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that erupted in initial voluminous flows, which were shortly intruded by granitic plutons. The large (up to 5 m wide) mafic dikes mark the final phase of igneous activity and were the targets of our investigation. Previous age constraints from the Malani suite are either reported as personal communications or are unreliable Rb/Sr dates and do not provide a complete picture of the tectonic evolution of the continent during the Rodinia breakup. We obtained a paleomagnetic direction with declination=349.8° and inclination=64.1° (k=116.4 and α95=11.5°), that overlaps with previously reported results. In addition, fine-grained mafic dikelets show reversed directions with a declination=195.3° and inclination=-59.7° (k=234.8 and α95=8.1°) and also record an overprint of normal polarity from the larger dikes. We also report an U/Pb age of 771 ±5 Ma from zircons in the Malani rhyolitic tuff and we are currently in the process of calculating an 40Ar/39Ar whole-rock age. These data combined with a baked contact test truly solidify the paleomagnetic pole, and thus give insight into the complicated Proterozoic and Early Cambrian history of India.

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

The configuration of the Precambrian supercontinent Rodinia and the subsequent assembly of Gondwana are under considerable debate due to a paucity of high quality paleomagnetic data. The Indian continent is crucial to this topic and plays an essential role in the history of East Gondwana amalgamation. In proto-Gondwana reconstructions the location of the central Indian craton is important in testing the existence and age of the proposed Rodinia supercontinent. Improved paleomagnetic and geochronologic data collected from numerous dikes in central India will help to better constrain the details of the supercontinent. We have collected samples from 4 late stage mafic dikes that intrude the Jalore Granite in the Malani Igneous Suite (MIS) in Rajasthan, Central India. The MIS is primarily composed of felsic rocks that erupted in initial voluminous flows, which were shortly intruded by granitic plutons. The large (up to 5 m wide) mafic dikes mark the final phase of igneous activity and were the targets of our investigation. Previous age constraints from the Malani suite are either reported as personal communications or are unreliable Rb/Sr dates and do not provide a complete picture of the tectonic evolution of the continent during the Rodinia breakup. We obtained a paleomagnetic direction with declination=349.8° and inclination=64.1° (k=116.4 and α95=11.5°), that overlaps with previously reported results. In addition, fine-grained mafic dikelets show reversed directions with a declination=195.3° and inclination=-59.7° (k=234.8 and α95=8.1°) and also record an overprint of normal polarity from the larger dikes. We also report an U/Pb age of 771 ±5 Ma from zircons in the Malani rhyolitic tuff and we are currently in the process of calculating an $^{40}Ar/^{39}Ar$ whole-rock age. These data combined with a baked contact test truly solidify the paleomagnetic pole, and thus give insight into the complicated Proterozoic and Early Cambrian history of India.

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1. Introduction

The notion of a Meso- to Neoproterozoic supercontinent that formed in the aftermath of the Grenvillian orogeny 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; see also Meert and Torsvik, 2003). There are myriad models for the configuration of the Rodinia supercontinent and the exact locations of its constituent parts are unresolved. The archetypal model for Rodinia outlines that it began to form at about 1300 Ma and reached maximum size at about 1000 Ma. Fragmentation and breakup of Rodinia eventually was initiated along a rift between western (present-day coordinates) Laurentia and East Antarctica-Australia sometime between 800-700 Ma (Bond et al., 1984; Dalziel 1991; Hoffman, 1991; Powell et al., 1993). At that point, it is hypothesized that rifting heralded a period of intense global cooling, sparking the development of multi-cellular life on Earth (Hoffman, 1998, McMenamin and McMenamin, 1990, Meert, 2003; Meert and Liberman, 2008). Knowledge of the distribution and geotectonic evolution of continents during the Neoproterozoic is critical for an improved understanding of the context and causes of extreme climatic changes and accelerated biologic evolution at the boundary between the Neoproterozoic and the Paleozoic.

The fragmentation of Rodinia was followed by the assembly of the superterrane Gondwana. East Gondwana is composed of cratonic blocks of India, Madagascar, Sri Lanka, East Antarctica, Australia and the Seychelles. The paleogeography of the cratons that make up East Gondwana prior to the formation of and after severance from Rodinia is debated. Some (Windley et al., 1994; Piper, 2000; Yoshida and Upreti, 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, and stayed in the same configuration within Rodinia and up to the formation of Gondwana. However, this scenario is viewed with skepticism. The alternative formation of Gondwana as a polyphase assembly of cratonic nuclei that had previously dispersed from the Rodinia supercontinent seems to be more consistent with available geologic, paleomagnetic and geochronologic data (Meert et al., 1995; Meert and Powell, 2001; Meert and Torsvik, 2003; Boger et al., 2002; Fitzsimons, 2000; Pisarevsky et al., 2003; Collins and Pisarevsky, 2005, Meert and Liberman, 2008). This dispute may 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 studies are incomplete in that they do not incorporate an age with paleoposition and thus do not place strong spatial-temporal constraints on ancient continental localities (Meert and Powell, 2001).

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). A traditional Gondwana fit would situate India at low latitudes at 750 Ma in order to comply with the geometry of Rodinia prior to breakup and the determined fit for East Antarctica. Paleomagnetic data are in disagreement with a low-latitude location for India at 750 Ma, and instead, the extant data imply a significantly higher paleolatitude (Torsvik et al., 2001a,b).

The tectonic setting of India during the proposed interval of Rodinia breakup is also unclear, and pertinent to deciphering its ancient location. Bhushan (2000) implied that the predominantly felsic magmatism of the Malani Igneous Suite (MIS) in northwestern India is a result of thermal melting of the base of the crust in a rift setting at around 700 to 800 Ma. The MIS is often described as 'anorogenic magmatism' related either to crustal melting during extension or to an active hot spot (Bhushan, 2000; Sharma, 2004). Alternatively MIS magmatism can be interpreted in the context of an Andean-type active margin (Torsvik et al., 2001a; Torsvik et al., 2001b, Ashwal et al., 2002), closely related to the nearby arc activity observed in the Seychelles islands and northeastern Madagascar, which lay along NW India at about 750 Ma. Magmatic activity in the Seychelles and northeastern Madagascar is attributed to northeastward subduction of the Mozambique Ocean (Handke et al., 1999; Meert et al., 2003; Tucker et al., 1999). The duration of magmatism and the source of igneous activity in the area are still questionable. In this paper, we report paleomagnetic and geochronologic data for the Malani Igneous Suite (MIS) in Rajasthan, northwestern India, one of the largest (51,000 km^2) felsic igneous suites in the world (Pareek, 1981; Bhushan, 2000) of accepted Neoproterozoic age (Figure 2). Paleomagnetic data from late stage mafic dikes paired with a U-Pb study of a rhyolitic tuff provides an improved, demonstrably primary, paleomagnetic pole for the MIS with a reliable temporal constraint. The data are used to derive a key paleopole for the Indian plate during the Neoproterozoic, and lead to a discussion on the drift of India between the dispersal of Rodinia and the formation of Gondwana.

2.Geology and Tectonic Setting

Magmatism in the Malani Igneous Suite (MIS) occurred in three intrusion phases. Activity commenced with an initial volcanic phase made up of 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. Malani felsic rocks are unmetamorphosed, but slightly tilted and folded. Late stage mafic dikes are all vertical to sub-vertical (Figures 3 and 4). The MIS unconformably overlies Paleo- to Mesoproterozoic metasediments, and basement granite gneisses and granodiorites of an unknown age (Pandit et al., 1999); and is unconformably overlain by the latest Neoproterozoic to Cambrian Marwar Supergroup made up of red-bed and evaporite sedimentary sequences (Pandit et al., 2001; Torsvik et al., 2001a).

A volcaniclastic conglomerate lies at the base of MIS (Bhushan, 2000) and basal rhyolitic tuffs denote the initiation of basaltic and largely felsic flows of the first stage of the suite. This is followed by the emplacement of granitic plutons and felsic dikes. Vertical to sub-vertical dolerite dikes crosscut all of the other components and thus mark the termination of magmatism. These mafic dikes intrude the Jalore Granite plutons south of Jodhpur and can be wide, up to 5 meters in extent (Figures 2, 3, and 4). The mafic dike sequence near Jalore contains a relatively dense concentration of dikes with a general N-S trend. Many of the larger dikes form conspicuous ridges only when enclosed in a granite host (Figure 4). Fresh in-place outcrop is difficult to find but we sampled 4 dikes within the sequence, most of which were N-S trending dikes, including a very thin N-S trending dikelet that is cut by a wider E-W trending dike. This dikelet is less than 2 cm wide, extremely fine grained and dark grey-black in color with obvious chilled margins (Figure 3b).

Among the multitude of tectonic settings proposed for Malani magmatism, it has been suggested (see Bhushan, 2000) that the first stage of associated basaltic and felsic flows is generated by a hot spot source or lithospheric thinning and melting at the base of the crust. However, India magmatism can also be compared with other Neoproterozoic igneous provinces. Paleomagnetic data juxtapose India alongside the Seychelles, and northeastern Madagascar is also placed along the India margin based on temporal and geological similarities (Ashwal et al., 2002). Both Madagascar and Seychelles have igneous activity from this time that is attributed to subduction (Figure 5; Torsvik et al., 2001b, Tucker et al., 2001, Ashwal et al., 2002). The paleoposition of India (at the western margin of Rodinia) in relation to the ancient supercontinent Rodinia and proto-East Gondwana, based on previous studies, conflicts with the hypothesis of rift tectonics and is more indicative of an Andean-type arc environment resulting from the subduction of the eastern Mozambique Ocean (Meert and Torsvik, 2003).

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 (Table 1). Athavale et al. (1963) were the first to apply paleomagnetic tests to rhyolitic flows, and their results are similar to those obtained by Klootwijk (1975), but lack any detailed stability tests. Torsvik et al. (2001a) found a statistically positive fold test on felsic rocks from Malani. Folding of the Malani rocks is post-eruption and pre-Marwar age, which constrains the age of the Malani pole to older than Cambrian. No reversals or other field tests have been found to further document the exact age of the magnetism. The lack of available or positive field

tests to fully constrain the age of magnetic acquisition may lead to doubt regarding the primary nature of the Malani pole.

