi Orogeny appears to be part of a larger deformational cycle that stretches across India via the Central Indian Tectonic zone (Fig. 1).

Bhowmik et al. (2009) suggested that the pre-1000 Ma Indian landmass consisted of at least three micro-continental blocks, the North Indian Block, the South Indian Block and the Marwar block (including the basement for the MIS), that underwent amalgamation at ~1000 Ma. Peak and retrograde stages of metamorphism are recorded in garnet-staurolite-kyanite schist and garnet-biotitemuscovite-quartz schist from the central domain of the Central Indian Sausar Mobile Belt as 1062 \pm 13 Ma and 993 \pm 19 Ma monazite ages (Bhowmik et al., 2012). The Aravalli/Delhi region is also characterized by granitic intrusions with ages of ~1000-1100 Ma (Biju-Sekhar et al., 2003; Buick et al., 2006; Deb et al., 2001; Just et al., 2011; Pandit et al., 2003). Ages of ~1100-900 Ma have been obtained from rims of some zircons from granitoid plutons occurring in the northern part of the Delhi Fold Belt (Biju-Sekhar et al., 2003). Other granitic rocks from the Aravalli region have been dated to ~1000-900 Ma (Biju-Sekhar et al., 2003; Kaur et al., 2006, 2007; Lescuyer et al., 1993; Pandit et al., 2003; Sivaraman and Raval, 1995; Volpe and Macdougall, 1990).

Neoproterozoic magmatic events following the Delhi orogeny in NW India include the collision related ~1000 Ma granitoids emplaced during east directed subduction of the western (Marwar) craton beneath the Archean-Paleoproterozoic craton (Roy and Jakhar, 2002). This magmatic event is manifested in the 968.3 \pm 1.2 Ma (U-Pb zircon) calc-alkaline Sendra granitoids (Fig. 2a; Pandit et al., 2003) along with 987 \pm 6.4 Ma (U-Pb zircon) rhyolites of the Sendra-Ambaji-Ajmer sector (Fig. 2a; Deb et al., 2001). A younger and more widespread thermal event resulting in emplacement of granitoids has been ascribed as post-dating the Delhi deformation and termed as Erinpura Granite (Heron, 1953). The 'Erinpura Granite' of Heron (1953) is a group of variably deformed granitoids (including granite, granodiorite and banded gneisses) exposed between Ajmer in the north and the northern state of Gujarat (located to the south of Mt. Abu in Fig. 2a). For a long time the 830 Ma (Choudhary et al., 1984; Rb-Sr data) was cited as the age of Erinpura Granite. More robust geochronologic data (U-Pb; U-Th-Pb) during the recent years have shown that these granites were emplaced over a much longer time span, between 860 and 820 Ma (Deb et al., 2001; Just et al., 2011; Solanki, 2011; van Lente et al., 2009). The Erinpura Granites are best exposed in the Sirohi-Jawai Dam region (Fig. 2b) where they also show evidence of migmatization and shearing. Sediments of Sirohi Group were deposited over the Erinpura Granite basement. Both the Erinpura Granite and the Sirohi Group metasediments share a common deformation history and are overlain by the felsic volcanics and intruded by granites of the 770–750 Ma (Gregory et al., 2009; Torsvik et al., 2001a,b) Malani Igneous Suite. Recent geochemical, deformation and geochronologic studies have also shown that the Mt. Abu granitoids, traditionally considered as late kinematic in relation to Delhi orogeny, are part of the Malani magmatic episode (de Wall et al., 2012).

The timing and duration of igneous activity in the MIS is debatable, but it is generally agreed that the province is Neoproterozoic in age. Magmatism occurred in three phases to form the third largest felsic igneous province in the world (Pareek, 1981) covering 51,000 km² (Bhushan, 2000). Activity commenced with an initial phase of basaltic then felsic volcanic flows followed by a second phase characterized by the intrusion of granitic plutons. Predominately felsic and minor mafic dyke swarms form the third and final phase of the igneous cycle. The Malani felsic volcanic rocks are unmetamorphosed, but slightly tilted and occasionally folded. Late stage mafic dykes are all vertical to sub-vertical. The MIS unconformably overlies Paleo- to Mesoproterozoic metasediments, granites, and granodiorites (Pandit et al., 1999) and unconformably underlies the Ediacaran to Cambrian Marwar Supergroup red-bed and evaporatic sequences (Torsvik et al., 2001a).

Malani felsic magmatism can be chemically classified into peraluminous (Jalore type) and peralkaline (Siwana type) varieties that show well defined spatial domains within the Province. Dykes are volumetrically less common in the MIS and individual dykes range in size from a few centimeters to 10 m in width. Gregory et al. (2009) sampled several dykes near Jalore. We sampled dykes intruding Siwana Granite to the west (near Redana), Jalore Granite to the north (Sankra) and older (unclassified) granite to the northeast (near Bilara) (Fig. 2b).

