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India's changing place in global Proterozoic reconstructions: A review of geochronologic constraints and paleomagnetic poles from the Dharwar, Bundelkhand and Marwar cratons

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ABSTRACT

The Precambrian history of the Earth is punctuated by a number of supercontinental assemblies and their disintegration. New paleomagnetic and geochronologic results from the Dharwar, Bundelkhand and Marwar cratons of the Indian subcontinent are presented here in an attempt to constrain the paleogeographic position of India within various proposed Precambrian supercontinents.

Our paleomagnetic results from the Paleoproterozoic Gwalior traps of the Bundelkhand craton, all of a single polarity, yielded a combined tilt-corrected mean declination = 73.9° and an inclination of +4.4° (k = 22, α95 = 11.2°). The paleomagnetic pole was calculated using a site location of 26°N, 78°E and is located at 15.4°N, 173.2°E.

The U–Pb isotopic studies on the zircons obtained from the alkaline mafic dyke sample from Anantapur dyke swarm of the Dharwar craton, southern India, yielded a concordant age of 1027.2 ± 13 Ma (2σ; MSWD = 5.0). An overall mean of our paleomagnetic studies combined with previously published results yielded a VGP at 10°N and 211°E with a mean declination = 65° and inclination = −57° (k = 31, α95 = 10).

In an effort to constrain the lower age limit of the Malani Igneous Suite (MIS) we report new U–Pb isotopic ages for the Harsani granodiorite. The granodiorite forms the basement for the Malani igneous province in NW India. The zircon U–Pb analyses from Harsani granodiorite yielded and age of 827.0 ± 8.8 Ma that we interpret as the age of intrusion and the 786.4 ± 5.6 Ma may relate to a disturbance marking onset of Malani volcanism.

Along with these new data, we also review the paleomagnetic results from our previous studies on the Harohalli alkaline dykes, Upper Vindhyan sequence, Majhgawan kimberlite, and a widespread paleomagnetic overprint that we interpret to be of ∼580 Ma in an attempt to constrain the paleogeography of the Indian subcontinent from 1.8 Ga to 580 Ma.

1. Introduction

The East Gondwana continent is comprised of India, Australia, East Antarctica, Madagascar and Sri Lanka. The tectonic history leading to the amalgamation of East Gondwana can be evaluated through the use of well-dated paleomagnetic poles. Madagascar, Sri Lanka and the exposed regions of East Antarctica are dissected by numerous orogenic belts related to Gondwana assembly and therefore target rocks in these regions are poor candidates for paleomagnetic study. In contrast, both India and Australia contain numerous unaltered sequences of sedimentary and igneous rocks that may be used to establish their drift histories prior to the final fusion of Gondwana.

In the past few years, we have focused on improving the Meso-Neoproterozoic drift history of India through the acquisition of robust paleomagnetic and geochronologic data from key sedimentary and igneous sequences. In this paper, we summarize those findings (Pradhan et al., 2008; Gregory et al., 2006, 2009; Malone et al., 2008) along with new preliminary geochronologic and paleomagnetic data from the Anantapur dikes (Dharwar craton), Gwalior volcanics (Bundelkhand craton) and the Malani Igneous Suite (Marwar craton). These new data, in combination with recently published paleomagnetic and geochronologic results lead to the proposal of a new set of paleogeographic maps for India.

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The paper also evaluates several controversial proposals regarding the geodynamic evolution of East Gondwana.

2. Geologic setting

Four distinct cratonic blocks are recognized in the Indian shield; (1) the Aravalli and Bundelkhand craton in northwestern and central regions; (2) the Bastar craton in south-central region; (3) the Singhbhum craton in eastern region; and (4) the Dharwar craton covering the southern half of peninsular India (Naqvi et al., 1974). These cratonic regions are bordered by orogenic belts (Fig. 1). The region to the west of the Aravalli–Delhi Proterozoic belts in NW India exposes well developed Phanerozoic sequences, however, it is one of the least understood in terms of ‘Precambrian basement’. This terrane is also known as the Marwar craton.