3.2 Geochronology

Previous geochronologic results from Malani felsic volcanics span about 100 million years (Table 2). Crawford and Compston (1970) reported a pioneering Rb-Sr age of 730 ±10 Ma for rhyolites (recalculated 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 for felsic volcanic rocks and granite plutons, emplaced during the first two stages of activity in the MIS (first and second stages, respectively), ranging from 779 ±10 to 681 ±20 Ma. This wide distribution of dates is partially a result of studies of the so-called ultrapotassic rhyolites found near our sampling locality. The youngest age Rb-Sr isochron age of 681 ±20 Ma (Rathore et al., 1999) comes from a solitary occurrence of the "ultrapotassic" rhyolite (Figure 2), without any rock description that would ascertain whether high potassium is a primary igneous character or a later alteration effect. Much younger apparent ages of 548 ±7 to 515 ±6 Ma were obtained from whole-rock $^{40}Ar/^{39}Ar$ data on Jalore granites. These apparent ages are interpreted as evidence for a thermal disturbance by Rathore et al. (1999), and are perhaps related to the Kuungan orogen (Meert 2003). Torsvik et al. (2001a) cited precise U-Pb ages of 771 ±2 and 751 ±3 Ma for rhyolite magmatism in the MIS (Tucker et al., unpublished), but without analytical details and sample descriptions.

4. Methods

4.1 Paleomagnetic 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. Three of the granite samples include a very small (width less than 2 cm) fined grained N-S trending dikelet, which is cut by the wide E-W trending mafic dike (Figure 3b).

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 using 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 a step-wise manner using a home-built AF-demagnetizer at fields up to 140 mT. Samples were also treated thermally in a stepwise manner, up to temperatures of 600˚C for ~60 minutes using an ASC-Scientific oven. Between each treatment, strong samples, generally the mafic dikes, were measured on a Molspin Magnetometer and weaker samples, generally dikelets and granites, were measured on an ScT cryogenic magnetometer. Characteristic remanence components (ChRc) were calculated with the least-square regression analysis implemented in the Super IAPD program (http://www.ngu.no/geophysics; Kirschvink, 1980).

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 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. 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 6). 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 μm, 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 unfoliated 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). 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 μm) prismatic zircon crystals. The show well-terminated pyramid tips and oscillatory zoning. They 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 6). This age is interpreted as the timing of magmatic crystallization and deposition of the rhyolite tuff.

5.2 Rock Magnetic Results:

Curie temperature runs on the mafic dike samples show a curve that is characteristic of magnetite, but with some alteration upon cooling (Figure 7b). Susceptibility is higher on heating than cooling, but curie temperatures are similar and in the typical range of magnetite. The heating Curie temperature T_cH is equal to 589.7˚C and the cooling Curie temperature T_cC is equal to 588.3˚C. Curie temperature tests for dikelet samples show a low susceptibility heating curve that may be a result of titanomagnetite and a cooling curve with higher susceptibility resulting from exsolution of titanomagnetite to form pure magnetite (Figure 7c). Mafic dikes also have an Isothermal Remanance Magnetization (IRM) plot that is indicative of magnetite (Figure 7a). Samples saturate at ~0.3 tesla and their intensity remains constant at higher fields, up to the highest applied field of 2 tesla. Sample I434-28 is a mafic dikelet, and has an IRM curve also characteristic of magnetite, but with a lower absolute J value at saturation. Thermal demagnetization curves show unblocking at the characteristic magnetite temperature range of 550 to 570°C (Figure 8a).

5.3 Paleomagnetic Results

Table 4 lists paleomagnetic results from each site in this study. Figure 8 shows the typical demagnetization plots of 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 8a). 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 8b). 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, but samples are dominated by multi-domain grains that have a strong, but unstable remanence (even with the application of low-temperature demagnetization).

Three samples were taken from the less than 2 cm wide dikelet pictured in figure 2b. The larger dike at site 34 crosscuts this very fine grained dike. When treated with both alternating field and thermal demagnetization, samples display oppositely directed magnetization from the three larger Malani dikes (Figure 10). Demagnetization trends include two distinct components and are weaker in intensity than those from the larger dikes. They show an increase in intensity at temperatures up to about 490˚C or fields to 40 mT. The low temperature and coercivity component is identical to the mean direction from the normal polarity dikes and we interpret this as evidence of baking of the smaller dike by the larger E-W trending dike. The baked overprint component has a declination=2.5, inclination=+57.5 (with k=17.1 and α_{95}=30.8). The high temperature and coercivity component has a reverse polarity with declination=195.3˚ and inclination=-59.7˚ (with k=234.8 and α_{95}=8.1). The McFadden and McElhinny (1990) reversal test demonstrates an angle of 10˚ between the three normal site means and the

reverse polarity individual samples. Although only a VGP, the reversal test has a classification of C.

The mean direction from all sites has a declination=349.8˚ and inclination=64.1˚ (with k=116.4 and α_{95}=11.5). Site I434 demonstrated reverse polarity in three samples of a small fine-grained dike. After inverting the reverse polarity direction, the mean direction from all four dikes has declination=358.8˚ and inclination=63.5˚ (with k=91.2 and α_{95}=9.7; Figure 9). The paleomagnetic pole calculated from the mean direction from each site falls at 68.5°N, 58.1°E (dp=14.8°, dm=18.5°). The mean paleomagnetic pole calculated from an average VGP of each site is 68.6°N, 57.5°E (A95=13.4°).

6. Discussion

6.1 Significance of paleomagnetic and geochronologic data

When results from Malani mafic dikes (this study) and rhyolitic volcanics (Torsvik et al., 2001a) are combined, a grand mean paleomagnetic pole for the MIS can be placed at 69.0°N, 83.2°E (dp=8.8°, dm=10.9°), which translates into a paleolatitude of 46.5° (+9.6°, -8.0°) for the Malani igneous suite at Jalore. The Malani pole has been cited as the representative pole for India during the late Neoproterozoic, yet the lack of a conclusive reversal or a field test was used by some authors to conclude that the paleomagnetic data were untrustworthy (see Yoshida and Upreti, 2006 for example). However the results of our study provide additional evidence for a primary magnetization. The fold test provided by Torsvik et al. (2001a) is now augmented by a baked contact test and dual polarity. The baked contact test lies in the normal polarity overprint that is found in fine-grained dikelet samples. This is a distinct overprint at low temperature and coercivity demagnetization acquired from crosscutting, normal polarity dikes. The anti-podal direction is close to 180° different from the reversed signature of

333 the smaller dikes (Figure 10). In addition, the Malani pole does not overlap with any
334 recent poles from the Indian subcontinent. The Malani pole has a unique location when
335 compared to common overprints in India (Deccan and Rajmahal Traps), which further
336 attests the quality of this pole (Figure 9).

337 No reverse polarity direction was noted in previous studies of the MIS. Torsvik et
338 al., (2001a) did resolve a B component in their samples that trends towards a reverse
339 polarity direction, but it was not antipodal to the normal polarity component. They
340 attributed it to a secondary origin, possibly due to hydrothermal alteration. In our study,
341 all samples taken from the small fine-grained mafic dikelet demonstrate a reverse polarity
342 direction, with a normal polarity overprint. The vector was not found in large dikes at the
343 same site. The reverse direction is exactly antipodal and passes the McFadden and
344 McElhinny reversal test with a C, which is significant when considering the unfortunately
345 small sampling section that was available for the reversed polarity rocks. Although only
346 a VGP, this reversed direction further validates the primary nature of the pole. We stress
347 that our VGP combined with previous study (Torsvik et al., 2001a) provides the most
348 reliable and precise Neoproterozoic pole for India.

349 The new zircon extrusion age of 771 ±5 Ma (Fig. 6) for a rhyolitic tuff places a
350 robust pin on the timing of the first stage of magmatism in the MIS. This age is
351 consistent with the oldest available Rb-Sr isochron age of 779 ±10 Ma (Rathore et al.,
352 1999), based on felsic volcanic rocks from widely spaced sampling sites. It is also
353 consistent with the first of two unpublished zircon dates at 771 ±2 and 751 ±3 Ma quoted
354 by Torsvik et al. (2001a) for rhyolite magmatism in the first stage of MIS magmatism.
355 Available Rb-Sr whole-rock geochronology (Crawford and Compston, 1970; Dhar et al.,

356 1996; Rathore et al., 1999) defines a time span of nearly 100 m.y. (779 ±10 to 681 ±20
357 Ma), so one cannot rule out that the second and third stages of the magmatism are
358 significantly younger than 771 ±5 Ma. Nevertheless, the consistency of paleomagnetic
359 data for the different stages of magmatism argues for a comparatively short duration of
360 magmatism. In Figure 11, published paleopoles determined from the early stage of
361 rhyolitic magmatism in the MIS (Athavale, 1963; Klootwijk, 1975; Torsvik et al., 2001a)
362 are compared to the paleopole derived from the third stage of magmatism of the suite
363 (mafic dikes, this study). All studies show equivalent results (Figure 11). Thus India did
364 not likely undergo a large extent of latitudinal movement during Malani magmatism,
365 even with errors taken into account. With reference to paleomagnetic data, the duration
366 of the Malani magmatism occurred without much change in location relative to the
367 earth's spin axis. The eruption may not have occurred over a 100 million year span as
368 suggested by Rb-Sr data (Rathore et al., 1999) because the Indian continent would likely
369 have undergone recognizable latitudinal movement the prolonged magmatic activity.
370 The MIS is often stated to be the result of a rift setting or a mantle plume (Singh
371 et al., 2006; Bhushan, 2000), despite the lack of large volumes of basaltic rocks that are
372 generally the result of a large-scale mantle heating event. Malani rocks are also
373 commonly attributed to Anorogenic-type (A-type) volcanism, but the mechanism for this
374 eruption type has not been explicitly stated. Subduction of an ancient ocean, the
375 Mozambique, has been suggested as a source for activity, but this has also been disputed
376 because of the lack of deformation in the area. However, it is certainly possible that the
377 undeformed Malani magmatic rocks represent the inboard result of a subduction zone,
378 and that deformed margin material has been eroded or buried. Madagascar is commonly

379 placed alongside India in Gondwana-fit reconstructions, and Seychelles has been
380 paleomagnetically placed adjacent to India's margin (Figure 5, Torsvik et al., 2001b).
381 Both micro-continents have volcanism attributed to the subduction of a Neoproterozoic
382 ocean (Torsvik et al., 2001b, Tucker et al., 2001, Ashwal et al., 2002). Considering the
383 nature and timing of magmatism in the Seychelles and India, it appears that the bulk of
384 granitic and subsequent mafic magmatism in those regions was constrained to the interval
385 from ~771-751 Ma.