Among the multitude of tectonic settings proposed for Malani volcanisms, it has been suggested (see Bhushan, 2000) that the first stage volcanism of associated basaltic and felsic flows is generated by a hot spot source or lithospheric thinning and melting at the base of the crust, with an extended (over 100 million years) history (Rathore et al., 1996, 1999). However, this is at odds with paleogeographic reconstructions that show India as an isolated fragment ~770 Ma. Paleomagnetic data can be used to juxtapose India alongside the Seychelles. Geological evidence suggests that parts Madagascar, Mauritia, East Antarctica and Sri Lanka were part of this continental assembly (Collins and Pisarevsky, 2005; Meert, 2003; Torsvik et al., 2013). Both Madagascar and Seychelles have igneous activity from this time that is attributed to subduction (Ashwal et al., 2002; Torsvik et al., 2001b; Tucker et al., 2001). Thus, the paleoposition of India in relation to the ancient supercontinent Rodinia and proto-East Gondwana conflicts with the hypothesis of a rift setting for the MIS and is more indicative of an Andean-type arc environment resulting from the subduction of the eastern Mozambique Ocean. Previous studies on the early rhyolitic tuffs and younger mafic dykes, coupled with paleomagnetic data, provide some temporal constraints on magmatic activity in India during this time and may help to clarify the mechanisms generating this activity.

3. Methods

3.1. Paleomagnetic methods

In an effort to further demonstrate the primary nature of the paleomagnetic signal in the Malani Igneous Province, we sampled ten mafic dykes and one small felsic dyke in Rajasthan near the towns of Redana, Sankra and Bilara (see Fig. 2b). The dykes intrude the Siwana and Jalore granites and have sharp contacts with the country rock (Fig. 3). All samples were drilled in the field using a





Fig. 2. (a) Generalized geologic map of the Aravalli–Delhi region showing the major boundaries between various lithotectonic units. Boxed region shows the area outlined in b. BGC = Banded Gneiss Complex. (b) Geological map of the study area including locations of previous studies (black circles) and current study sampling locations (red stars). a, modified from Roy and Jakhar (2002).

gasoline-powered drill (water-cooled). Samples were oriented via magnetic compass and sun compass to check for any local deviations of the magnetic field. Whenever possible, we sampled a profile across the dyke and out into the country rock for a baked contact test. Samples were then returned to the University of Florida and cut into standard-size specimens. Natural remanent magnetization (NRM) intensities were measured on each sample and pilot alternating field (AF) and thermal demagnetization were conducted on paired specimens. All samples were measured on a 2G 77R cryogenic magnetometer at the University of Florida. In general thermal treatment proved more effective in isolating the main direction and the remaining samples were treated using stepwise thermal demagnetization using an ASC TD-48 thermal demagnetizer. Small samples from each site were crushed and subjected to Curie temperature analysis on a KLY-3S susceptibility bridge attached to a CS-3 heating unit. Af-treated samples were also used for isothermal remanence acquisition experiments to help identify the magnetic carriers in the rocks. The resulting data were analyzed using Super IAPD software.

3.2. Geochronologic methods

Samples were taken from each of the larger dykes along with the paleomagnetic samples in 2009. The samples were broken down with a sledge hammer and jaw crusher and further disk milled to reduce sediment into sand grain size. Samples were further separated by size using a succession of 400 μ m (40 mesh) and 250 μ m (60 mesh) sieves. Density separation by water table, heavy liquid and magnetic separation techniques were then carried out to isolate individual grains of zircon. These grains were examined with an optical microscope and handpicked from the appropriate fractions (non-magnetics at 5°, 0.5 A). Zircons were then mounted into an epoxy plug and polished to expose surfaces of the zircons. Cathodoluminescence (CL) imaging was then taken by SEM (Scanning Electron Microscope), as well as reflected light microscope imaging. The epoxy plugs were sonicated and cleaned in nitric acid to remove any common Pb surface contamination.

Fig. 1. (a) Generalized tectonic map of Indian subcontinent including Purana Basins, fold belts and cratonic regions. Fold belts; AFB = Aravalli Fold Belt, DFB = Delhi Fold Belt, EGMB = Eastern Ghat Mobile Belt, SMB = Satpura Mobile Belt, NSL = Narmada Son lineament, CIS = Central Indian Suture and PCSZ = Palghat-Cauvery Shear Zone. Purana; Basins; VB = Vindhyan Basin; PG = Prahnita-Godavari Basin; Ch.B = Chhattisgarh Basin; CuB = Cuddapah Basin; KBB = Kaladgi-Bhima Basin; MB = Marwar Basin; IB = Indravati Basin. Other Elements; EDD = Eastern Dharwar Domain; WDD = Western Dharwar Domain; MR = Mahandi Rift; R = Rajhmahal Traps; CG = Closepet Granite. SIB = South Indian Block; NIB = North Indian Block. (b) Geodynamic map of Rodinia showing the paleomagnetically unconstrained position of India in an East Gondwana configuration.

Zircon U-Pb analyses were carried out at the Department of Geological Sciences, University of Florida, using the "Nu-Plasma" (Nu Instruments, UK) laser ablation multi-collector inductively coupled plasma mass spectrometer (LA-MC-ICP-MS). The mounted zircon grains were ablated using an attached New Wave 213 nm ultraviolet laser, using a laser spot size of 30 µm for U-Pb analyses. Ar and He carrier gas was used for sample transport into the mass spectrometer. Before each ablation, a "zero" measurement was taken for 20 s in order to monitor corrections for isobaric interferences, especially from ²⁰⁴Hg, a common impurity in argon gas. Following this "zero" period, laser ablation commenced for 30 s, keeping a constant ablation pit depth, therefore reducing the existence of elemental fractionation. Ablation spot locations were recorded to insure the direct correlation of U-Pb ages to any zonation observed in the zircon. Data were recorded for rims and cores separately. Ablations occurred in intervals of 10 zircons, directly preceded and followed by ablation of two FC-1 standard zircons.