In addition to the cratonic rocks and adjacent orogenic belts, many regions contain purported Meso- to Neoproterozoic sedimentary basins. These so-called “Purana” basins (Fig. 1) include the Vindhyan, Chhattisgarh, Prahnita-Godavari, Cuddapah, Bhima, Indravati, Badami and Kaladgi basins. Age constraints are generally lacking in most of these basins; however, Chakraborty (2006) tentatively called all of these basins ‘classic examples of Proterozoic intracontinental basins’ within India and remarked on similarity in their lithologies, depositional environments and stratigraphic architecture. Recent work in both the Vindhyan and Chhattisgarh basins (the results come from these basins only) supports Meso-Paleoproterozoic ages for these basins (Malone et al., 2008; Patranabis-Deb et al., 2008; Basu et al., 2008; Das et al., 2009).

Each of the above mentioned cratons has also been intruded by a number of igneous bodies including large swarms of mafic dykes, kimberlites, lamproites and granitoids. The ages of many of these bodies are still poorly constrained, however some recent geochronologic work (French et al., 2008; Halls et al., 2007; Gregory et al., 2006; Pradhan et al., 2008) have begun to sort out these distinct intrusive events in the evolution of the Indian subcontinent.

2.1. The Aravalli and Bundelkhand cratons

The Aravalli and Bundelkhand cratons (Fig. 2) are bounded to the northeast by the Mesoproterozoic Vindhyan Basin and Indo-Gangetic alluvium and to the south by the northern edge of the Deccan Traps. The Great Boundary Fault (GBF) separates the Aravalli cratonic block to the west and the Bundelkhand–Gwalior block