386 *6.2 Implications for the configuration of Rodinia*

387 It is suggested (Powell et al., 1993; Windley et al., 1994; Dalziel, 1997; Yoshida
388 and Upreti, 2006) that a coherent East Gondwana existed from the Mesoproterozoic
389 through the bulk of the Precambrian and until the assembly of Gondwana at 550-530 Ma.
390 However this is largely based on data with high flexibility of interpretation and poor age
391 control, as well as the lack of evidence for appropriately aged oceanic sutures between
392 East Gondwana cratons. Yoshida and Upreti (2006) discuss evidence for the
393 Neoproterozoic juxtaposition of India and Australia-East Antarctica based on similarities
394 in cratonic and orogenic detrital zircon and neodymium isotopic signatures. Yet the
395 notion of a united East Gondwana through the Proterozoic and Cambrian is contradicted
396 by high quality paleomagnetic data (Meert and Van der Voo, 1997; Meert, 2001; Torsvik
397 et al., 2001a), and also in Fitzsimons (2000) review of evidence for appropriately aged
398 mobile belts separating distinct segments of East Gondwana elements, which accounts for
399 a later (Cambrian) ocean closure. In their discussion of the proximity of India and
400 Australia-East Antarctica, Yoshida and Upreti (2006) argue that the paleomagnetic data
401 used to constrain the possible separation of these continents do not include a well-
402 constrained age and have been reset by the later Pan-African event (~530-510 Ma). We

403 emphasize that this is not a valid argument because both the Malani pole reported in this
404 paper and the highly reliable pole from the Mundine Well dike swarm in Australia
405 (Wingate and Giddings, 2000) include necessary field and contact tests to argue against
406 any resetting, and both are well-dated.

407 The paleolatitude of the Mundine Well dikes is 20.2˚ (+5.5°, -4.8°) and this can
408 be compared to the paleolatitude of the Malani dikes from our study (46.5°, +9.6°, -8.0°),
409 indicating a separation of greater than 40° in latitude using the conventional East
410 Gondwana fit (Figure 12). For East Gondwana to be a coherent group at 750 Ma, it is
411 necessary for India to be located along the paleoequator, according to its placement in the
412 typically accepted Gondwana fit (deWit et al., 1988) relative to the locations of Australia
413 and Antarctica within Rodinia reconstructions (Figure 12). It is possible that the
414 southeast margin of India was located along the northwestern margin of Australia, but no
415 geologic evidence such as oceanic sutures or similar-aged orogenic belts have been found
416 to support this orientation. Younger-aged sutures between Gondwana components also
417 indicate a more complex Gondwana amalgamation. The East Africa Orogen is described
418 by Stern (1994) as an 800-650 Ma collision of IMSLEK cratons (*I*ndia, *M*adagascar, *S*ri
419 *L*anka, *E*ast Antarctica, and the *K*alahari craton) with the Congo craton and Arabian-
420 Nubian shield (ANS). The later Kuunga Orogen (Meert et al., 1995) places the final
421 Gondwana assembly at about 550 Ma with the amalgamation of Australia-Antarctica
422 with the IMSLEK-Cong-ANS group. These major Pan-African orogenies are congruent
423 with a younger East Gondwana assembly, and placing India alongside East Antarctica
424 and Australia at 770 Ma fails to account for the existence of the considerably younger
425 sutures.

7. Conclusions

The MIS provides the best paleomagnetic pole for the Indian subcontinent at ~750-770 Ma, with a combined pole that plots at 69.0˚ N, 83.2˚ E (dp=8.8˚, dm=10.9˚). Our study further strengthens the case for a primary magnetization from the MIS with a reversal found in mafic dikelets and a baked contact test. The first documented U-Pb age of 771±5 Ma provides a more accurate and concordant lower age limit for Malani volcanism. When combined with geochronologic data from mafic dykes in the Seychelles, our age determination also hints at a shorter duration of magmatic activity in the MIS than previously stated.

India was previously stated to be a part of East Gondwana from about 1.1 Ga until the assembly of Gondwana around 550 Ma (Yoshida and Upreti, 2006). However, paleomagnetic data place India and the Seychelles at higher latitudes than coeval poles from Australia (Wingate and Giddings, 2000). These three robust paleomagnetic results (Mundine dykes, Malani Igneous Suite and Mahe Dikes) argue strongly against an amalgamated East Gondwana at 750 Ma and explain the younger Pan-African belts between these cratons. Thus, we argue that if paleomagnetism is to make any contribution to Neoproterozoic plate tectonic models, the new Malani pole must be seriously considered in any geodynamic explanation for the assembly of Gondwana.

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Figure Legends

Figure 1: Typically accepted Gondwana fit for 560 Ma, taken from deWit et al., 1988. Reconstructions that use a Gondwana fit come from this model.

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 at site I434 (b) Photo of 1 cm wide N-S trending mafic dikelet from site I434.

Figure 4: Satellite photo from Google Earth® of the mafic dikes in the Malani Igneous Suite near the city of Jalore. Large dikes trend N-S.

Figure 5: Reconstruction of India, Seychelles (Sey) and Madagascar (Mad) in India coordinates. Seychelles is placed according to the Euler pole defined in Torsvik et al., (2001) and Madagascar is placed according to its Gondwana fit alongside India.

Figure 6: 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 7: (a) Isothermal Remanence Magnetization (IRM) plots from four Malani samples. Sample I434-28 is a mafic dikelet. All samples saturate at about 0.3 tesla. (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 a mafic dikelet. Due to alteration during heating, susceptibility of sample during cooling is much higher than during heating, and axes are labeled accordingly.

Figure 8: (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 ºC 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: 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 ºC and AF measurements are in millitesla (mT).

Figure 11: Stereoplot of means from this study and previous studies from the Malani Igneous Suite, with our reverse polarity mean and the C component from Torsvik et al., (2001a) indicated. Closed circles represent positive inclinations.

Figure 12: Reconstruction at 770 Ma of pertinent East Gondwana components. Grey India outline is plotted as a VGP from this study, with the Seychelles euler rotation fit from Torsvik et al., (2001b) and Madagascar is placed according to the Gondwana fit. Australia is plotted according to the Mundine Wells dikes VGP, and Antarctica and India are placed in their Gondwana fit locations, in the Australia reference frame. There is >20º of latitudinal displacement between the Malani and Mundine Wells study sites.