The U–Pb isotopic data were recorded using Nu instruments Time Resolved Analysis (TRA) software. This software allows the user to calculate isotopic ratios from a desired time segment of data, aiding in the avoidance of complications due to grain defects or surface contamination. The raw isotopic data garnered from the LA-MC-ICP-MS were imported into a Microsoft Excel® spreadsheet where corrections for instrumental drift and mass bias were undertaken. Data reduction is based on standard zircons (FC-1) from the Duluth Gabbro, dated at 1099.0 \pm 0.7 Ma and 1099.1 \pm 0.5 Ma by Black et al. (2003). Figures were generated using Isoplot/Ex plotting software Version 4.11 by Ludwig (2008).

4. Results

4.1. Paleomagnetic results

Of the eleven dykes sampled for paleomagnetic study, nine yielded consistent and stable direction (Table 1). Results from sites I95 and I96, both taken from the Sankra region, were problematic. Individual specimen behavior was stable and high temperature directions were obtained from linear trajectories, but collectively these high temperature directions were highly scattered. Natural remanent magnetization intensities (NRM) for the dyke samples ranged between 0.3 and 3 A/m with the modal intensity of ~2.0 A/m.

The remaining nine dykes showed stable behavior during demagnetization (Figs. 4 & 5). These dykes yielded a mean direction with Dec = 5.2° , Inc = $+61.3^{\circ}$ (k = 68, $a95 = 6.3^{\circ}$; Fig. 6a,b). This direction overlaps with paleomagnetic directions from previous studies on Malani rhyolites and dykes (Fig. 6a,b; Gregory et al., 2009; Klootwijk, 1975; Torsvik et al., 2001b;). The single felsic dyke yielded a mean direction with Dec = 341° , Inc = $+63.9^{\circ}$ (k = 46, $a95 = 9^{\circ}$). The mean paleomagnetic pole for all Malani studies is calculated from the VGPs of the individual sites listed in Table 1 (Fig. 6b). The pole falls at 69.4° N, 75.7° E (N = 27 sites, $A95 = 6.5^{\circ}$).

We also performed baked contact tests at Sites I92 and I916. The Malani mafic dykes at Site I92 intrude the Siwana granite. The dyke at Site I916 is 1.75 m wide and intrudes the pre-Malani (unclassified) granites. Sampling was limited to a couple of cores adjacent to the dyke (8 and 14 cm from the margin) and 3 samples from the unbaked region (>2 m from the margin). The two samples adjacent to the dyke gave a mean direction with Dec = 344, Inc = +65 (Table 1). The unbaked samples behaved chaotically and yielded no consistent directions. At site I92, the dyke was ~5 m in width. We collected samples from the baked zone (<45 cm from the contact), in the hybrid zone (~1.2 m from the contact) and unbaked samples (>5 m from the contact). Fig. 5a–c shows results from the dyke, the baked zone and the hybrid zone. The Siwana granite that was intruded by these later-stage mafic dykes is part of the Malani igneous province, but shows a direction that is antipodal to the main direction observed

in the bulk of Malani samples (see also Gregory et al., 2009). The baked contact test at site I92 is more robust than the test in Gregory et al. (2009) and we argue that the baked contact tests in the Malani mafic dykes provide conclusive evidence for a primary magnetization dating to the timing of intrusion of the dykes.

In an effort to identify the magnetic carriers in the dykes we examined the demagnetization behavior (unblocking temperatures T_{ub}), isothermal remanence acquisition studies (IRM) along with selective Curie temperature analyses. Fig. 7a shows a range of T_{ub} and some samples show a loss of intensity in the 300–350 °C range that suggests the presence of pyrrhotite. Most of the samples show a more discrete unblocking temperature range (Figs. 4, 5 and 7a) consistent with the presence of low-Ti magnetite. Isothermal remanence acquisition and backfield coercivity of remanence curves from the dyke samples all show saturation by 0.2–0.3 T and backfield coercivity values <0.1 T (Fig. 7b). Curie temperature experiments on the dyke samples showed a range of behaviors. Fig. 7c (felsic dyke) and d (mafic dyke) show heating and cooling curves that are nearly reversible whereas other samples (Fig. 7e and f) indicate that there is some alteration during heating.

Torsvik et al. (2001b) demonstrated (via a positive fold test) that the Malani remanence was older than the flat-lying Marwar Supergroup of Ediacaran age (i.e. older than ~570 Ma; Malone et al., 2008; Turner et al., in review). Gregory et al. (2009) examined the paleomagnetic record from several late-stage mafic intrusions and concluded (based on baked contact results from cross-cutting dykes) that the magnetization in the dykes was primary. Gregory et al. (2009) also provided the first U–Pb ages from the MIS at 771 Ma for the felsic rocks and asserted that the mafic dykes were likely



Fig. 3. (a) Mafic dyke at site I9–16. This dyke intrudes the so-called 'unclassified granites' near the town of Bilara.

