Paleomagnetism and geochronology of the Malani Igneous Suite, Northwest India: Implications for the configuration of Rodinia and the assembly of Gondwana

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Abstract

New paleomagnetic and geochronologic data on the Malani Igneous Suite (MIS), Rajasthan, Central India, improve the paleogeographic reconstruction of the Indian subcontinent between dispersal of the Mesoproterozoic supercontinent Rodinia and late Neoproterozoic assembly of Gondwana. The MIS comprises a voluminous initial phase of felsic and mafic volcanism followed by granitic plutonism. A zircon U-Pb age on a rhyolitic tuff constrains the initial volcanism in the MIS at 771 ±5 Ma. Large (up to 5 m wide) mafic dikes mark the final phase of igneous activity. A paleomagnetic direction obtained from 4 mafic dikes has a declination=358.8° and inclination=63.5° (with k=91.2 and α95=9.7). It overlaps with previously reported results from felsic MIS rocks. This normal direction includes a fine-grained mafic dikelet that showed a reversed direction with declination=195.3° and inclination=-59.7° (k=234.8 and α95=8.1°) and also records an overprint of normal polarity from the larger dikes. The VGP obtained from this study on mafic dikes is combined with previous studies of the Malani suite to obtain a mean paleomagnetic pole of 67.8°N, 72.5°E (A95=8.8°). Supported by a tentative baked contact test, we argue that this pole is primary, and permits improved reconstruction of the Indian subcontinent for 771-750 Ma. Data on the MIS, and equivalent data on Seychelles at 750 ±3 Ma, are compared with paleomagnetic data on the 755 ±3 Ma Mundine Well dikes in Australia, to indicate a latitudinal separation of nearly 25° between the Indian and Australian plates. These suggest that East Gondwana was not amalgamated at c. 750 Ma and therefore these two cratons were assembled later into the Gondwana supercontinent, during the ca. 550 Ma Kuunga Orogeny.

Keywords: Rodinia, Malani Igneous Suite, Neoproterozoic, continental reconstruction, NW India, paleomagnetism, geochronology
1. Introduction

The hypothesis of a Meso- to Neoproterozoic supercontinent formed in the aftermath of Grenvillian orogenesis began to develop in the 1970's (Piper, 1976; Bond et al., 1984). The name of ‘Rodinia’ was proposed in the early 1990’s (McMenamin and McMenamin, 1990; Dalziel, 1991; Moores, 1991; Hoffman, 1991). There are myriad configurations proposed for the Rodinia supercontinent and the exact paleolocations of its constituents are unresolved (Dalziel, 1991; Moores, 1991; Hoffman, 1991; Meert and Torsvik, 2003; Li et al., 2008). The archetypal model for Rodinia outlines that the supercontinent began to form at about 1300 Ma and reached maximum size at about 1000 Ma. Fragmentation and breakup of Rodinia was initiated sometime between 800-700 Ma along a rift between western (present-day coordinates) Laurentia and East Antarctica-Australia (Bond et al., 1984; Dalziel 1991; Hoffman, 1991; Powell et al., 1993). It is hypothesized that this rifting heralded a period of intense global cooling, sparking the development of multi-cellular life on Earth (Hoffman, 1998; Meert and Lieberman, 2008). Knowledge of the distribution and geotectonic evolution of continents related to Rodinia breakup is critical for an improved understanding of the context and causes of extreme climatic changes and accelerated biologic evolution at the enigmatic boundary between the Neoproterozoic and the Paleozoic.

The assembly of the supercontinent Gondwana followed the fragmentation of Rodinia. Eastern Gondwana comprised cratonic blocks that are currently within India, Madagascar, Sri Lanka, East Antarctica, Australia and the Seychelles. The paleogeography of these cratons prior to the formation and after breakup of Rodinia is not well constrained. Some (Windley et al., 1994; Piper, 2000; Yoshida and Uperti, 2006;
Squire et al., 2006; Paulsen et al., 2007) argue that these cratons came together in a single collisional event around or even earlier than 1300 Ma, were fused in that same configuration within Rodinia, and remained so until the breakup of Gondwana in the Mesozoic. More consistent with available geologic, paleomagnetic and geochronologic data is the alternative formation of eastern Gondwana as a polyphase assembly of cratonic nuclei that were severed and separately dispersed from the Rodinia supercontinent (Meert et al., 1995; Meert and Torsvik, 2003; Meert, 2003; Boger et al., 2002; Fitzsimons, 2000; Pisarevsky et al., 2003; Collins and Pisarevsky, 2005). This dispute may ultimately be resolved through the acquisition of high-quality paleomagnetic data coupled to high-resolution geochronologic ages from the various cratons that comprise Gondwana. Unfortunately, many extant studies are incomplete in that they do not incorporate an age with paleoposition and thus do not place strong spatial-temporal constraints on ancient continent localities.