Figure 1

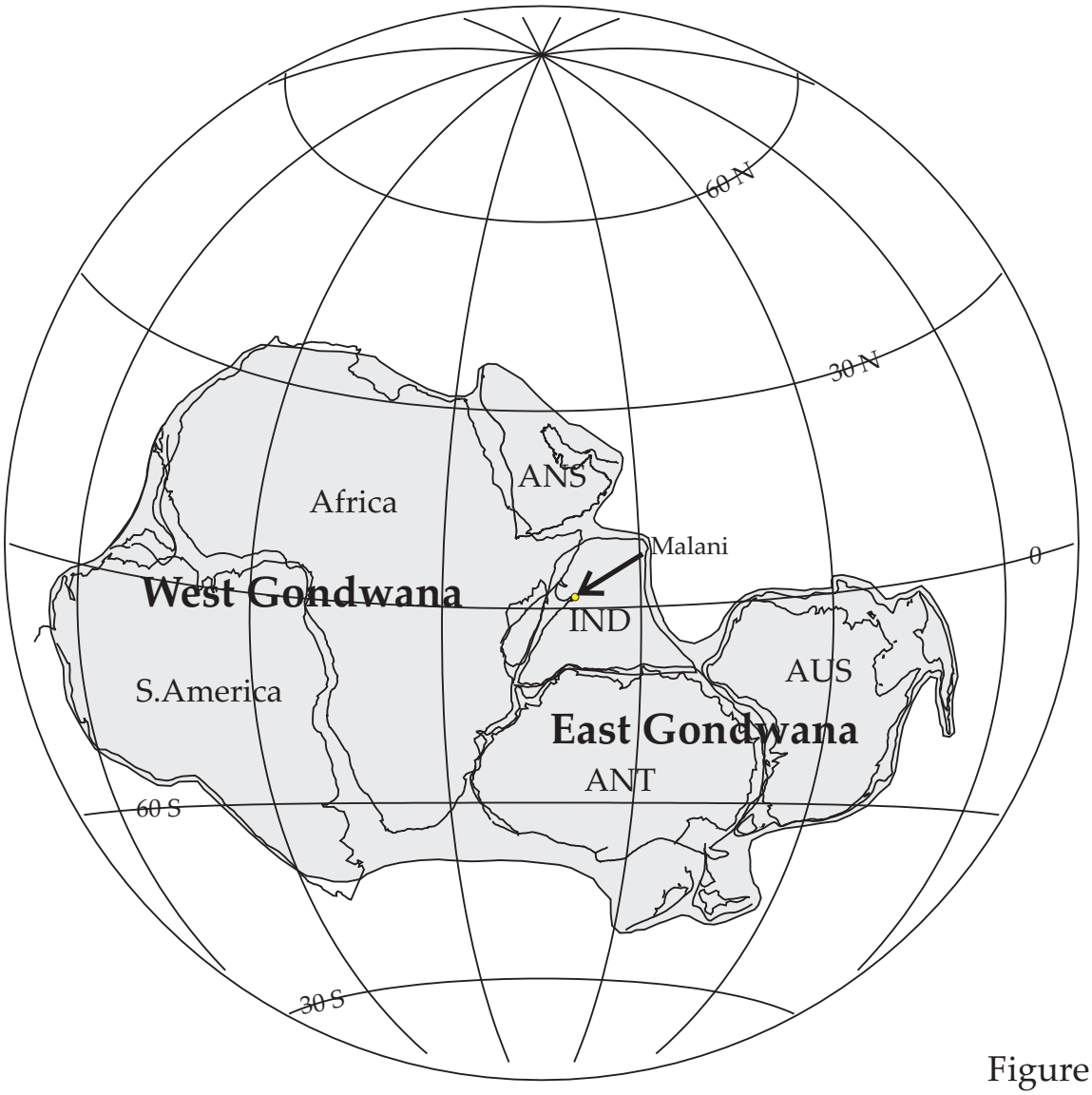


Figure 1

Figure 2

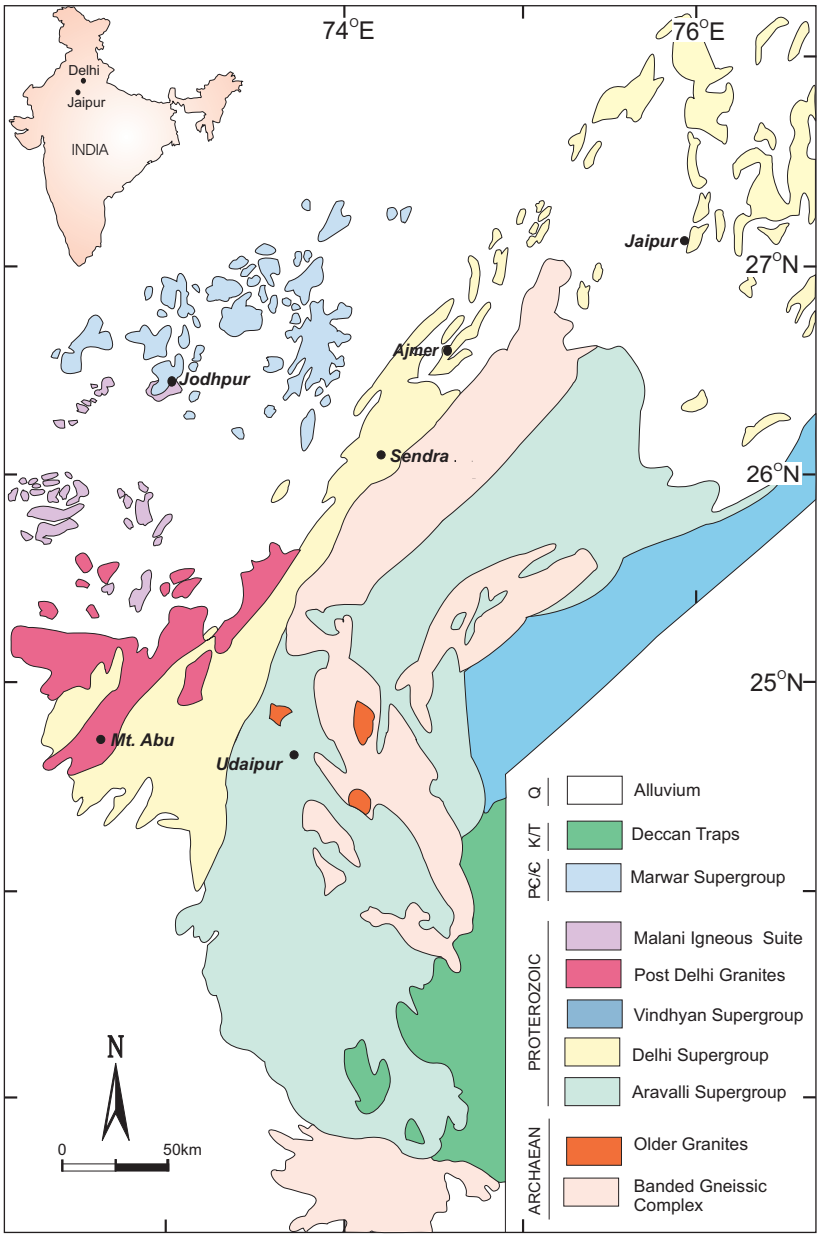
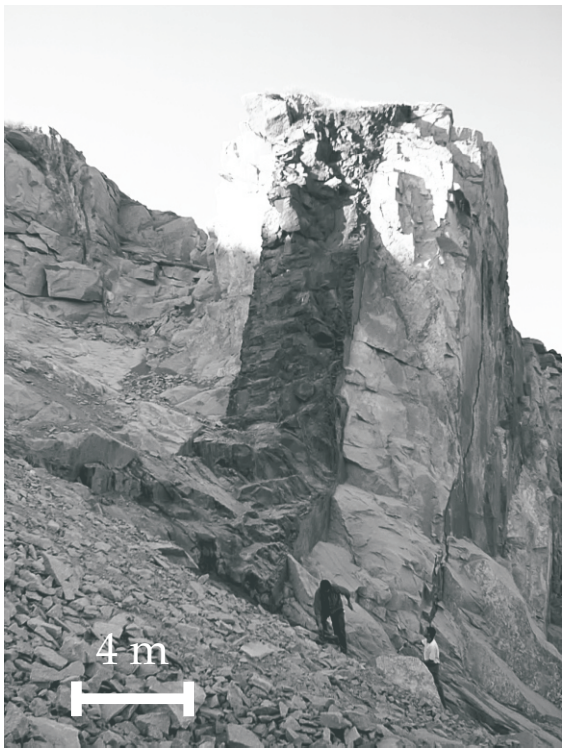