Table 1	
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Paleomagnetic	resu	lts.
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Site name	Latitude/longitude	n/N	Dec	Inc	К	A95	VGP lat	VGP long	dp,dm
This study									
I9-1	25.844° N, 70.948° E	9/9	003°	63.8°	84	5.7°	70.2° N	77.2° E	7.2°,9.1°
I9-2 (dyke)	25.844° N, 70.951° E	8/8	011°	60.9°	66	6.9°	71.5° N	70.9° E	8.1°,10.6°
I9-2 (bake) ^a		3/3	034°	63.0°	99	12.5°	57.0° N	70.9° E	15.4°,19.7°
I9-2 (host) ^a		2/2	187.6°	-64.8°	-	-	68.4° S	254.1° E	
19-3	25.842° N, 70.944° E	4/4	028°	60.0°	24	19°	62.4° N	120.8° E	22°,29°
19-4	25.839° N, 70.940° E	3/3	024°	58.0°	30	23°	66.1° N	122.5° E	25°,34°
I9-14	26.125° N, 73.565° E	7/8	330°	68.4°	194	4.3°	55.9° N	40.0° E	6.1°,7.3°
I9-15 ^b	26.125° N, 73.563° E	7/7	341°	63.9°	46	9.0°	65.3° N	40.5° E	11.4°,14.3°
I9-16	26.099° N, 73.539° E	6/9	001°	60.5°	55	8.2°	74.6° N	76.4° E	9.5°,12.5°
I9-16 (bake) ^a		2/2	344°	65°	-	-	65.4° N	46.0° E	-,-
I9-17	26.098° N, 73.538° E	8/8	007°	51.1°	96	5.7°	81.6° N	119° E	5.2°,7.7°
19-18	26.097° N, 73.538° E	8/8	007°	55.6°	191	4.0°	78.3° N	102.6° E	4.1°,5.7°
Mean this study		60/64	005°	61.3°	68	6.3°	72.6° N	80.8° E	$A95 = 8.1^{\circ}$
Gregory et al. (2009)									
I434 (Normal)	25.342° N, 72.601° E	23/27	351.4°	72.6°	130	2.7°	56.9° N	64.3° E	4.3°,4.8°
I434 (Reverse)	25.342° N, 72.601° E	3/3	195.3°	-59.7°	235	8.1°	70.2° S	288.8° E	9.2°,12.2°
I435	25.341° N, 72.601° E	6/8	349.8°	61.8°	245	4.3°	70.5° N	49.8° E	5.1°,6.7°
I436	25.341° N, 72.616° E	9/9	355.4°	58.2°	91	9.7°	75.9° N	57.7° E	4.1°,5.6°
Mean all dykes		106/116	005.5	62.5°	76	4.4°	71.9° N	79.0° E	$A95 = 6.9^{\circ}$
(excludes baked/host	t directions)								
Torsvik et al. (2001a,b)	N used							
1	26.0° N, 73.0° E	5	38.6°	70.6°	189	5.6°	49.7° N	106.8° E	8.4°,9.7°
3	26.3° N, 73.0° E	13	17.2°	51.8°	678	1.6°	73.8° N	136.7° E	1.5°,2.2°
4	26.3° N, 72.6° E	13	312.8°	72.3°	52	5.8°	44.5° N	039.0° E	9.1°,10.3°
5	26.2° N, 72.5° E	6	356.2°	64.1°	511	3.0°	70.1° N	64.7° E	3.8°,4.8°
6	26.4° N, 72.5° E	11	024.7°	46.7°	179	3.4°	68.0° N	152.8° E	2.8°,4.4°
8	25.7° N, 72.4° E	16	354°	59.4°	322	2.1°	74.6° N	54.9° E	2.4°,3.2°
10	25.2° N, 72.6° E	4	339.9°	64.0°	52	12.9°	63.9° N	39.5° E	16.4°,20.5°
13	25.6° N, 72.5° E	5	57.5°	74°	109	7.3°	38.0° N	104.7° E	11.9°,13.2°
14	25.7° N, 72.4° E	7	12.7°	62.1°	201	4.3°	69.5° N	99.6° E	5.2°,6.7°
Klootwijk (1975)									
RI-2	26.3° N, 73.0° E	6	003.9°	62.5°	133	6.5°	72.2° N	82.2° E	7.9°, 10.2°
RI-3	26.3° N, 73.0° E	4	023.5°	82.5°	298	5.3°	39.6° N	80.6° E	10.1°,10.3°
RI-7	25.8° N, 72.2° E	4	340.0°	45.0°	55	12.5°	72.1° N	349.0° E	10.0°,15.8°
RI-10	25.8° N, 72.2° E	5	346.5°	52°	162	6.0°	76.4° N	15.4° E	5.6°,8.2°
RI-12	25.8° N, 72.2° E	3	337.0°	54.5°	316	7.0°	68.2° N	12.7° E	7.0°,9.9°
RI-13	25.7° N, 73.2° E	4	345.0°	81.0°	491	4.0°	42.5° N	67.1° E	7.5°,7.7°
Mean (all)		27 sites	002.9°	63.7°	40	4.2°	69.4° N	75.7° E	$A95 = 6.5^{\circ}$

Legend: n/N = number of samples used/number collected, N used = number of samples used for mean in studies by Klootwijk (1975) and Torsvik et al. (2001a,b); dec = declination, inc = inclination, k = kappa precision parameter, a95 = circle of 95% confidence about the mean, VGP lat/long = virtual geomagnetic pole coordinates, dp/dm = cone of confidence along site latitude (dp) and orthogonal to site latitude (dm); A95 = circle of 95% confidence about mean paleomagnetic pole.