The location of India within Gondwana is critical for evaluating the various tectonic models related both to the assembly of greater Gondwana and models of Rodinia. Greater India is placed alongside East Antarctica in the traditional Gondwana fit at 560 Ma (Figure 1; deWit et al., 1988), and some extrapolate this India-Antarctica-Australia connection to exist within Rodinia and even earlier supercontinents (Dalziel, 1991; Weil et al., 1998; Owada et al., 2003). However, due to paleomagnetic, geochronologic, and geologic correlations (or lack thereof), many workers have since suggested that India maintained a significant latitudinal offset from the archetypal Gondwana fit with Antarctica (Fitzsimons, 2000; Torsvik et al., 2001a; Powell and Pisarevsky, 2002).
The Malani Igneous Suite (MIS) in northwest India provides potentially critical paleomagnetic and geochronologic data for the Indian subcontinent during the late Neoproterozoic. Outcropping in southwest Rajasthan (Figure 2), the MIS is estimated to be one of the largest felsic igneous suites in the world (>51,000 km²; Pareek, 1981; Bhushan, 2000). Paleomagnetic studies from the MIS define the key paleomagnetic pole for the Indian subcontinent between 770-750 Ma. In this study, we augment previous work via the addition of paleomagnetic data from late-stage mafic dikes along with precise U-Pb ages from earlier erupted rhyolitic tuffs. Combined, these data contribute a key paleopole for the Indian plate during the Neoproterozoic, and lead to a discussion on the drift of India between the diffusion of Rodinia and the formation of Gondwana.

2. Geology and Tectonic Setting

Magmatism in the MIS occurred in three phases (Pareek 1981). Activity commenced with an initial volcanic phase made up of minor basaltic then felsic flows. The second phase is characterized by the intrusion of granitic plutons. Predominately felsic and minor mafic dike swarms form the third and final phase of the igneous cycle (Heron, 1953; Pareek, 1981; Srivastava, 1988). Malani felsic rocks are unmetamorphosed, but slightly tilted in some areas. Late stage mafic dikes are all vertical to sub-vertical (Figure 3a). The MIS unconformably overlies Paleo- to Mesoproterozoic metasediments, and basement granite gneisses and granodiorites of an unknown age (Pandit et al., 1999). The suite is unconformably overlain by the flat-lying late Neoproterozoic to Cambrian Marwar Supergroup, made up of red-bed and evaporite sedimentary sequences (Pandit et al., 2001).
A volcaniclastic conglomerate lies at the base of MIS (Bhushan, 2000) and basal rhyolitic tuffs denote the initiation of the first stage of the suite. Vertical to sub-vertical dolerite dikes crosscut all of the other components and thus mark the termination of magmatism. These mafic dikes are up to 5 meters wide (Figure 3a) and are found locally within the MIS intruding the Jalore granite. The mafic dike sequence near Jalore contains a relatively dense concentration of dikes with a general N-S trend. One large dike trends E-W and likely exploits an existing structural weakness in granite. Many of the larger dikes form conspicuous ridges only when enclosed in a granite host (Figure 3a) and weather out as bouldery traces visible in satellite images (Figure 4a).

Neoproterozoic magmatism in India can be compared with equivalent Neoproterozoic igneous provinces on nearby cratons. Paleomagnetic data juxtapose the Seychelles alongside India, and northeastern Madagascar is also placed along the India margin based on geochronological and geological similarities (Collins, 2006; Torsvik et al., 2001b; Ashwal et al., 2002). The sequence of rocks on Seychelles is rather similar to the Malani suite, and it is postulated that the geochemical signatures in the Seychelles are sourced from the Archean Banded Gneiss Complex in Rajasthan (Ashwal et al., 2002). The majority of Neoproterozoic granitoid and doleritic activity in the Seychelles falls within 755-748 Ma (Ashwal et al., 2002), with a span of ages ranging from 808-703 Ma (Stephens et al., 1997). If the Seychelles suite of Neoproterozoic rocks is analogous to the Malani province, the dolerite dikes sampled in this study can be considered as equivalents to dolerite dikes of Seychelles. The Seychelles dikes are geochemically related to Seychelles granitoids (Ashwal et al., 2002), and a U-Pb zircon age at 750.2±2.5 Ma from one of those dikes (Takamaka dike) indicate they are nearly coeval with the
felsic magmatic suite (Torsvik et al., 2001b). Slightly younger, but overlapping, ages (715-754 Ma) from the Daraina sequence in northern Madagascar are also correlated to the igneous activity in the Seychelles and India (Tucker et al., 1999).

Among the multitude of tectonic settings proposed for Malani magmatism, it is suggested (see Bhushan, 2000) that the first stage of associated basaltic and felsic flows was generated by a hot spot source or lithospheric thinning and melting at the base of the crust due to extension (Sharma, 2004). However, both Madagascar and Seychelles have igneous activity that is attributed to subduction of the Mozambique Ocean (Figure 1 inset; Handke et al., 1999; Torsvik et al., 2001b; Tucker et al., 2001; Ashwal et al., 2002). This is interpreted as an Andean-type active margin, closely related to the nearby and coeval arc activity observed in the Seychelles islands and northeastern Madagascar. The duration of magmatism and the source of igneous activity in the MIS, Seychelles and northeastern Madagascar are still questionable (Collins and Windley, 2002; Collins, 2006).