Figure 2

Figure 3



a

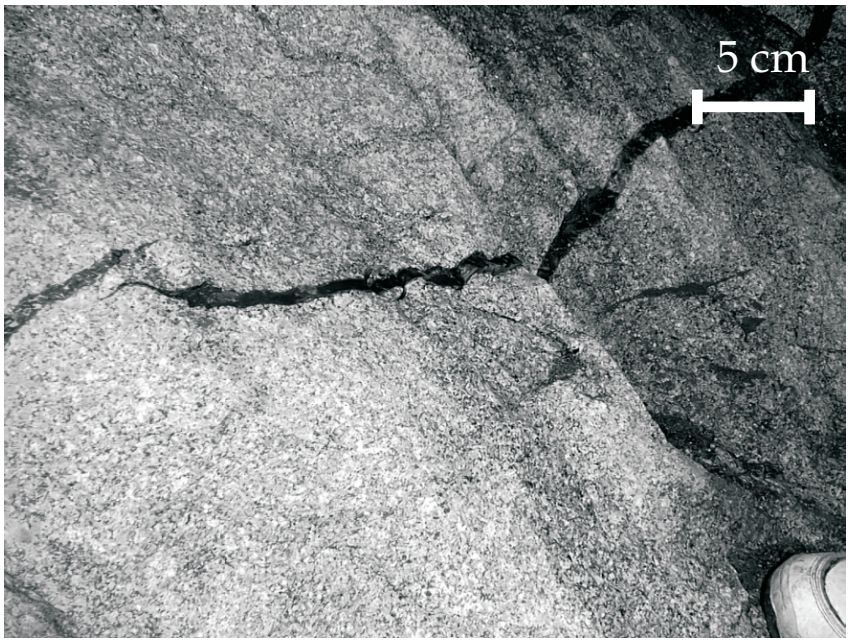


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Figure 3

Figure 4

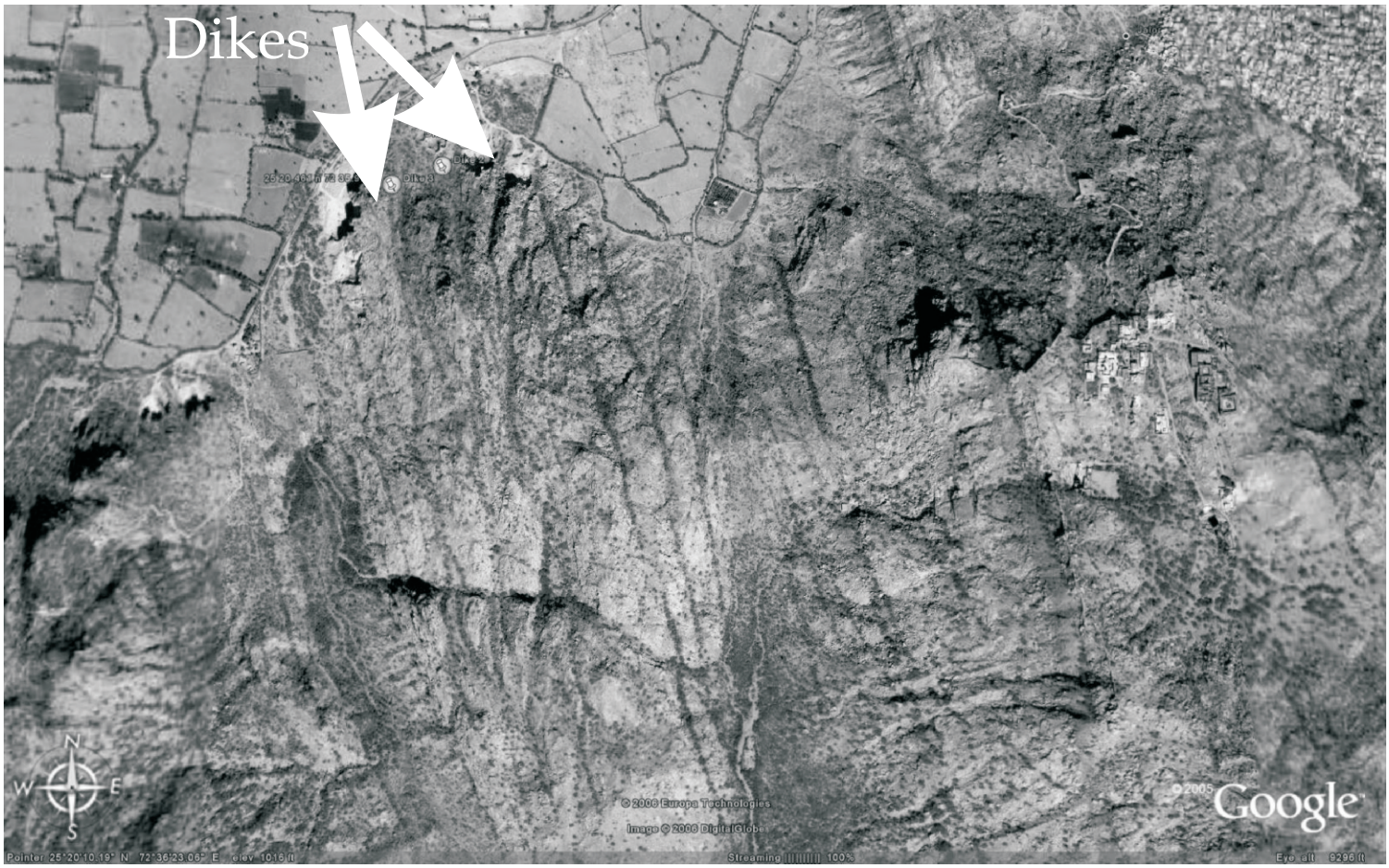


Figure 4

Figure 5

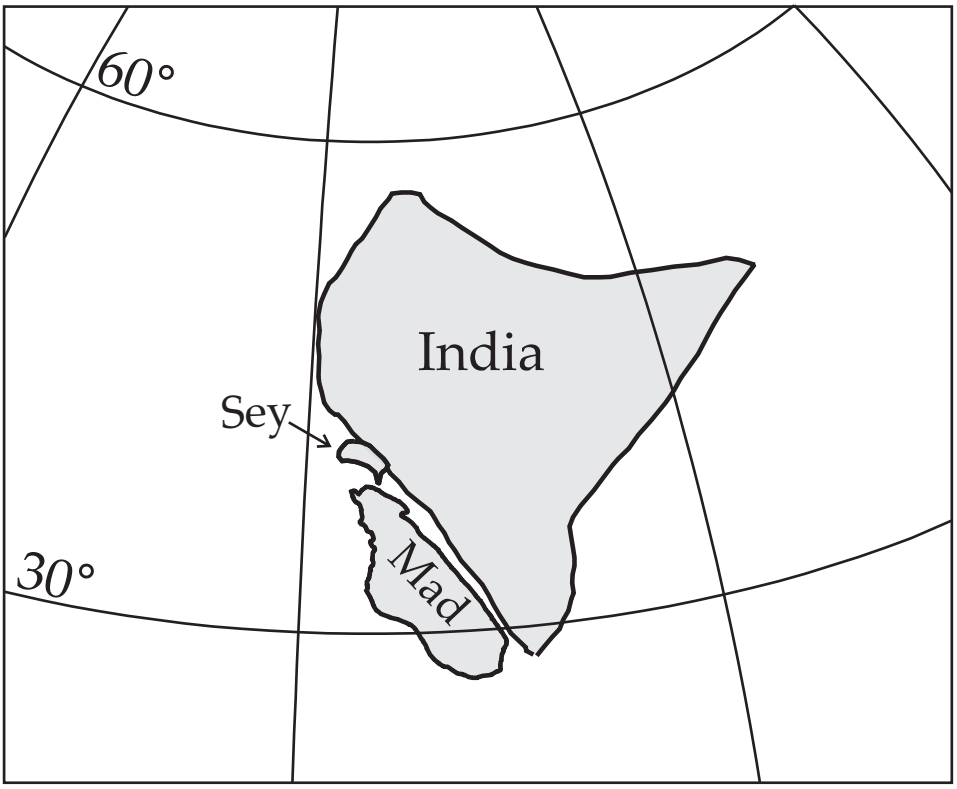


Figure 5

Figure 6

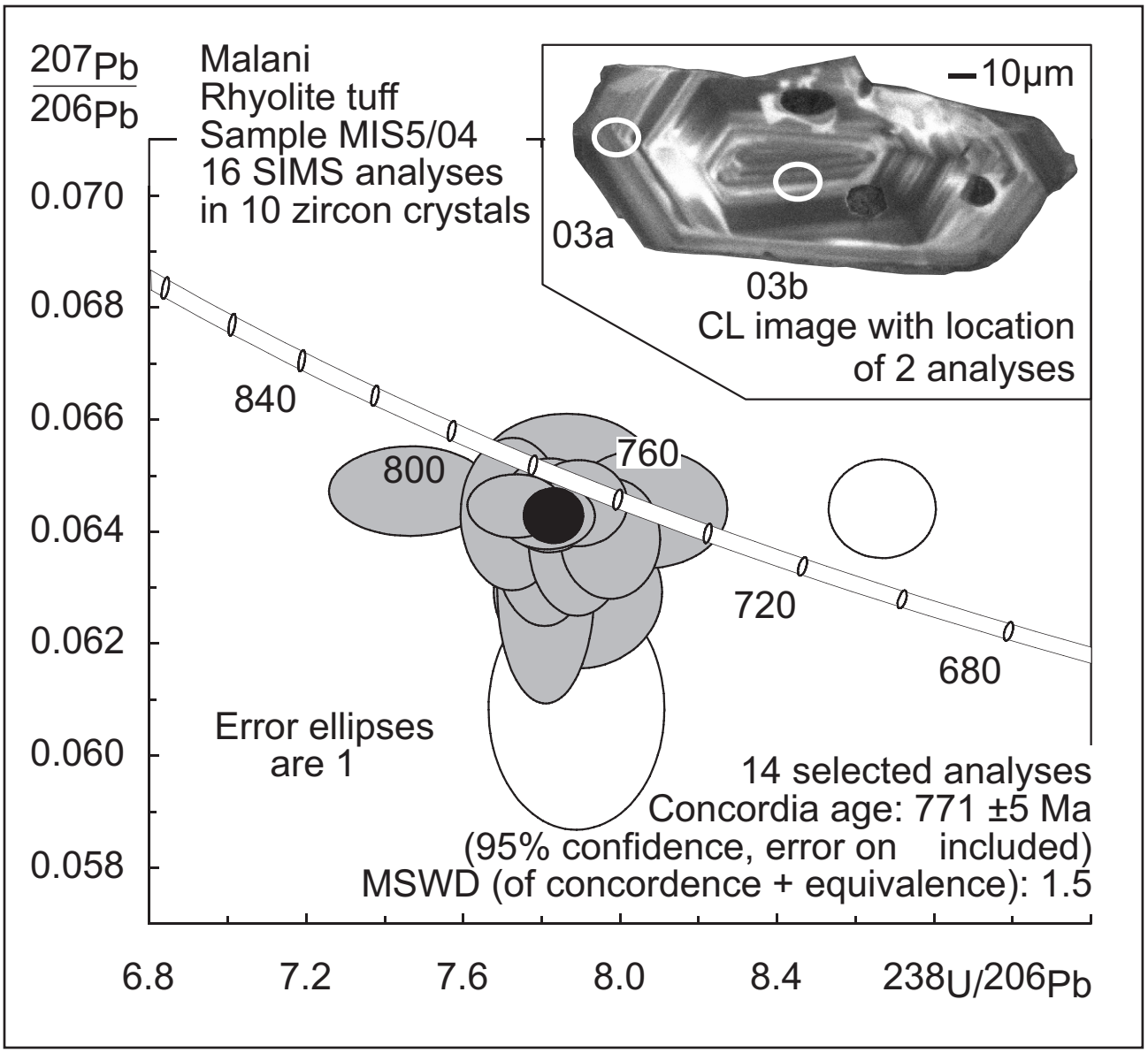
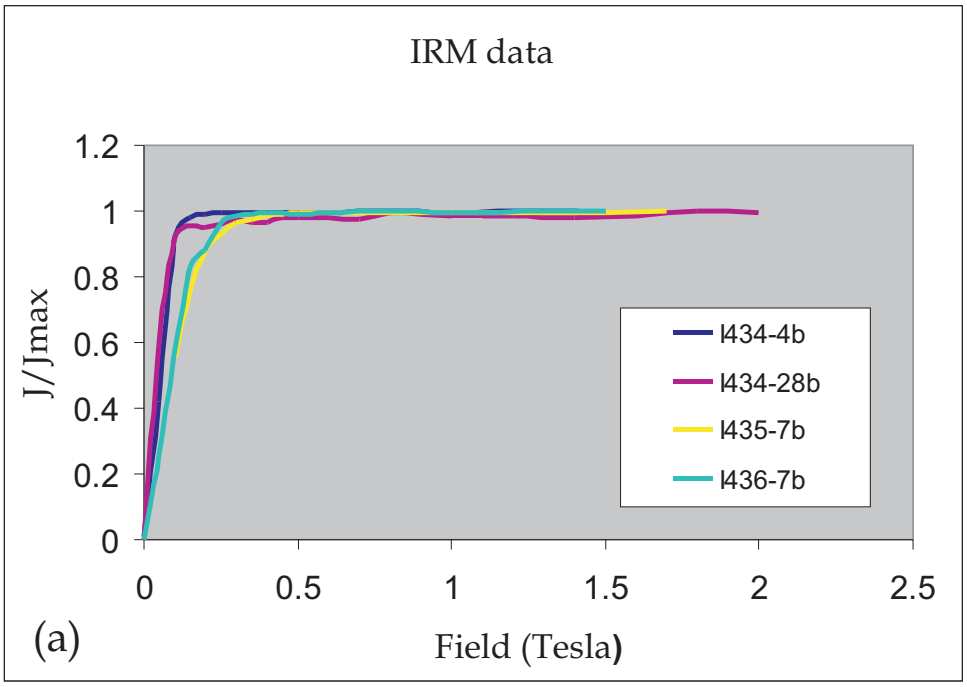
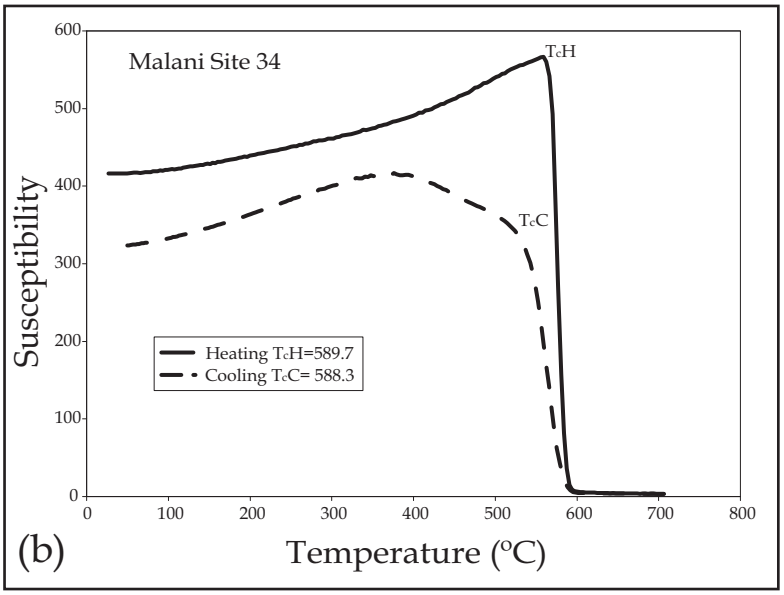