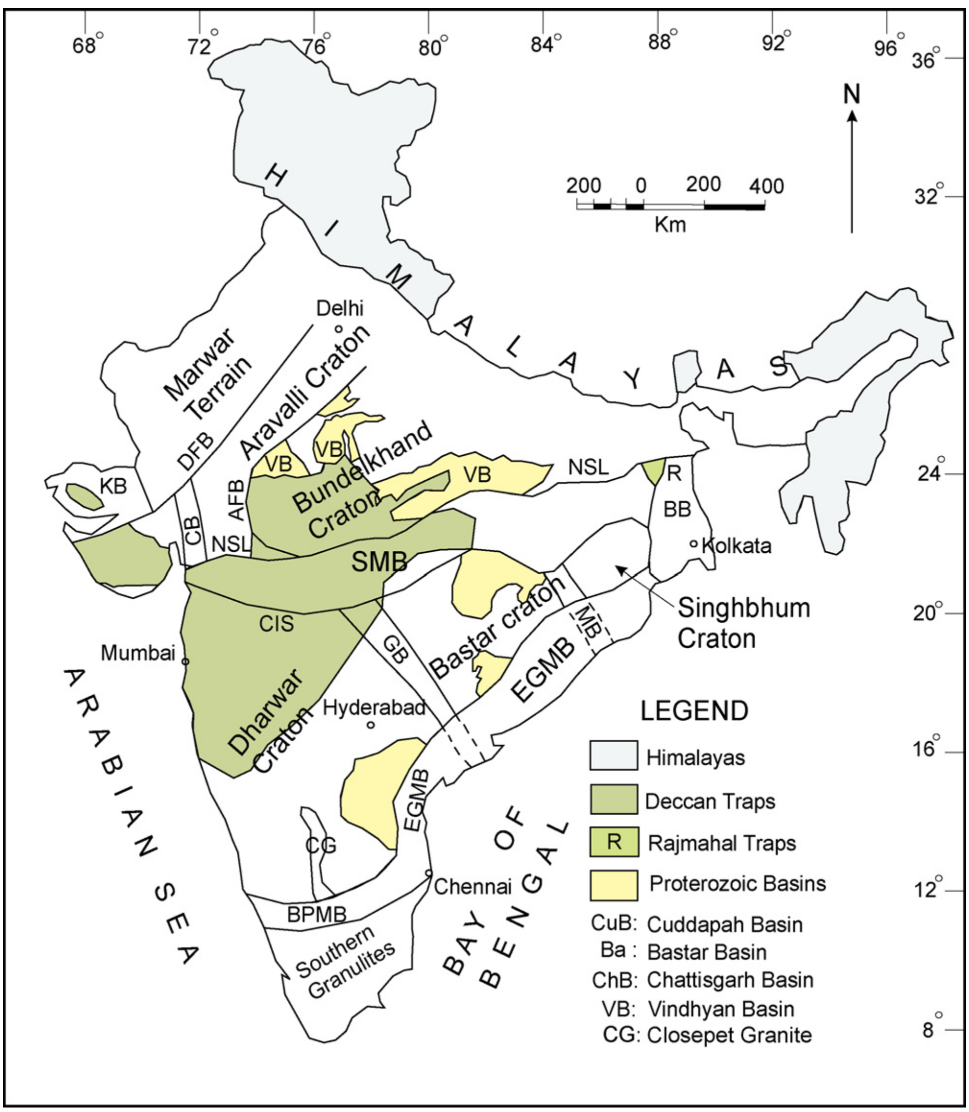

Fig. 1. Generalized tectonic map of Indian subcontinent showing Precambrian cratons, mobile belts and lineaments. AFB = Aravalli Fold Belt, DFB = Delhi Fold Belt, EGMB = Eastern Ghat Mobile Belt, SMB = Satpura Mobile Belt, NSL = Narmada–Son lineament, CIS = Central Indian Suture and BPMP = Bhavani Palghat Mobile Belt (modified from Vijaya Rao and Reddy, 2001).