3. Previous Studies

3.1 Paleomagnetism

Numerous paleomagnetic studies have been performed on the felsic members of the MIS to determine the paleoposition of India at ca. 771-750 Ma (Table 1). Athavale et al. (1963) were the first to apply paleomagnetic tests to rhyolitic flows, and their results were similar to those obtained by Klootwijk (1975), but both studies lacked any detailed stability tests. Torsvik et al. (2001a) found a statistically positive fold test on felsic rocks from Malani that constrained the age of magnetism to pre-Marwar age (>Cambrian). Late stage mafic dikes had not been subjected to paleomagnetic study prior to our work. No reversals or positive field tests were found in previous studies to further document the
exact age of magnetism, and this lack of additional positive field tests to fully constrain
the age of magnetic acquisition has invoked some doubt in the primary nature of the
Malani pole (Yoshida and Upreti, 2006).

3.2 Geochronology

Previous geochronologic results from Malani felsic volcanics span about 100
million years (Table 2). Crawford and Compston (1970) reported a Rb-Sr age of 730 ±10
Ma for rhyolites (re-calculated with a decay constant of 1.42 x10^-11; see Steiger and
Jager, 1977). Later, Dhar et al. (1996) and Rathore et al. (1999) reported whole-rock Rb-
Sr isochron ages ranging from 779 ±10 to 681 ±20 Ma for felsic volcanic rocks and
granite plutons, emplaced during the first two stages of activity in the MIS (first and
second stages, respectively). This wide distribution of dates is partially a result of studies
of the so-called ultrapotassic rhyolites found near our sampling locality. The youngest
Rb-Sr isochron age of 681 ±20 Ma (Rathore et al., 1999) resulted from a solitary
occurrence of “ultrapotassic” rhyolite, reported without any rock description that would
ascertain whether high potassium is a primary igneous character or later alteration effect.
Much younger apparent ages of 548 ±7 to 515 ±6 Ma were obtained from whole-rock
40Ar/39Ar data on Jalore granites. These apparent ages are interpreted as evidence for a
thermal disturbance by Rathore et al. (1999) that may be related to the Kuungan or the
Malagasy orogenies (Meert, 2003; Collins and Pisarevsky, 2005); however, the
metamorphic grade of MIS rocks is incompatible with any significant thermal resetting
(Ashwal et al., 2002). Torsvik et al. (2001a) cited precise U-Pb ages of 771 ±2 and 751
±3 Ma for rhyolite magmatism in the MIS (Tucker, unpublished), but without analytical
details and sample descriptions.
4. Methods

4.1 Paleomagnetic Sampling and Experiments

Samples were obtained in the field using a gasoline powered hand drill and oriented using magnetic and sun compasses. Readings from the sun compass were used to correct for the local declination and any magnetic interference from the outcrop. Twelve samples from Jalore Granite and about 50 samples from four mafic dikes were taken at three sites (Figure 4). Fresh in-place outcrop is difficult to find and sampling was only possible where the granite host prominently crops out and exposes unweathered dikes. Three samples were taken from a small (width less than 2 cm) fine grained N-S trending dikelet (Figure 3b), which is crosscut by a 4-meter wide E-W trending mafic dike. This dikelet is aphanitic and dark grey-black in color with chilled margins (Figure 3b). The dikelet was sampled at less than 1 meter away from the larger dike, within a half-dike width distance in order to observe the effects of dike emplacement on surrounding rocks. There was no clear generative connection between this small dikelet and larger (nearby) N-S dikes; however, we cannot eliminate the possibility that it is rooted in a larger dike that was not exposed at this particular level in the quarry. It was possible to drill only three cores, as boulders obstructed the remaining dikelet outcrop.

Samples were cut into standard sized specimens and stored in a magnetically shielded space in the University of Florida paleomagnetic laboratory. A few preliminary samples were stepwise treated thermally or with an alternating field to determine the best method of demagnetization. After analyzing the behavior of preliminary samples, a series of steps were chosen for either alternating field or thermal demagnetization. Alternating field demagnetization was applied in steps using a home-built AF-demagnetizer at fields up to 140 mT. Samples were also treated thermally, in a stepwise
manner and up to temperatures of 600°C for ~60 minutes using an ASC-Scientific oven. Between each treatment, strong samples (generally mafic dikes) were measured on a Molspin Magnetometer and weaker samples (dikelets and granites) were measured on an ScT cryogenic magnetometer. Characteristic remanence components (ChRc) were calculated with least-square regression analysis implemented in the Super IAPD program (http://www.ngu.no/geophysics).

4.2 Rock Magnetic Experiments

The magnetic susceptibility of each sample was measured on an Agico SI-3B bridge before treatment. Curie temperature experiments were run on select powdered samples using a KLY-3S susceptibility bridge with a CS-3 heating unit. For this experiment, the susceptibility of a crushed sample is measured at increments during heating and cooling. The character of magnetic minerals in the sample can then be determined in detail based on the change in susceptibility with temperature. Isothermal Remanence Acquisition (IRM) studies were also performed using an ASC-IM30 impulse magnetizer to further characterize magnetic mineralogy.