^a Not used to calculate means

^b Felsic dyke.

late-stage intrusions based on a comparison to mafic dykes in the Seychelles (Torsvik et al., 2001a). Our new paleomagnetic studies add to the robustness of previous results from the Malani Igneous Province and the baked contact test provides additional support for the primary nature of the magnetic remanence in the Malani sequence. Below we describe how our geochronologic results demonstrate that the MIS mafic sequence is only slightly younger than the main felsic pulse and that Malani magmatism was largely confined to the interval from ~770 to 750 Ma.

4.2. Geochronologic results

In an effort to develop a comprehensive tectonic history of the MIS region, we sampled the mafic dykes (I92) for geochronologic studies along with the granitic rocks that were intruded by dykes I914-I918 (near Bilara, Fig. 2b).

The mafic dyke at Site I92 varied in thickness between ~5 and 6 m and samples were collected from the center (most coarse-grained) of the dyke. A total of seven zircons gave useful results (Table 2) although all analyses were slightly discordant (Fig. 8a). Six out of the seven zircons gave mean 206 Pb/ 238 U age of 704 \pm 5 Ma (MSWD = 0.93, probability = 0.46; Fig. 8b). Due to the fact that all

zircons are discordant, we consider this to be a minimum age for the mafic dykes in the region and a better estimate can be obtained using the ²⁰⁷Pb/²⁰⁶Pb ages. As can be seen on Fig. 8a data plot slightly below the concordia, that is consistent with recent lead loss. In order to estimate the true age of the dykes, we assume that the discordance in the zircon is due to recent lead loss. In that analysis the upper intercept age is 759 ± 12 Ma (Fig. 8a; MSWD = 1.8, probability = 0.11). This upper intercept age is consistent with the weighted average²⁰⁷Pb/²⁰⁶Pb age of 752 ± 18 Ma (MSWD = 3.4, probability = 0.002; Table 2). Given the evidence for Pb-loss in the zircons, we consider the weighted average ²⁰⁷Pb/²⁰⁶Pb age as the most reasonable approximation for the age of the mafic magmatism in the Malani. This age is consistent with the ages of mafic dykes obtained in the Seychelles by Torsvik et al. (2001b).

There are multiple suites of granitic intrusions in proximity to the MIS (Fig. 2b). Previous geochronological work demonstrates that some of the granites are directly associated with the MIS (Pradhan et al., 2010; van Lente et al., 2009). Other intrusions are part of the so-called Erinpura Suite (Heron, 1953; Roy and Jakhar, 2002) and an even older suite of granites dated to between 1100 and 1000 Ma that may be associated with the end of the Delhi orogenic cycle (Biju-Sekhar et al., 2003; Buick et al., 2006; Just et al., 2011; Pandit



Fig. 4. (a) Zijderveld and stereonet diagrams of a thermally treated sample from site 19–18 showing the characteristic North-down (+ inclination) direction. (b) Zijderveld and stereonet diagrams of a thermally treated sample from site 19–14 showing a slightly steeper north and down (+ inclination) direction. Closed (open) circles on the Zijderveld diagrams represent the horizontal (vertical) components of magnetization. Closed (open) circles on the stereoplots represent positive (negative) inclinations.

et al., 2003). In addition to direct dating of the granites, detrital zircon ages from the Marwar Supergroup are dominated by 800–1000 Ma zircons suggesting that the major pulses of felsic plutonism are associated with the Erinpura and Delhi pulses (Malone et al., 2008; McKenzie et al., 2011; Turner et al., in review).

The dykes at sites I916–I918 intrude one of the so-called 'unclassified granites' south of Bilara City (Fig. 2b). Zircons from sample I9GS-8 (collected near dyke I916); reveal variable morphologies (Fig. 9a–c) and a spread in ages (Fig. 9d). Cathodolumiscent (CL) images reveal bright cores and darker margins within individual zircon grains/ fragments (Fig. 9a–c). We analyzed both cores and rims for their ages and found that cores are older than the darker rims (Fig. 9e,f and Table 2). Fig. 9d shows all of the analyses from sample I9GS-8 on a Concordia plot.

Fig. 9e shows the weighted average 207 Pb/ 206 Pb age for the cores at 1101 ± 13 Ma (n = 10/10; 95% confidence, MSWD = 1.4).

Fig. 9f shows the weighted average ${}^{207}\text{Pb}/{}^{206}\text{Pb}$ age for the rims at 1021 \pm 10 Ma (n = 22/23; 95% confidence; MSWD = 2.9).