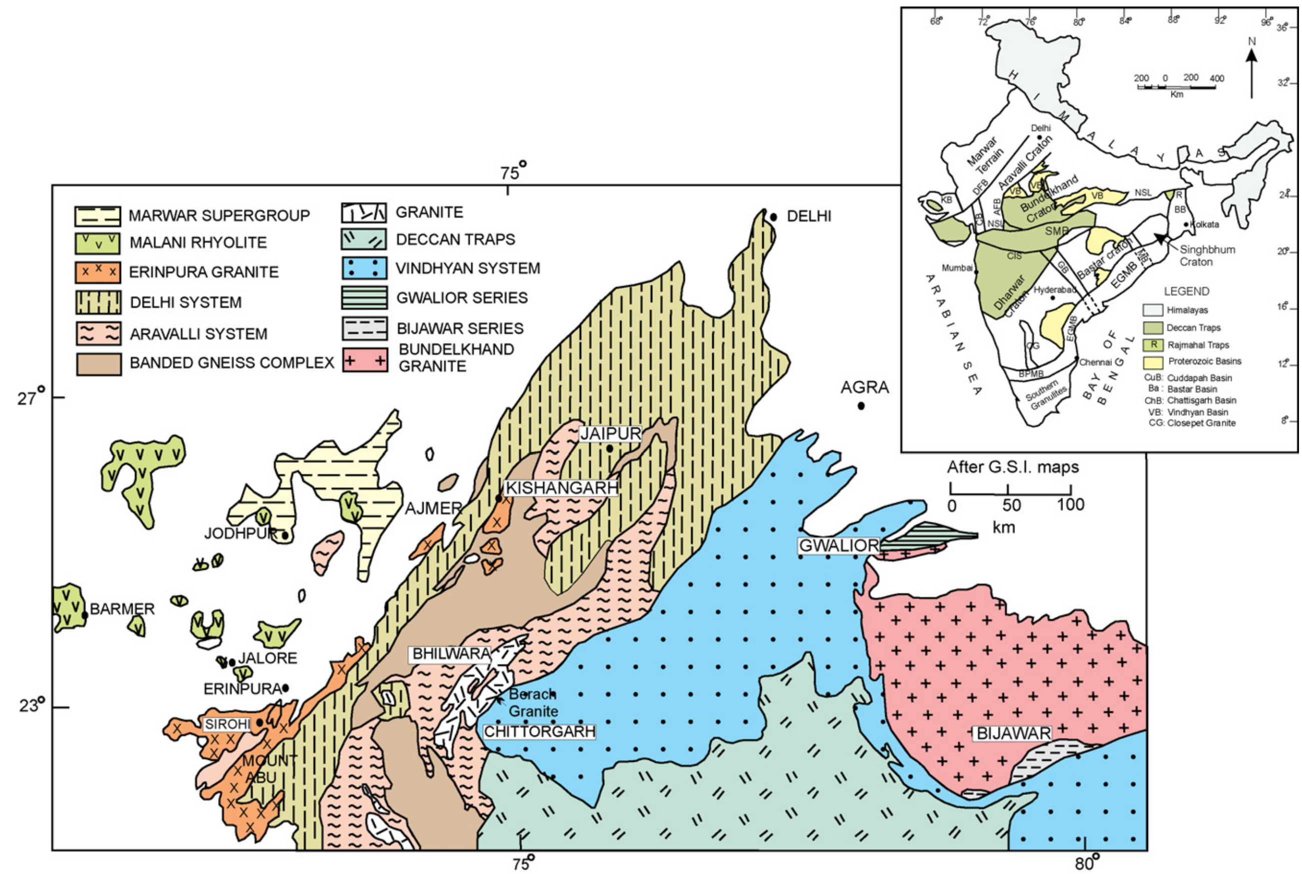

Fig. 2. Sketch map of the major units in the Aravalli–Bundelkhand craton, NW India (after Naqvi and Rogers, 1987; Ramakrishnan and Vaidyanadhan, 2008).

to the east of the GBF. The NE-trending Aravalli–Delhi Fold Belt (NDFB) defines the western boundary of the Aravalli/Bundelkhand craton(s). The Bundelkhand and Aravalli cratons are also separated from the Bastar and Singhbhum cratons in the south by the Narmada–Son lineament (Goodwin, 1991; Naqvi and Rogers, 1987).

Most of the Aravalli craton is underlain by the 3.3 Ga Banded Gneiss Complex (hereafter BGC; Wiedenbeck et al., 1996; Roy and Kröner, 1996). The BGC is composed of migmatites, gneisses, schists, amphibolites, pelites and metasedimentary rocks. The BGC in the Aravalli region is bounded by the Aravalli–Delhi Fold Belts. Age constraints on both the Aravalli and Delhi Fold Belts are only poorly constrained to 2.5–1.9 Ga and 1.8–0.85 Ga, respectively (Gupta et al., 1980, 1997). The ages of metamorphism in the Aravalli craton have tighter constraints. Roy et al. (2005) argue that the main pulse of metamorphism took place between 1725 and 1621 Ma at the outset of the Delhi Orogenic Cycle. Buick et al. (2006) also obtained metamorphic ages of ~1720 Ma for part of the Delhi Belt that was formerly thought to be reworked high-grade metamorphic rocks of Archaen age. Buick et al. (2006) also report a younger metamorphic episode that took place between ~950 and 940 Ma and suggested that these ages may be part of a larger metamorphic and igneous event (Pandit et al., 2003; Tobisch et al., 1994). Support for this metamorphic event is also observed in detrital zircon spectra from the Sonia and Girbakhar sandstones in the Marwar Supergroup of Rajasthan (Malone et al., 2008). The best constrained magmatic events took place between 1711 and 1660 Ma (Kaur and Mehta, 2007; Kaur et al., 2009) and appear to be coincident with the main phase of metamorphism documented by both Buick et al. (2006) and Roy et al. (2005). Wiedenbeck et al. (1996) analyzed ion microprobe $^{207}Pb/^{206}Pb$ zircon isotopic data on Berach Granite and suggested a ~2.5 Ga stabilization age for the southern segment of the Aravalli craton, based on the uniformity of the Late Archaean and Early Proterozoic crystallization ages.

Other tectono-metamorphic events in the Aravalli region include a metallogenic event at around 990 Ma followed by a tectonothermal event between 990 and 836 Ma (Deb et al., 2001; Roy, 2001). The last major episode of Neoproterozoic igneous activity took place during the emplacement/eruption of the Malani igneous rocks between ~770 and 750 Ma (Torsvik et al., 2001a; Gregory et al., 2009). The Malani province is overlain by the sedimentary sequences of the late Neoproterozoic (to Early Cambrian) Marwar Supergroup (Pandit et al., 2001).

The Bundelkhand craton lies to the east of the Aravalli–Delhi Fold Belt (Fig. 3). The most conspicuous feature of the region is the Bundelkhand Igneous Complex that intrudes enclaves of schists, gneisses, banded iron formations, mafic volcanic rocks and quartzites (Goodwin, 1991). Ages of the enclaves are not known, but there are a few ages on the granites that intrude them. The Bundelkhand granite is dated to 2492 ± 10 Ma (Mondal et al., 2002), and is therefore contemporaneous with the intrusion of the Berach Granite in the Aravalli craton dated ~2500 Ma (Sivaraman and Odam, 1982; Tucker, personal communication). Numerous mafic dykes of unknown age intrude the Bundelkhand Igneous Complex. Rao (2004) suggests that most of the mafic dikes were emplaced in two phases, one at 2.15 Ga and the second at 2.0 Ga based on the $^{40}Ar/^{39}Ar$ age determination of the dolerite dykes.