4.3 Geochronology

Zircon was purified from one sample of rhyolitic tuff using a water table, heavy liquids and a magnetic separator. Available crystals were mounted in epoxy and polished to approximately half thickness. Cathodoluminescence (CL) images were obtained with a scanning electron microscope (Figure 5). U-Pb analyses were performed by secondary ion mass spectrometry (SIMS) using the CAMECA IMS 1270 instrument at the NORDSIM laboratory, Swedish Museum of Natural History, Stockholm (Table 3). The analytical method, data reduction, error propagation and assessment of the results are outlined in Whitehouse et al. (1999). The analyses were conducted with a spot size of ca.
20 \textmu m, calibrating to the Geostandard of 91500-reference zircon with an age of 1065 Ma (Wiedenbeck et al., 1995). The error on the U-Pb ratio includes propagation of the error on the day-to-day calibration curve obtained by regular analysis of the reference zircon. A common Pb correction was applied using the $^{204}$Pb concentration and present-day isotopic composition (Stacey and Kramers, 1975). The ISOPLOT program (Ludwig, 1995) was used to regress and present the SIMS U-Pb data.

5. Results

5.1 Geochronologic Results:
Zircon U-Pb geochronology was conducted on a sample of rhyolitic tuff representing the first stage of volcanism in the MIS. The sample, Mis5/04, was collected close to Jodhpur (26º17.963'-72º58.357') at site 3 of Torsvik et al. (2001a) where a U-Pb TIMS age of 751 ± 3 Ma was reported as ‘personal communication’. The sample shows ca. 5mm automorphic phenocrysts of quartz, plagioclase and K-feldspar in a microcrystalline devitrified groundmass of rose color. The sample contains few large (ca. 200 \textmu m) prismatic zircon crystals. They show well-terminated pyramid tips and oscillatory zoning and contain common fluid and mineral inclusions. Their habit is typical for zircon formed in a volcanic/subvolcanic magmatic environment. Sixteen analyses were made on 10 zircon crystals. Fourteen of them are concordant and define a concordia age of 771 ±5 Ma (MSWD = 1.5; Figure 5). This age is interpreted as the timing of magmatic crystallization and deposition of the rhyolite tuff.

5.2 Rock Magnetic Results:
Mafic dikes have an Isothermal Remanance Magnetization (IRM) plot that is indicative of magnetite (Figure 6a). Dike samples saturate at ~0.3 T and their intensity remains constant at higher fields, up to the highest applied field of 2 T. Sample I434-28b
is a mafic dikelet, and has an IRM curve also characteristic of magnetite, but with a lower absolute J value at saturation (Figure 6a). Curie temperature runs on samples from the large mafic dikes show a curve that is characteristic of magnetite, but with some alteration upon cooling (Figure 6b and c). Susceptibility is slightly higher during heating than cooling, but Curie temperatures of all tested dike samples are similar and in the typical range of magnetite. The heating Curie temperature $T_{cH}$ of one dike sample is equal to 589.7°C and the cooling Curie temperature $T_{cC}$ is equal to 588.3°C. Figures 5d and 5e display Curie temperature results from the small dikelet sampled. When subjected to temperatures up to 700°C, these mafic dikelets displayed substantial alteration and comparatively high susceptibility while cooling (Figure 6d). Curie temperature tests were performed on the same samples up to only 600°C, which is the highest temperature applied during demagnetization. When subjected to the normal range of temperatures, these dikelet samples showed far less alteration (Figure 6e). We conclude that the alteration observed at lower temperatures is probably due to exsolution and conversion from Ti-magnetite to pure magnetite. Thermal demagnetization curves show unblocking at the characteristic magnetite temperature range of 550 to 570°C (Figure 7a).

5.3 Paleomagnetic Results

Table 4 lists paleomagnetic directions/statistics for each of the dikes in this study. The mean direction resolved from four mafic dikes has a declination=358.8° and inclination=63.5° ($k=91.2$ and $α_95=9.7$), after inverting one reverse polarity dikelet. The Virtual Geomagnetic Pole (VGP) calculated from the average direction of each dike falls at 70.2°N, 70.1°E ($dp=12.1^°$, $dm=15.4°$). Figure 7 shows the typical demagnetization plots from two mafic dike sites. Most samples show a stable demagnetization trend, dependent on the treatment applied. Thermally treated samples unblock between 550 and
570˚ C and quickly lose over 50 percent of their intensity at this temperature range (Figure 7a). Samples treated with an alternating field lose intensity at a more gradual rate and do not generally unblock past greater than 80-85 percent of the original strength (Figure 7b). Most samples have a low temperature or low coercivity overprint that has no consistent direction, but is quickly removed. Jalore granite samples were taken with the intent to perform a baked contact test at site 34, but samples are dominated by multi-domain grains that have a strong, but unstable remanence, even with the application of low-temperature liquid nitrogen demagnetization. No stable directions were obtained from any granite samples, and intensity data also have no detectable trend with increasing distance from the large dike (up to 20 meters away).