Figure 6

Figure 7





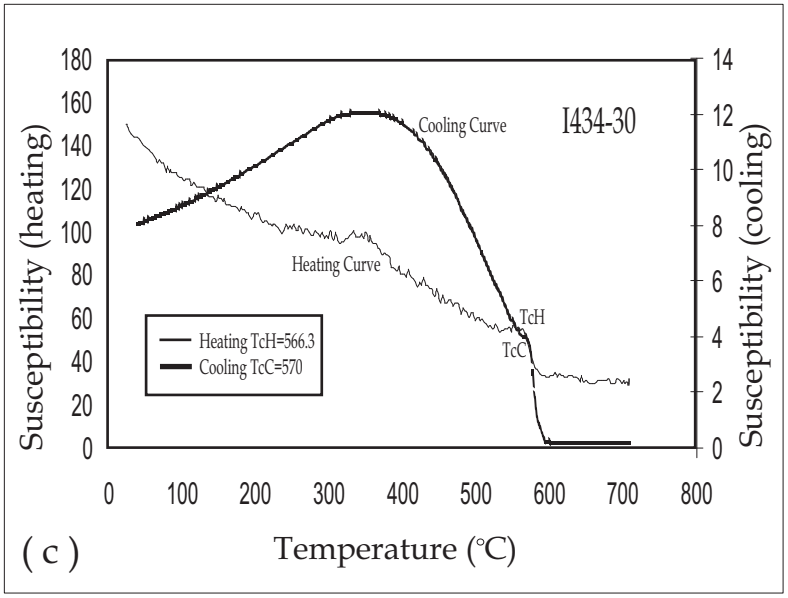
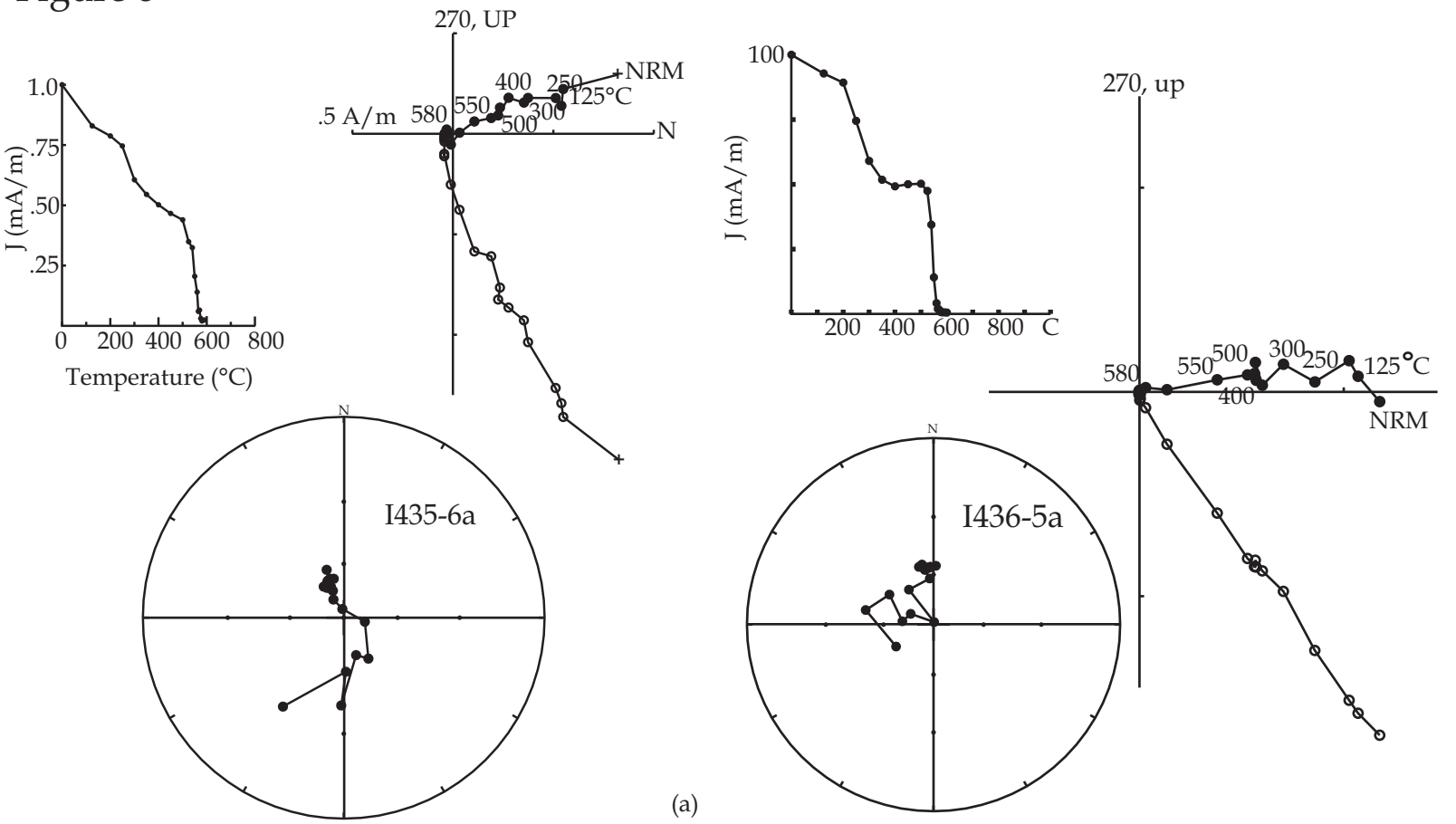


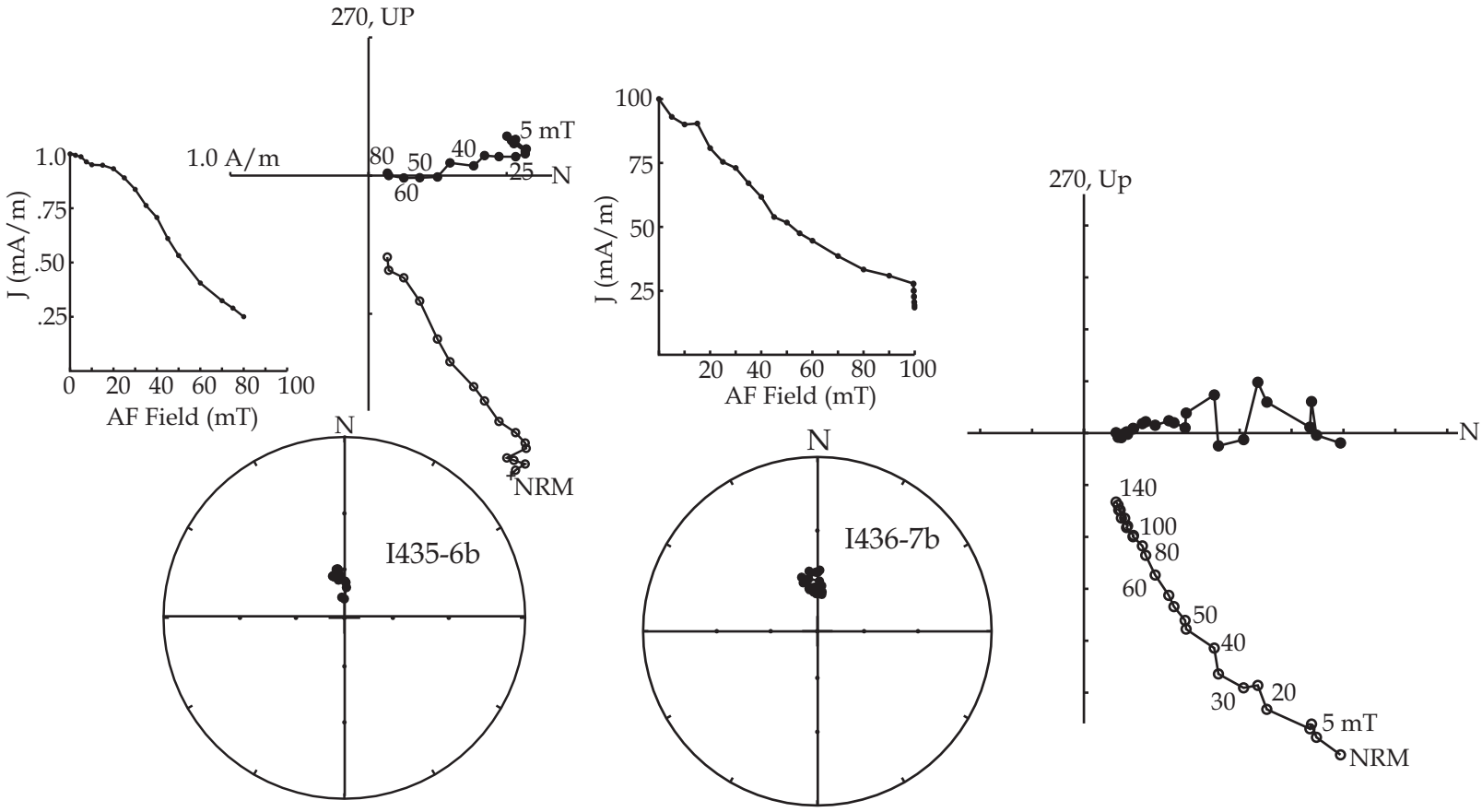
Figure 7

Figure 8

Figure 8



(a)



(b)