5. Discussion

5.1. Age/paleomagnetism of the Malani igneous province

Previously reported ages for the Malani magmatism range from 680 to 780 Ma (Crawford and Compston, 1970; Dhar et al., 1996; Rathore et al., 1999). Rathore et al. (1999) reported whole-rock Rb–Sr isochron ages ranging from 779 \pm 10 to 681 \pm 20 Ma for felsic volcanic rocks and granite plutons, emplaced during the first two stages of activity in the MIS, while Dhar et al. (1996) postulated a single ~725 Ma age (whole rock Rb–Sr) for both peraluminous and peralkaline granites. Torsvik et al. (2001a) cited precise U–Pb ages of 771 \pm 2 and 751 \pm 3 Ma for rhyolite magmatism in the MIS although no analytical data



Fig. 5. Zijderveld and stereonet diagrams for (a) baked contact test for ~5 m wide dyke at site 192. Thermally treated dyke sample showing characteristic north and down direction. (b) Granite sample collected at 45 cm from the contact showing completely overprinted direction (north and down) and (c) sample collected from the granite ~1.2 m away from the contact showing a low-temperature direction to the northeast and down (blue colors) and a high-temperature direction to the south and up (red colors). (d) Sample collected from the unbaked granite >5 m from the dyke showing a southerly directed (up) component. Symbols are the same as in Fig. 4.

were provided. Gregory et al. (2009) provide a more robust U–Pb concordia age of 771 \pm 5 Ma (MSWD =1.5) for felsic volcanism in the Malani sequence. Additional constraints on igneous activity come from a variety of sources. van Lente et al. (2009) and Dharma-Rao et al. (2012) provide U–Pb ages for the Sindreth felsic volcanic (Fig. 2b) of 767 \pm 2.9 Ma, 765.9 \pm 1.6 Ma, 761 \pm 16 Ma, 765 \pm 7 Ma and 768 \pm 7 Ma. van Lente et al. (2009) also report ages of 800 \pm 2 Ma and 873 \pm 3 Ma for tonalitic basement rocks in the region. Pradhan et al. (2010) report an age of 827 \pm 9 Ma along with younger discordant ages of 786 \pm 6 Ma for the Harsani granodiorite (Fig. 2b) that also lies beneath the MIS. These data suggest that Malani volcanism was preceded by a protracted interval of granitic intrusion ranging from ~900 to 800 Ma.

Gregory et al. (2009) argued that the mafic dyke intrusions into the granitic rocks near Jalore (Fig. 2b) were coeval with mafic dykes intruding granitic bodies in the Seychelles. The Takamaka dyke (Seychelles) was dated by Torsvik et al. (2001b) to 750.2 \pm 2.5 Ma (U–Pb zircon). Paleomagnetic data from the Seychelles can be rotated into close agreement with the MIS paleomagnetic pole and indicate a tight fit between India and the Seychelles at 750 Ma (see also Torsvik et al., 2001a,b).

Our new geochronologic data from a mafic dyke intruding the Siwana granite yielded seven discordant analyses with $^{206}Pb/^{238}U$ ages ranging from 700 to 727 Ma (weighted mean $^{206}Pb/^{238}U$ age 704 Ma). We consider that the weighted mean $^{207}Pb/^{206}Pb$ age gives a more reasonable approximation to the real crystallization age of thedykes at 752 \pm 18 Ma. Based on these data, we conclude that the dykes were intruded ~750 Ma and represent late stage magmatic activity associated with the MIS.

Paleomagnetic data are summarized in Table 1 and include results from this study, Gregory et al. (2009), Klootwijk (1975) and Torsvik et al. (2001b). Fig. 6b shows all the VGPs from various studies of Malani dykes and flows. A grand mean is derived from 27 different sites (Fig. 6a) and yields a mean Declination = 3° , Inclination =

 $+ 64^{\circ}$ (k = 40, a95 = 4.2°). The resultant mean paleomagnetic pole falls at 69.4° N, 75.7° E (A95 = 6.5°). The paleomagnetic studies on the MIS represent one of the most robust Neoproterozoic poles across the globe. The paleomagnetic data pass a fold test that constrains the magnetization to be older than ~580 Ma and also positive baked contact tests on dyke samples that confirm a primary remanence (Gregory et al., 2009; Torsvik et al., 2001a; this study).

6. Conclusions

Gregory et al. (2009) demonstrated the latitudinal offset between India's position, as constrained by the Malani pole (India-B) compared to its position in the traditional East Gondwana fit at 750 Ma (India-A). The East Gondwana fit of India (India-A) was fixed by using paleomagnetic data from the Mundine Wells dykes (MW; Wingate and Giddings, 2000) in Australia and reconstructing India's paleoposition according to the MW pole. In principle, our new data do not drastically alter the conclusions of Gregory et al. (2009) although the paleomagnetic data from Australia were re-evaluated by Li and Evans (2011). Li and Evans (2011) argue for a ~40° rotation of south and west Australia from Northern Australia for pre-650-600 Ma poles as a result of crustal shortening during the Paterson and Peterman orogeny. If this assumption is correct, then the configuration illustrated by Gregory et al. (2009) requires slight modification. In Fig. 10a, we modify the Australia configuration slightly to account for this rotation, but the latitudinal offset between India (based on the Malani pole) and its expected position in an East Gondwana configuration is ~45°. Given the errors about both the mean MW pole and the Malani pole, the latitudinal offset could be lowered by only eight degrees. A second option would be to assume the opposite polarity pole for the Malani dykes India-C. That reconstruction (Fig. 10a) results in a latitudinal offset and an orientation difference compared to the traditional East Gondwana configuration.