When treated with both alternating field and thermal demagnetization, samples of the fine-grained dikelet at site 34 display a high-temperature component that is antipodal to the three larger Malani dikes (Figure 8b). Demagnetization trends of the dikelets include two distinct components and samples are weaker in intensity than the larger dikes. They show an increase in intensity at temperatures up to about 490˚C or fields to 40 mT (Figure 8b). The low temperature and low coercivity component is identical to the mean direction from the normal polarity dikes with a declination=2.5, inclination=+57.5 (k=17.1 and α95=30.8), which is much steeper than the present-earth field in the region (inclination=43.4˚). The high temperature and high coercivity component has a reverse polarity with declination=195.3˚ and inclination=-59.7˚ (k=234.8 and α95=8.1).

6. Discussion

6.1 Significance of paleomagnetic and geochronologic data

When results from Malani mafic dikes (this study, 4 sites) are combined with the trachyte and rhyolitic volcanics from Torsvik et al. (2001a; 9 sites) and Klootwijk (1975;
6 sites, Table 4), a mean direction is obtained with declination=001°, inclination=63.0° (k=32.9, α95=5.9) and paleolatitude of 44.5°. From this mean direction, a paleomagnetic pole for the MIS is placed at 67.8°N, 72.5°E (A95=8.8°) after averaging VGPs from the 19 sites. The angular dispersion (S) of measured VGPs can be compared to the latitudinal variation in VGP angular dispersion as determined by Merril et al. (1996) from IGRF90 (1990 International Geomagnetic Reference Field). VGP’s from the Malani suite at paleolatitude 44.5° have an angular variance of 20.7° about the mean pole, calculated from the best estimate of angular variance for VGPs (equation 6.4.2 in Merril et al., 1996). This value lies within the average VGP scatter for intermediate latitudes that represents the time-averaged field about the earth’s spin axis. The mean paleomagnetic pole for the MIS thus sufficiently averages secular variation, and such a scatter is generally inconsistent with a blanket remagnetization of the area.

The focus of this study is to reinforce the mean pole for India at ca. 771-750 Ma with paleomagnetic data from the last stage of MIS magmatism, and pair this with a robust age determination with published analytical results. The fortuitous sampling of a small dikelet with unique magnetic behavior provides even further, albeit tentative, support for the primary nature of the Malani pole. No reverse polarity direction or baked contact test was determined in previous work on the Malani suite. There are three possible interpretations for the magnetism observed in the dikelet: (1) the dikelet was emplaced in the same swarm as larger mafic dikes and experienced a true self-reversal, (2) the result is spurious and an unstable anomaly, or (3) the dikelet was emplaced during a main field reversal and baked by the intrusion of subsequent mafic dikes, some time later during a normal polarity field. Option (1) is unlikely based on descriptions of
observed natural self-reversing behavior. True self-reversal very rarely occurs in exsolved titanomagnetite compositions of basalt flows. The high Curie temperature phase (magnetite) aligns itself with the external field and influences the low temperature phase to the point of reversal (Merril and McElhinny, 1983). This occurs in coarse, multi-domain grains during a slower cooling than that associated with aphanitic dikelet emplacement (Petherbridge, 1977; Merril and McElhinny, 1983). The Malani dikelet has a high temperature direction that is reversed from the rest of the suite, which most likely formed parallel to the external field. This high temperature direction carries the reverse direction, thus even if this is a self-reversal, the reverse polarity direction in the dike is primary and only the low-temperature normal polarity could be an artifact of a true self-reversal. While sampling density is not sufficient to pass statistical reversal tests (i.e. McFadden and McElhinny, 1990, reversal test), all three samples from the dikelet demonstrated a normal overprint and antipodal directions upon heating.

In our opinion, option (3) best fits the results of the dikelet when compared to the larger dike intrusion. The dikelet was sampled at just within half dike-width away and thus still susceptible to partial baking by the large dike. Magnetic intensity increases in all samples as the normal polarity direction is removed (Figure 8b), which is typical behavior for the demagnetization of magnetic moments that are antipodal to the primary high temperature direction. We suggest that the dikelet was emplaced during a reversed polarity field and was later baked by the adjacent larger dike, resulting in a normal polarity overprint and a reverse primary direction. It is not uncommon for multiple dike intrusions to occur over enough time to include a field reversal. The Harohalli dike swarm in India (Pradhan et al., 2008) and the Matachewan dikes in southern Canada...
(Irving and Naldrett, 1977; Halls, 1991; Halls and Zhang, 1998; Symons et al., 1994) are examples of dike swarms that were emplaced in multiple phases and include dual-polarity paleomagnetic results.