Figure 9

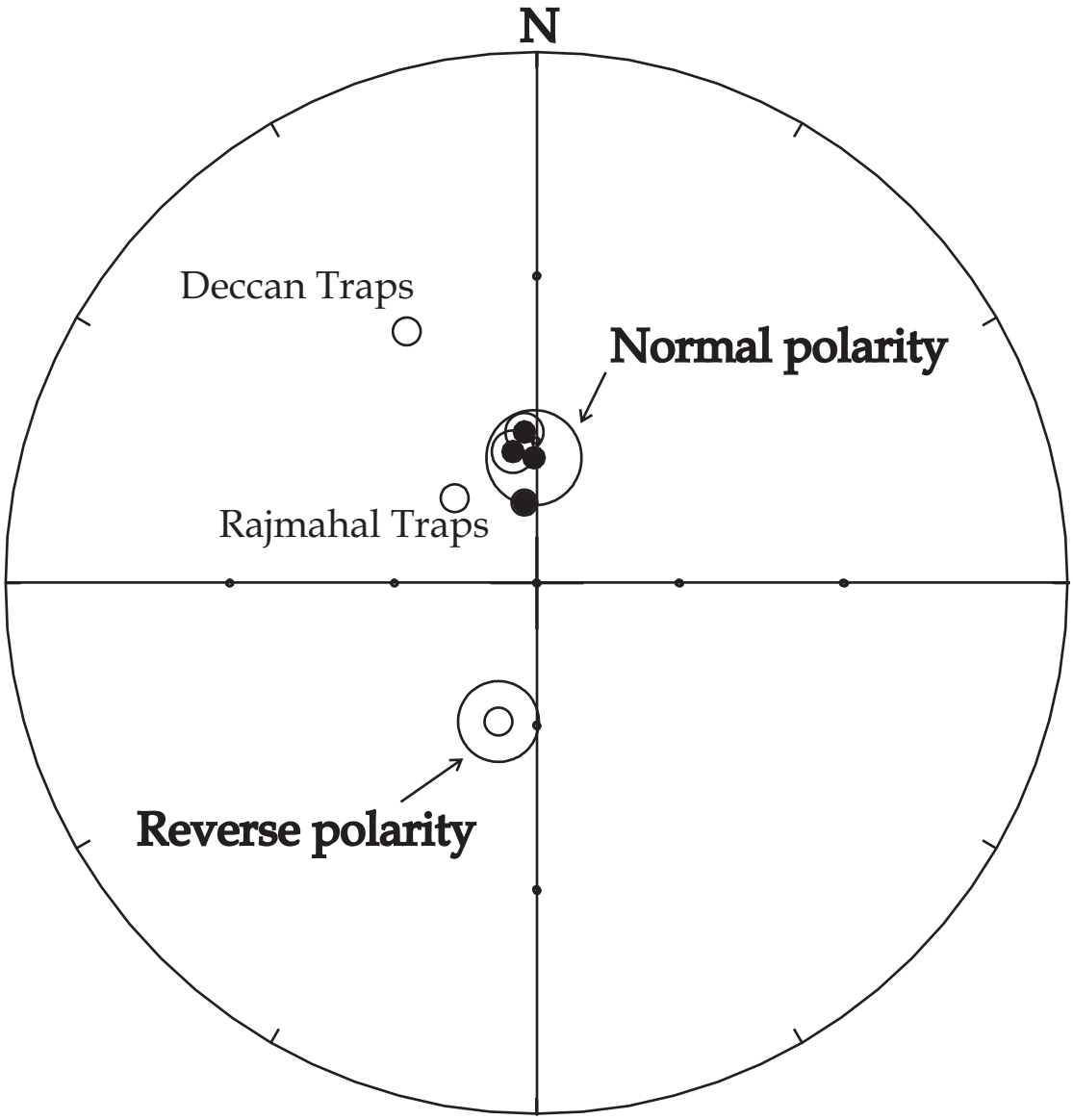

N
Deccan Traps
Normal polarity
Rajmahal Traps
Reverse polarity

Figure 10

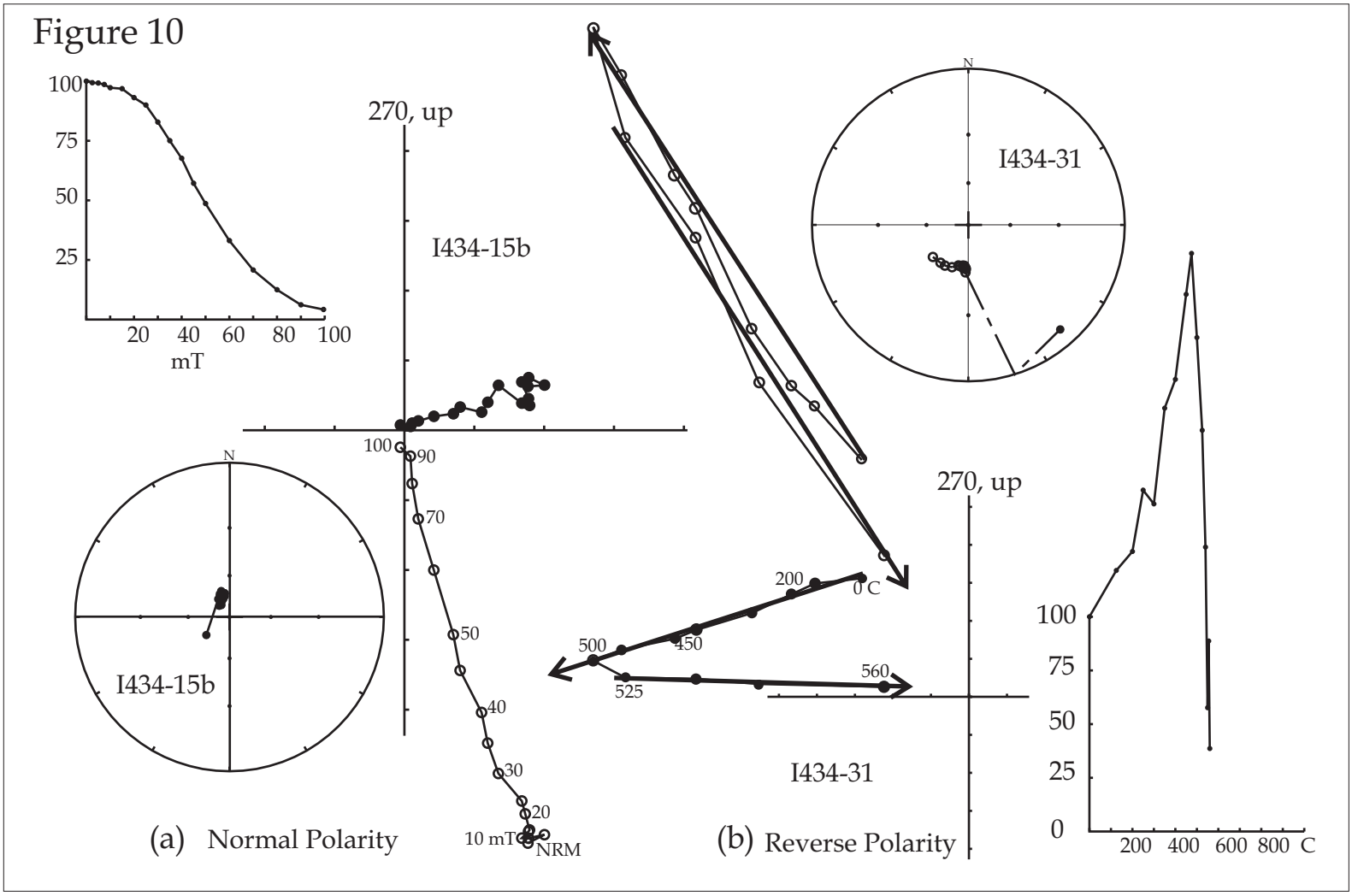


Figure 10
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Figure 11

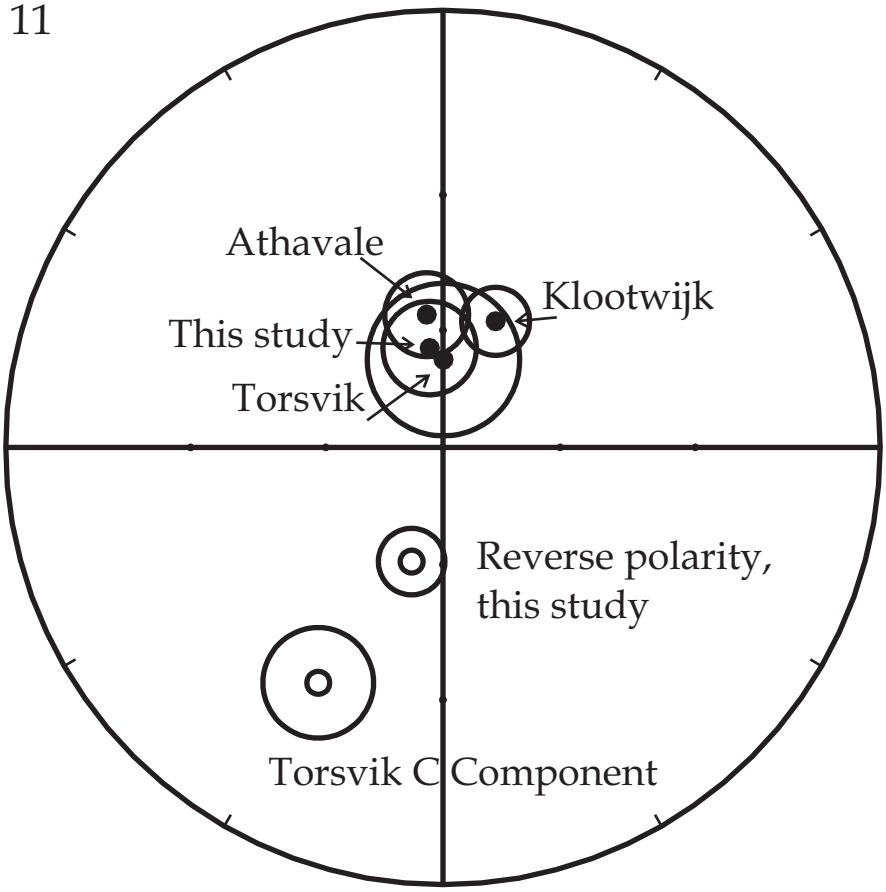
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Figure 12