Overlying the Bundelkhand granite are metasedimentary rocks of the 1854 ± 7 Ma Hindoli Group (Deb et al., 2002) that some consider equivalent to the Gwalior Group. These metasedimentary rocks are slightly older than the depositional ages of sedimentary sequences in the Vindhyan Basin (~1700–1050 Ma; Ray et al., 2002, 2003; Rasmussen et al., 2002; Sarangi et al., 2004; Malone et al.,

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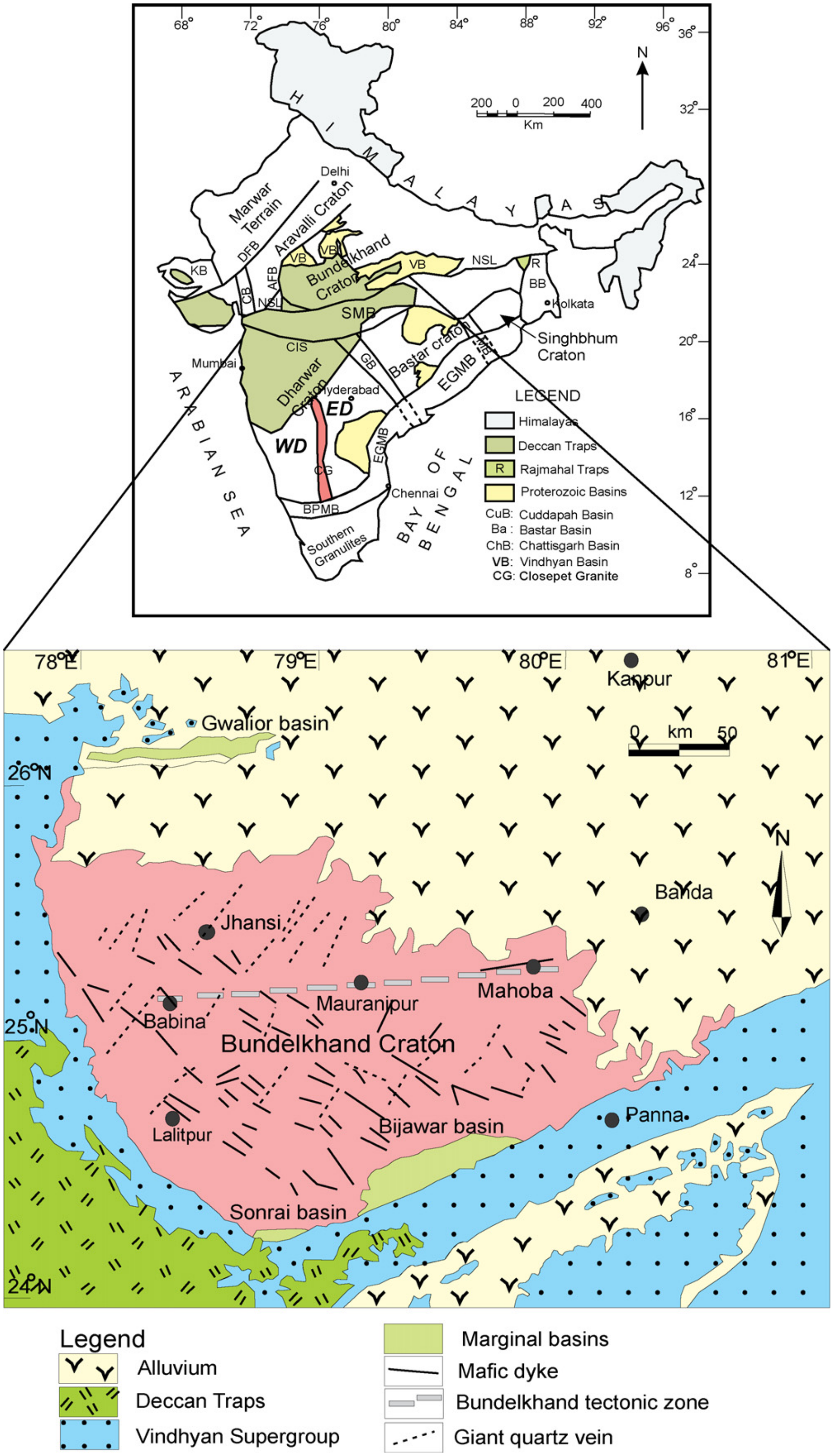

Fig. 3. Sketch map of the Bundelkhand craton showing mafic dyke swarms including the Great Dyke of Mahoba (grey-dashed line; after Malviya et al., 2006).