The Malani pole is cited as a representative pole for India during the late Neoproterozoic, yet some authors conclude that the lack of a decisive reversal or field test deems Malani paleomagnetic data untrustworthy (see Yoshida and Upreti, 2006 for example). However the results of our study not only add to the existing MIS paleomagnetic data set, but also provide additional evidence for a primary magnetization. The fold test yielded by Torsvik et al. (2001a) is now augmented by results that show a primary reverse TRM in the sequence overprinted by a normal-polarity magnetization in the mafic dikelet. Although this does not constitute a ‘classic’ baked contact test, the result is consistent with baking of the smaller dike by the adjacent E-W trending dike. In addition, the Malani results do not overlap with younger poles from the Indian subcontinent nor is it consistent with a recent field overprint (Figure 9). The positive fold test determined by Torsvik et al. (2001a) constrains the age of the pole to older than Cambrian and there are no paleomagnetic poles from the India craton within 750 to 560 Ma that have similar directions to the MIS that could represent a regional overprint. The Malani pole is also distinct from the more common overprints observed in Indian rocks in this region (Deccan and Rajmahal Traps) and from Carboniferous-Cretaceous paleomagnetic results observed in the Gondwana Supergroup and an analysis of post-Cretaceous paleomagnetic poles from India (Mallik et al., 1999; Acton, 1999).

The new zircon extrusion age of 771 ±5 Ma (Fig. 6) for a rhyolitic tuff places a robust date on the timing of the first stage of magmatism in the MIS. This age is
consistent with the first of two ‘personal communication’ zircon dates at 771 ±2 and 751 ±3 Ma quoted by Torsvik et al. (2001a) for rhyolite magmatism in the first stage of MIS magmatism. These ages were determined with TIMS analysis at Washington University, St. Louis, on samples from sites 3 and 4 of Torsvik et al. (2001a), but analytical details were not given in the publication. Available Rb-Sr whole-rock geochronology (Crawford and Compston, 1970; Dhar et al., 1996; Rathore et al., 1999) defines a time span of nearly 100 m.y. (779 ±10 to 681 ±20 Ma), so one cannot rule out that the second and third stages of the magmatism are significantly younger than 771 ±5 Ma. Nevertheless, the consistency of paleomagnetic data for the different stages of magmatism argues for a comparatively short duration of activity. Paleomagnetic data from Malani dikes overlap with the data from the 750.2 ±2.5 Ma Takamaka mafic dikes in Seychelles (Torsvik et al., 2001b) providing additional support for the correlation between Malani and Seychelles. In Figure 10, published site directions determined from the early stage of rhyolitic magmatism in the MIS (Klootwijk, 1975; Torsvik et al., 2001a) are compared to directions derived from the third stage of magmatism of the suite (mafic dikes, this study). The mean direction from all studies is indicated (starred, Figure 10). We suggest that this indicates a relatively short eruptive history for the Malani suite, contradicting the over 100 million year span of apparent ages derived from Rb-Sr data (Rathore et al., 1999). Younger ages from Rb-Sr data can be accounted for by local disturbances or element mobility during minor episodes of metasomatism. Considering the nature and timing of magmatism in the Seychelles and India, the bulk of granitic and subsequent mafic magmatism in those regions was constrained to the interval from c. 771 to 751 Ma.
6.2 Implications for the configuration of Rodinia

It is postulated (Powell et al., 1993; Windley et al., 1994; Dalziel, 1997; Yoshida and Upreti, 2006) that a coherent East Gondwana existed from the Mesoproterozoic through the bulk of the Precambrian and until the Mesozoic breakup of Gondwana. This conclusion is largely based on paleomagnetic and detrital zircon data with high flexibility of interpretation and poor age control, as well as the alleged lack of evidence for appropriately aged oceanic sutures between eastern Gondwana cratons. Yoshida and Upreti (2006) discuss evidence for the Neoproterozoic juxtaposition of India and Australia-East Antarctica based on similarities in cratonic and orogenic detrital zircon and neodymium isotopic signatures. Yet the notion of a united East Gondwana through the Proterozoic and Cambrian is contradicted by high quality paleomagnetic data (Meert and Van der Voo, 1997; Meert, 2001; Torsvik et al., 2001a; Collins and Pisarevsky, 2005). Fitzsimons (2000) and Meert (2003) also review the evidence for appropriately aged mobile belts separating distinct segments of eastern Gondwana elements, which accounts for a later (Cambrian) ocean closure. In their discussion of the proximity of India and Australia-East Antarctica, Yoshida and Upreti (2006) argue that the paleomagnetic data used to constrain the possible separation of these continents do not include a well-constrained age and have been reset by later Pan-African events (~550-510 Ma). We emphasize that this is not a valid argument because both the Malani pole reported in this paper and the highly reliable pole from the 755 ±3 Ma Mundine Well dike swarm in Australia (Wingate and Giddings, 2000) include necessary field and contact tests to argue against any resetting, and both are well-dated. Furthermore, the Malani pole is quite distinct from ~550-510 Ma Gondwana poles (Meert, 2003).
The paleolatitude of the 755 ±3 Ma Mundine Well dikes is 20.2° ±4.8° and this can be compared to the paleolatitude of the Malani dikes from our study (44.5° ±6.5°), indicating a latitudinal separation of nearly 25° between Australia and India (Figure 11).