Fig. 6. (a) Stereoplot of site mean directions and their α_{95} . Red circles are from the dykes in this study. Closed (open) circles represent positive (negative) inclinations. PEF = represents the present Earth's field at Jodphur (Fig. 2b). (b) Virtual geomagnetic poles from the above cited studies (same color-coding). The mean paleomagnetic pole for the Malani rhyolites is shown by a black star (and α_{95} circle). See Table 1 for complete listing of results.

a, green circles from Gregory et al. (2009); gray circles from Torsvik et al. (2001a) and blue circles from Klootwijk (1975).

At 750 Ma, India was part of a larger fragment of eastern Gondwana block that included the Seychelles-Mauritia, Madagascar, Sri Lanka and the Enderby Land-Prydz Bay region of East Antarctica (Fig. 10b). Subduction of the Mozambique Ocean beneath Seychelles-Mauritia, northern Madagascar and northwestern India formed a lengthy continental arc that remained active during the formation of Gondwana (Meert and Lieberman, 2008). Geochronological data from the Malani mafic dykes yield a *minimum* 704 Ma age for the dykes. A better estimate for the crystallization age is provided by the ²⁰⁷Pb/²⁰⁶Pb mean of 752 \pm 18 Ma that is consistent with previous comparisons to late-stage mafic dyke swarms in the Seychelles that are dated to 750 Ma. We argue that intrusion of these mafic (and minor felsic) dykes represent the final pulse of MIS magmatism in Rajasthan.

Basement rocks that are intruded by the mafic dykes at sites (I914– I918) near Bilara yielded zircon core ages of ~1100 Ma with younger rims averaging ~1020 Ma. We argue that this provides further evidence for a significant orogenic event ~1000 Ma that may relate to the collision of the Marwar block with the Banded Gneiss Complex/Bundelkhand craton in north-central India. Other ~1000 Ma orogenesis is also known along the Central Indian Tectonic Zone (CITZ) and the Eastern Ghats Mobile Belt (Dobmeir and Raith, 2003). Globally, this same time interval is thought to represent the amalgamation of the supercontinent Rodinia and may also have resulted in the closure of the major "Purana" basins in India (Bickford et al., 2011; Bhowmik et al., 2012; Malone et al., 2008; Patranabis-Deb et al., 2007; Turner et al., in review).

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Fig. 7. (a) Unblocking temperature T_{ub} for several dyke samples from this study. Intensity drops around 300–350 °C are due to the presence of pyrrhotite in some samples. Most samples show discrete T_{ub} between 500 and 570 °C typical of titanomagnetite. (b) Isothermal remanence acquisition studies (and backfield coercivity of remanence for dyke samples in this study). All samples show saturation by 0.2–0.4 T typical of magnetite. (c) Curie temperature run for dyke sample 1915–4 (felsic dyke) showing nearly reversible heating and cooling curves (red = heating; blue = cooling). (d) Curie temperature run for dyke sample 191-4 showing nearly reversible heating and cooling curves. (e) Curie temperature run for dyke sample 1916–5. The heating curve shows a small susceptibility drop around 350 °C (pyrrhotite?) and a Hopkinson peak at around 575 °C. Sample shows evidence of alteration during the heating/cooling cycle. (f) Curie temperature run for mafic dyke sample 1914-3 that showed considerable alteration during the heating/cooling cycle.

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Table 2	
Geochronologic	results.