2008). The 1073 ± 13.7 Ma Majhgawan kimberlite (Gregory et al., 2006) intrudes the lower Vindhyan as well as the Kaimur sandstone in the lower part of the Upper Vindhyan sequence.

2.2. The Dharwar craton

The Dharwar craton (DC) in southern India (Fig. 1) is the largest and one of the most extensively studied of the Precambrian cratons of Indian Peninsular shield. Together with the Southern Granulite Terrane (SGT), the Dharwar craton forms the Dravidian Shield covering an area of more than 238,000 km^2 (Goodwin, 1991). To the east, the DC is bounded by the Eastern Ghats Mobile Belt (EGMB) and to the south by the charnockites and khondalites of the SGT. The NE margin is bordered by the Godavari Rift, and the Narmada–Son lineament marks the northern boundary (Rogers, 1985). The DC is truncated on the west due to the earlier separation of Madagascar from India during the breakup of Gondwanaland (Agarwal et al., 1992) and a small piece of the Western Dharwar craton may now occupy north-central Madagascar (Tucker et al., 1999). The northwest segment of the Dharwar craton is blanketed by the extensive basaltic flows of the Deccan Traps (Cretaceous–Eocene).

The Dharwar craton is divided into western and eastern domains on the basis of lithological variations, differences in volcano-sedimentary facies, magmatism and metamorphic characteristics (Ramakrishnan and Vaidyanadhan, 2008; Ramakrishnan, 1994; Peucat et al., 1993; Radhakrishna and Vaidyanadhan, 1997). The N–S trending linear outcrop of 2.55–2.51 Ga Closepet granite (Friend and Nutman, 1991) marks the division between the Eastern and Western Dharwar cratons (Ramakrishnan and Vaidyanadhan, 2008; Naqvi and Rogers, 1987). The Western Dharwar craton (WDC) is dominated by tonalite–trondhjemite Peninsular Gneisses (3.4–2.7 Ga; Jayananda et al., 2000, 2006) and supracrustals/greenstone schist belts dating to (3.3–2.6 Ga; Anil Kumar et al., 1996; Trendall et al., 1997a,b; Nutman et al., 1996). The Eastern Dharwar craton (EDC), on the other hand, is predominantly composed of 3.0–2.55 Ga granites and gneisses, with subordinate linear greenstone belts of limited dimensions (Balakrishnan et al., 1990; Vasudev et al., 2000; Jayananda et al., 2000; Chadwick et al., 2000; Chardon et al., 2002; Banks et al., in press).

Meso-Neoproterozoic rocks of igneous and sedimentary origin are adjacent to the EDC in the large crescent shaped Cuddapah basin (Fig. 1) overlying the Peninsular Gneiss (Pichamuthu, 1967; Nagaraja Rao et al., 1987). The Dharwar craton experienced widespread mafic magmatism during the Proterozoic along with the intrusion of Meso-Neoproterozoic diamondiferous kimberlites and lamproites (Rao and Pupper, 1996; Murthy and Dayal, 2001; Chalapathi Rao et al., 2004). In addition to the kimberlites and lamproites, there are other mafic intrusives including metadolerites/metanorites, tholeiitic and alkali-olivine basaltic dykes forming dense E–W and NNW to NW trending swarms crosscutting the greenstone and gneissic basement of the Dharwar craton (Murthy et al., 1987; Kumar and Bhalla, 1983; Radhakrishna and Joseph, 1996; Chalapathi Rao et al., 2005). The E–W trending mafic dykes are well developed in the eastern portion of the craton around the Cuddapah basin. The ENE trending dykes form the densest cluster along the southern margin of the basin and these can be traced further west, toward the Closepet granite batholith as widespread albeit impersistent bodies (Murthy, 1995).