If we use the Mundine pole as representative for East Gondwana at 750 Ma, it is necessary for the Malani region of India to be located along the paleoequator adjacent to East Antarctica according to its placement in the typically accepted Gondwana fit (deWit et al., 1988). Thus, the misfit between the latitude required by the Malani pole and India’s “traditional” position is more than 45°. It is possible that the southeast margin of India was located along the northwestern margin of Australia, but no geologic evidence such as oceanic sutures or similar-aged orogenic belts have been found to support this orientation. Younger-aged sutures between Gondwana components indicate a more complex Gondwana amalgamation as a series of distinct Pan-African orogenies that occurred between ~700 and 500 Ma (Fitzsimons, 2000; Meert, 2003; Collins and Pisarevsky, 2005). The East African Orogen (EAO) is the ~700-650 Ma result of collision between Madagascar, Somalia, Ethiopia and Arabian Nubian shield (collectively Azania block) and the Congo, Tanzania and Bangweulu block, first developed by Stern (1994) and has since been modified (Collins and Pisarevsky, 2005).

The later Kuunga Orogen (Meert et al., 1995) places the final Gondwana assembly at about 550 Ma with the amalgamation of Australia-Antarctica with IMSLEK (India, northeastern Madagascar, Sri Lanka, East Antarctica, and the Kalahari craton) group. The Malagasy orogeny is also suggested to occur simultaneously with the Kuunga orogeny as the EAO constituents collided with southeastern India (Collins and Pisarevsky, 2005).

These major Pan-African orogenies are congruent with a complex Gondwana assembly.
7. Conclusions

The MIS provides the best paleomagnetic pole for the Indian subcontinent for the time interval from 771-750 Ma, with a combined pole of 67.8°N, 72.5°E (A95=8.8°).

Our study strengthens the case for primary magnetization of the MIS based on the primary reversed direction overprinted by a baked normal-polarity magnetization in a mafic dikelet. The U-Pb zircon age of 771 ± 5 Ma provides an accurate and concordant lower age limit for Malani volcanism. When combined with geochronologic data from mafic dykes in the Seychelles (750.2 ± 2.5, Torsvik et al., 2001b), our age determination also hints at a shorter duration of magmatic activity in the MIS than previously stated.

East Gondwana is considered by some authors to be a stable configuration from about 1.1 Ga until the Mesozoic breakup of Gondwana (Yoshida and Upreti, 2006). However, paleomagnetic data (Torsvik et al., 2001b, this study) place India and the Seychelles at much higher latitudes than coeval poles from Australia (Mundine dikes, Wingate and Giddings, 2000). Three robust paleomagnetic results (Mundine dykes, Malani Igneous Suite and Takamaka Dikes) are not congruent with an amalgamated East Gondwana at 750 Ma and therefore we argue that the younger Pan-African belts between these cratons resulted from the Neoproterozoic-Cambrian suturing of eastern Gondwana. Thus, if paleomagnetism is to make any contribution to Neoproterozoic plate tectonic models, the Malani pole must be seriously considered in any geodynamic explanation for the assembly of Gondwana.

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**Figure Legends**

**Figure 1**: Traditional Gondwana fit for 560 Ma, taken from deWit et al., 1988. Inset highlights the paleoposition of the Seychelles (Sey) and Madagascar (Mad) relative to India at 750 Ma, reconstructed using the Malani pole (Torsvik et al., 2001a) and the Seychelles Euler pole of rotation (Torsvik et al., 2001b). Euler rotation parameters are Seychelles: 13.3°N, 332.9°E, +48.5°; Madagascar: 20.9°N, 13.8°E, +48.5°.

**Figure 2**: Map showing Precambrian stratigraphic units of the Aravalli Mountain Region in NW India with sampling area boxed (adapted from GSI publications and other published work).

**Figure 3**: (a) Photo of a large E-W trending dike in a granite quarry in Jalore (site I434) (b) Photo of 1 cm wide N-S trending mafic dikelet from site I434. Locations of (b) is within box in (a).

**Figure 4**: Google Earth© satellite image of topography and dike traces near Jalore. Azimuths of dike traces are indicated with white lines. Dikes 34, 35, and 36 are the large dikes that were sampled at each respective site. Collection sites are indicated with stars.

**Figure 5**: Inverse concordia diagram showing U-Pb analyses of zircon and CL image of one zircon crystal from a rhyolitic tuff representing the first stage of magmatism in the Malani Igneous Suite. The concordia age of 771 ±5 Ma reflects magmatic crystallization of the rock.

**Figure 6**: (a) Isothermal Remanence Magnetization (IRM) plots from four Malani samples. Sample I434-28 is a mafic dikelet. All samples saturate at about 0.3 T.
(b) Curie temperature test of typical mafic dike sample from site I434. TcH indicates Curie temperature during heating, and TcC indicates Curie temperature during cooling.

(c) Curie temperature test of sample I435-7b, the large mafic dike sampled at site 35. Heating TcH = 555.2°C, Cooling TcC = 546.1°C.

(d) Curie temperature test of a mafic dikelet run up to 700°C with significant alteration and high susceptibility during cooling.