Grain name	²⁰⁷ Pb/ ²³⁵ U	2σ (%)	²⁰⁶ Pb/ ²³⁸ U	2σ (%)	Err Corr.	²⁰⁶ Pb/ ²³⁸ U (Ma)	2σ (Ma)	²⁰⁷ Pb/ ²³⁵ U (Ma)	2σ (Ma)	²⁰⁷ Pb/ ²⁰⁶ Pb (Ma)	2σ (Ma)	% Disc.
Malani dyke												
Mal-2	1.0497	2.2	0.11628	1.9	0.84	710	13	729	12	790	26	3
Mal-10	1.0236	2.6	0.11470	1.9	0.75	701	13	716	13	765	36	2
Mal-12	1.0137	2.2	0.11517	1.7	0.78	703	12	711	12	736	15	1
Mal-19	1.0135	2.3	0.11456	2.0	0.86	700	13	711	12	747	13	2
Mal-22	1.0180	2.1	0.11465	1.6	0.76	700	10	713	10	755	28	2
Mal-23	1.0432	2.4	0.11700	1.8	0.75	714	12	725	12	764	34	2
Mal-30	1.0919	3.4	0.11921	2.0	0.61	727	14	749	18	820	56	3
Cores I9GS8												
J1	1.9676	4.8	0.18509	4.6	0.96	1096	47	1104	32	1124	26	2
J2	2.0381	3.9	0.18996	3.3	0.85	1122	34	1128	27	1142	42	2
J5	1.8748	3.8	0.18005	3.6	0.94	1068	35	1072	25	1082	26	1
J10	2.1124	5.8	0.20070	5.7	0.97	1180	61	1153	40	1104	28	-7
J11	1.7450	3.9	0.16750	3.5	0.90	999	31	1025	25	1083	33	8
J12	2.0330	3.9	0.19255	3.7	0.94	1136	38	1126	27	1110	28	-2
J13	1.9776	4.2	0.18659	3.6	0.87	1104	37	1108	28	1118	41	1
J28	2.1132	5.8	0.20231	5.6	0.97	1189	61	1153	39	1089	28	-9
J30	1.8026	3.4	0.17218	2.8	0.81	1025	26	1046	22	1093	41	6
J31	1.9325	3.6	0.18485	3.1	0.88	1094	31	1092	24	1090	34	0
Rims I9GS8												
J3	1.7763	4.0	0.17501	3.8	0.95	1040	37	1037	26	1031	26	-1
J4	1.7785	4.3	0.17634	4.1	0.95	1048	40	1037	28	1018	26	-3
J6	1.7409	5.4	0.17308	5.2	0.97	1030	50	1024	34	1012	26	-2
J7	1.6873	3.0	0.16791	2.7	0.90	1001	25	1004	19	1011	26	1
J8	1.7382	4.3	0.17149	3.9	0.91	1021	37	1023	27	1028	35	1
J9	1.8554	4.5	0.18147	4.3	0.96	1076	42	1065	29	1046	27	-3
J14	1.6751	4.7	0.16567	4.5	0.96	989	41	999	29	1023	26	3
J15	1.7676	3.9	0.17447	3.7	0.94	1038	35	1033	25	1027	26	-1
J16	1.6131	2.9	0.15806	2.6	0.89	947	23	975	18	1042	27	9
J18	1.8849	9.0	0.18608	8.9	0.99	1101	90	1076	59	1027	29	-7
J19	1.9072	4.4	0.18619	4.2	0.95	1102	42	1083	29	1049	27	-5
J21	1.6050	3.7	0.16228	3.4	0.94	970	31	972	23	978	26	1
J22	1.6354	3.9	0.16556	3.7	0.94	988	34	984	24	976	26	-1
J23	1.8752	5.6	0.18662	5.5	0.97	1104	55	1072	37	1011	28	-9
J24	1.8139	3.1	0.17947	2.8	0.89	1065	28	1050	20	1022	29	-4
J25	1./362	5.0	0.17118	4.8	0.97	1019	45	1022	32	1030	26	1
J26	1.7755	6.6	0.1/436	6.4	0.97	1037	62	1036	43	1037	32	0
J29	1.5135	5.1	0.15256	5.0	0.97	916	42	936	31	985	27	/
133	1.4335	3.5	0.14596	3.2	0.92	8/9	26	903	21	964	27	9
J35	1.6563	2.9	0.16126	2.5	0.85	965	22	992	18	1055	31	9
138	1./2/1	6.4 5.2	0.16940	6.3	0.98	1010	59	1019	41	1040	29	<u>ک</u>
139	1./838	5.2	0.1/435	5.0	0.97	1037	48	1039	34 25	1047	27	1
J40	1.5644	4.1	0.15/39	٥.४	0.95	943	34	920	25	988	26	5

Notes: Err Corr. = Error correlation; % Disc. = % discordance between ²⁰⁶Pb/²³⁸U age and ²⁰⁷Pb/²³⁵U age.

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Fig. 8. (a) Concordia diagram for mafic dyke sample showing 6/7 analyses regressed through the present day (0 ± 5 Ma). Upper intercept age is 759 \pm 12 Ma (MSWD = 1.8). (b) 206 Pb/ 238 U ages for seven analyses (blue accepted, red rejected) with a mean 206 Pb/ 238 U age of 704 \pm 5 Ma (MSWD = 0.93, probability = 0.46). (c) 207 Pb/ 206 Pb ages for seven analyses (all accepted) yielding an age of 752 \pm 18 Ma represents the best estimate for the age of crystallization.



Fig. 9. (a–c) Cathodoluminescent photos of zircon grains from geochronological sample 19-GS8. This is the so-called 'unclassified granite' intruded by dyke 19-16–19-18 near Bilara (Fig. 2b). Ages are shown for cores and rims and arrows denote location of the laser ablation spot (235 U/ 238 U concordia ages). (d) Concordia diagram for all analyses from the unclassified granites (cores and rims); (e) 207 Pb/ 206 Pb ages for ten laser spots in the bright (CL) cores of the zircons (none rejected) with a mean of 1101 \pm 13 Ma and (f) 207 Pb/ 206 Pb ages for 23 laser spots along the rims of zircons (one rejected) yielding a mean of 1021 \pm 10 Ma.



Fig. 10. (a) Paleolatitudinal comparison of India using the Malani pole (and antipole) to India's proposed position within a united East Gondwana indicating ~45° of latitudinal offset. In this diagram, India-A is the position expected for India assuming that the East Gondwana configuration is correct. In India-A, India was positioned according to paleomagnetic data from the Mundine Wells pole. India-B represents the paleolatitudinal position of India according to the data reported in this study. India-C is positioned according to the paleomagnetic data reported herein using the opposite polarity of the pole reported herein. (b) Tectonic setting of eastern Gondwana elements at 750–770 M with subduction of the Mozambique Ocean beneath Madagascar, Seychelles-Mauritia and northwestern India. Euler poles for rotation for the figure in a (for northern and western Australia see Li and Evans, 2011); India-A Euler parameters are 42.7° N, 153.8° E, $\Delta = +38.9^\circ$; for East Antarctica the Euler parameters are 1.63° N, 222.8° E, $\Delta = -75.2^\circ$; for India-B Euler parameters are 0° N, 345.7° E, $\Delta = +20.6^\circ$; for India-C Euler parameters are 0° N, 345.7° E, $\Delta = -159.4^\circ$.