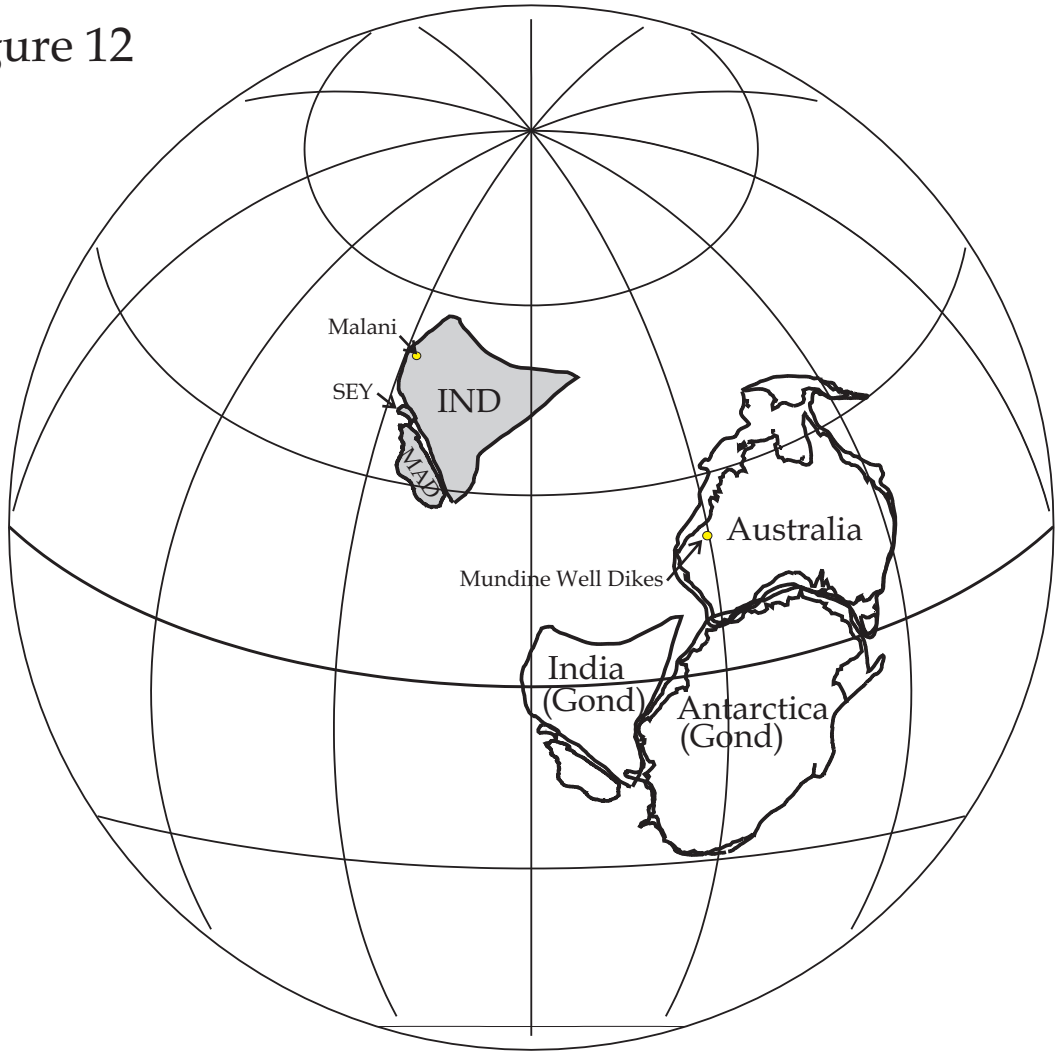
Malani
SEY
IND
MAD
Australia
Mundine Well Dikes
India
(Gond)
Antarctica
(Gond)

Table 1

Table 1: Summary of Paleomagnetic Poles

Pole Name	Age (Ma)	Pole latitude	Pole longitude	A95 or dp/dm[a]	dec[b]	inc[b]	α_{95} [c]	κ[d]	Reference
India									
Malani, aplite dike	750	74.6 N	49.8 E	16.2	352.5	60	16.2	18.6	Rao et al., 2003
Malani, rhyolite	745±10	80.5 N	43.5 E	8/11.5˚	354.5	53.5	8		Klootwijk, 1975
Malani, felsic volcanics	751±3, 771±2	74.5 N	71.2 E	7.4/9.7˚	359.5	60.4	6.4	29.9	Torsvik et al., 2001
Malani, rhyolite	740	78.0 N	45.0 E	11.0/15.0˚	353	56	10		Athavale et al., 1963
Malani, mafic dikes, felsic volcanics*	771±5*	69.0 N	83.2 E	8.8/10.9˚	349.8	64.1	11.5	116.44	this study, *site 3 of Torsvik et al, 2001a
Seychelles									
Mahe dikes[IND]	750.2±2.5	79.8 N	78.6 E	9.9/14.9˚	1.4	49.7	11.2		Torsvik et al., 2001
Australia									
Mundine Well dikes[IND]	755	41.47 N	130.92 E	4.1/4.1˚	14.8	31.1	5		Wingate and Giddings, 2000

a: A_{95}= cone of 95% confidence about the mean pole; dp/dm cone of 95% confidence about the paleomagnetic pole in the co-latitude direction (dp) and at a right angle to the co-latitud

b: dec/inc= mean declination/ inclination

c: α_{95}= circle of 95% confidence about the mean

d: κ= kappa precision parameter

le direction (dm).

Table 2

Table 2: Summary of Geochronologic Results

Site	Study	Method	Age (Ma)
Malani			
rhyolites	Crawford and Compston (1970)	Rb/Sr (recalc with new constant)	730±10
rhyolites	Klootwijk (1975)	Rb/Sr	745±10
felsic volcanics	Rathore et al. (1996)	Rb/Sr isochron	779±10
ultrapotassic rhyolites	Rathore et al. (1999)	Rb/Sr isochron	681±20
Jalore granites	Rathore et al. (1999)	Rb/Sr isochron	727±8
peralkaline volcanics	Rathore et al. (1999)	Rb/Sr isochron	693±8
rhyolite	this study, site 3 of Torsvik et al., 2001a	U/Pb	771±5

Table 3

Table 3**:** SIMS zircon U–Pb data on rhyolite tuff from Malani igneous suite.

ID	U (ppm)	Th (ppm)	Pb (ppm)	$^{206}Pb/^{204}Pb$ [a]	$^{207}Pb/^{206}Pb$	±σ (%)	$^{207}Pb/^{235}U$	±σ (%)	$^{206}Pb/^{238}U$	±σ (%)	R [b]	$^{206}Pb/^{238}U$ [c] (Ma)	±σ	$^{206}Pb/^{238}U$ [d] (Ma)	±σ	Disc. [e] 2σ lim. (%)
MIS5/04: ryholite tuff [f]																
n1808-01a [g]	222	120	31	10257	0.06439	0.9	1.024	1.4	0.1154	1.0	0.75	704	7	703	7	
n1808-03a	414	202	64	17681	0.06449	0.8	1.127	1.3	0.1267	1.0	0.79	769	8	770	8	
n1808-03b	400	175	62	22494	0.06444	0.6	1.149	1.2	0.1294	1.0	0.87	784	8	785	8	
n1808-04a	85	63	14	5821	0.06372	1.5	1.126	1.8	0.1281	1.0	0.57	777	8	779	8	
n1808-05a	183	106	29	28736	0.06445	0.9	1.137	1.4	0.1279	1.0	0.77	776	8	777	8	
n1808-05b	196	149	33	6602	0.06430	1.4	1.148	1.8	0.1295	1.1	0.62	785	8	786	9	
n1808-05c	55	31	9	3629	0.06296	2.2	1.112	2.4	0.1281	1.0	0.43	777	8	779	8	
n1808-06a	149	113	24	6027	0.06385	1.1	1.104	1.5	0.1254	1.1	0.68	762	8	762	8	
n1808-06b	134	99	22	8903	0.06380	1.4	1.115	1.7	0.1268	1.0	0.60	769	8	771	8	
n1808-07a	401	316	67	13951	0.06426	0.6	1.134	1.2	0.1280	1.0	0.86	777	8	777	8	
n1816-01a	143	101	23	6033	0.06493	1.2	1.139	2.3	0.1272	1.9	0.85	772	14	772	15	
n1816-01b	197	154	32	14111	0.06377	1.0	1.119	2.2	0.1273	2.0	0.89	772	14	773	15	
n1816-02a [g]	46	24	7	3182	0.06076	2.4	1.062	3.0	0.1268	1.9	0.62	770	14	774	14	0.5
n1816-03a	88	57	14	13350	0.06288	1.4	1.099	2.3	0.1268	1.8	0.78	769	13	771	13	
n1816-03b	200	164	35	15016	0.06472	0.8	1.196	2.0	0.1340	1.8	0.91	811	14	812	14	
n1816-06a	138	54	20	10092	0.06440	1.1	1.101	2.0	0.1240	1.7	0.84	754	12	754	12	

a: Measured $^{206}Pb/^{204}Pb$ ratio

b: R, correlation coefficient of errors in isotopic ratios

c: ^{204}Pb corrected age

d: ^{207}Pb corrected age

c: age discordance at the closest approach of 2 σ 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

Table 4: Paleomagnetic results

Site name	Lat/Long	n/N[a]	Declination	Inclination	Kappa (κ)[b]	α95[c]	VGP latitude[d]	VGP longitude[d]	dp, dm[e]
I434 (normal)	25˚ 20.517'N, 72˚ 36.084'E	23/27	351.4	72.6	129.55	2.7	56.9N	64.3E	4.3, 4.8
I434 (reverse)	25˚ 20.517'N, 72˚ 36.084'E	3/3	195.3	-59.7	234.79	8.1	70.2N	108.8E	9.2, 12.2
I435	25˚ 20.483'N, 72˚ 36.057'E	6/8	349.8	61.8	244.78	4.3	70.5N	49.8E	5.1, 6.7
I436	25˚ 20.461'N, 72˚ 36.992'E	9/9	355.4	58.2	256.88	3.8	75.9N	57.7E	4.1, 5.6
Combined mean		4 dikes	349.8	64.1	116.44	11.5			

a: n= samples used; N= samples collected

b: κ= kappa precision parameter

c: α_{95}= circle of 95% confidence about the mean

d: VGP latitude/longitude = virtual geomagnetic pole

e: dp,dm= cone of confidence along site latitude (dp) and orthogonal to site latitude (dm)