(e) Curie temperature test of the same mafic dikelet run up to 600°C, the typical extent of demagnetization temperature. This test shows very little alteration.

Figure 7: (a) Thermal and (b) alternating field (AF) demagnetization results of mafic samples from sites 35 and 36. In stereoplots, closed circles represent positive inclinations. In Zijderveld diagrams closed (open) circles represent the horizontal (vertical) plane. NRM = Natural Remanent Magnetization. Thermal measurements are in °C and AF measurements are in millitesla (mT).

Figure 8: Demagnetization results from site 34. (a) Normal polarity sample subjected to AF demagnetization. (b) Reversed polarity dikelet sample with arrows pointing in direction from NRM to origin of both the overprint and reverse polarity vector. In stereoplots, closed circles represent positive inclinations. In Zijderveld diagrams closed (open) circles represent the horizontal (vertical) plane. NRM = Natural Remanent Magnetization. Thermal measurements are in °C and AF measurements are in millitesla (mT).

Figure 9: Stereoplot of individual site means, overall mean and reversed polarity mean with common India overprints from the Deccan Traps and Rajmahal Traps indicated.

Figure 10: Stereoplot of directions from three Malani investigations, averaged to the mean pole for the MIS. Circles are from mafic dikes (this study); triangles and squares are directions from each site of rhyolite and trachyite volcanics. Closed symbols represent positive inclinations.

Figure 11: Reconstruction at 770-750 Ma of pertinent eastern Gondwana components. Grey India outline is plotted from the new mean Malani paleomagnetic pole, with the Seychelles euler rotation fit from Torsvik et al., (2001b) and Madagascar is placed according to the Gondwana fit with India. Australia is plotted according to the Mundine Wells dikes VGP, and Antarctica and India are placed in their Gondwana fit locations, in Australian coordinates. There is >20° of latitudinal displacement between the Malani and Mundine Wells study sites. Euler rotation parameters for the Malani reconstruction are:

India: 0°N, 162.5°E, -22.2°; Seychelles: 13.3°N, 332.9°E, +48.5°; Madagascar: 20.9°N, 13.8°E, +48.5°. Euler rotation parameters for the Gondwana fit reconstruction in Australian coordinates are: Australia: 0°N, 45.0°E, +44.0°; Antarctica: 1.6°N, 222.8°E, -75.18°; India: 38.3°N, 141.4°E, +41.1°; Seychelles: 66.7°N, 85.7°E, +38.2°; Madagascar: 22.5°N, 68.5°E, +68.6°.
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<th>Pole Name</th>
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<th>Pole latitude</th>
<th>Pole longitude</th>
<th>$\alpha_{95}$</th>
<th>$\kappa$</th>
<th>Reference</th>
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a: $\alpha_{95}$ cone of 95% confidence about the mean pole; $\text{dp/dm}$ cone of 95% confidence about the paleomagnetic pole in the co-latitude direction (dp) and at a right angle to the co-latitude direction (dm).
b: dec/inc = mean declination/inclination

c: $\alpha_{95}$ = circle of 95% confidence about the mean

d: $\kappa$ = kappa precision parameter

*U-Pb Age data reported in this study, samples are from site 3 of Torsvik et al., 2001

**Virtual Geomagnetic Pole (VGP) from four dikes
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- **a:** Measured $^{206}\text{Pb}^{204}\text{Pb}$ ratio
- **b:** $R$, correlation coefficient of errors in isotopic ratios
- **c:** $^{204}\text{Pb}$ corrected age
- **d:** $^{207}\text{Pb}$ corrected age
- **e:** age discordance at the closest approach of 2σ error ellipse to concordia
- **f:** coordinates of the sample: 26°17.963'-72°58.357'
- **g:** analysis not selected for calculation of concordia age
Table 4: Paleomagnetic results

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<th>Declination</th>
<th>Inclination</th>
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<td><strong>Combined mean paleomagnetic pole</strong></td>
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<td>A95=8.8</td>
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<sup>a</sup> n= samples used; N= samples collected  
<sup>b</sup> κ= kappa precision parameter  
<sup>c</sup> α<sub>95</sub>= circle of 95% confidence about the mean  
<sup>d</sup> VGP latitude/longitude = virtual geomagnetic pole  
<sup>e</sup> dp, dm= cone of confidence along site latitude (dp) and orthogonal to site latitude (dm)
Figure 5

Malani Rhyolite tuff
Sample MIS5/04
16 SIMS analyses in 10 zircon crystals

03a
03b
CL image with location of 2 analyses

840
800
760
720
680

Error ellipses are 1σ

14 selected analyses
Concordia age: 771 ±5 Ma
(95% confidence, error on λ included)
MSWD (of concordance + equivalence): 1.5

207Pb
206Pb

0.070
0.068
0.066
0.064
0.062
0.060
0.058

6.8 7.2 7.6 8.0 8.4 238U/206Pb
Figure 7
Click here to download high resolution image
Figure 8

(a) Normal Polarity

(b) Reverse Polarity
Figure 9

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Figure 10
Click here to download high resolution image

- This study
- Torsvik et al.
- Klootwijk et al.