Radiometric data on these doleritic dykes suggest at least three major episodes of dyke emplacement in the region that occurred at 1.9–1.7, 1.4–1.3 and 1.2–1.0 Ga (Murthy et al., 1987; Padmakumari and Dayal, 1987; Mallikarjuna Rao et al., 1995; Chatterji and Bhattacharji, 2001). A high precision baddeleyite age of 1885.4 ± 3.1 Ma for the Pullivendla mafic sill from the Cuddapah basin has been interpreted to coincide with the widespread ∼1.9 Ga basaltic magmatism occurred in the widely separated Large Igneous Provinces (French et al., 2008). The whole rock Rb–Sr isochron age of 2370 ± 230 Ma (Ikramuddin and Stuber, 1976) and a Sm–Nd isochron age of 2454 ± 100 Ma (Zachariah et al., 1995) for other easterly trending dykes are further refined by a highly precise U–Pb baddeleyite age of 2367 ± 1 Ma (Halls et al., 2007). These age data suggest that most of the easterly dykes in the vicinity of Cuddapah are Paleoproterozoic in age and intruded during two major magmatic episodes centered at ∼2.1 and ∼2.4 Ga.

3. Methods

3.1. Paleomagnetic methods

All paleomagnetic samples were collected using a water-cooled portable drill. The samples were oriented using both sun and magnetic compass and readings were corrected for local magnetic declination and deviations. Subsequently they were cut into cylindrical specimens, and measurements were made on either a Molspin® spinner magnetometer or a 2G 77R Cryogenic magnetometer at the University of Florida. Samples were stepwise demagnetized by using either thermal or alternating field (AF) methods. Samples with a very high initial NRM were treated in liquid nitrogen baths prior to thermal or AF treatment to remove more viscous multidomain magnetism. Linear segments of the demagnetization trajectories were analyzed via principal component analysis (Kirschvink, 1980) using the IAPD software (Torsvik et al., 2000).

Representative sample fragments from each site were ground into a fine powder and analyzed on a KLY-3S susceptibility bridge with a CS-3 heating unit in order to characterize the magnetic carriers in the samples.

3.2. Geochronologic methods

We analyzed two alkaline to doleritic dyke samples from Anantapur district, Andhra Pradesh and two samples of granitic material from the Barmer district in Rajasthan for their U–Pb isotopic signatures. Using standard gravity and magnetic separation techniques, zircon grains were concentrated from pulverized samples in various laboratories at the University of Florida. The samples were first crushed, then disk milled and sieved to <80 μm (dolerites) or >80 μm (granites) grain size. The fractions were then rinsed, followed by water table treatment with slow sample feed rates. This was followed by heavy liquid mineral separation with multiple agitation periods to reduce the number of entrapped grains in the lower density fraction. Finally, the sample is repeatedly passed on a Frantz Isodynamic magnetic separator up to a current of 1.0 A (2–4° tilt). Approximately 20–30 fresh looking (clear), euhedral to nearly anhedral zircon grains were handpicked from the two samples of the same site labeled I595 (dolerite) and 10 subhedral to euhedral zircon grains from the Barmer sample under an optical microscope to ensure the selection of only the clearest grains and fractions of grains. Further hand-picking of the grains reduced the number to only four to five good grains from the Anantapur dolerites and eight grains from the Barmer granitoids. The zircons were then mounted in resin and then polished to expose median sections. Further sonication and cleaning of the plugs in nitric acid (HNO_3) helped to remove any common-Pb surface contamination.

U–Pb isotopic analyses were conducted at the Department of Geological Sciences (University of Florida) on a Nu Plasma multicollector plasma source mass spectrometer equipped with three ion counters and 12 Faraday detectors. The MC–ICP-MS is equipped with a specially designed collector block for simultaneous acquisition of ^{204}Pb (^{204}Hg), ^{206}Pb and ^{207}Pb signals on the ion-counting detectors and ^{235}U and ^{238}U on the Faraday detectors (see Simonetti

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et al., 2005). Mounted zircon grains were laser ablated using a New Wave 213 nm ultraviolet beam. During U–Pb analyses, the sample was decrepitated in a He stream and then mixed with Ar-gas for induction into the mass spectrometer. Background measurements were performed before each analysis for blank correction and contributions from ^{204}Hg. Each sample was ablated for ∼30 s in an effort to minimize pit depth and fractionation. Data calibration and drift corrections were conducted using the FC-1 Duluth Gabbro zircon standard. Data reduction and correction were conducted using a combination of in-house software and Isoplot (Ludwig, 1999). Additional details can be found in Mueller et al. (2008).

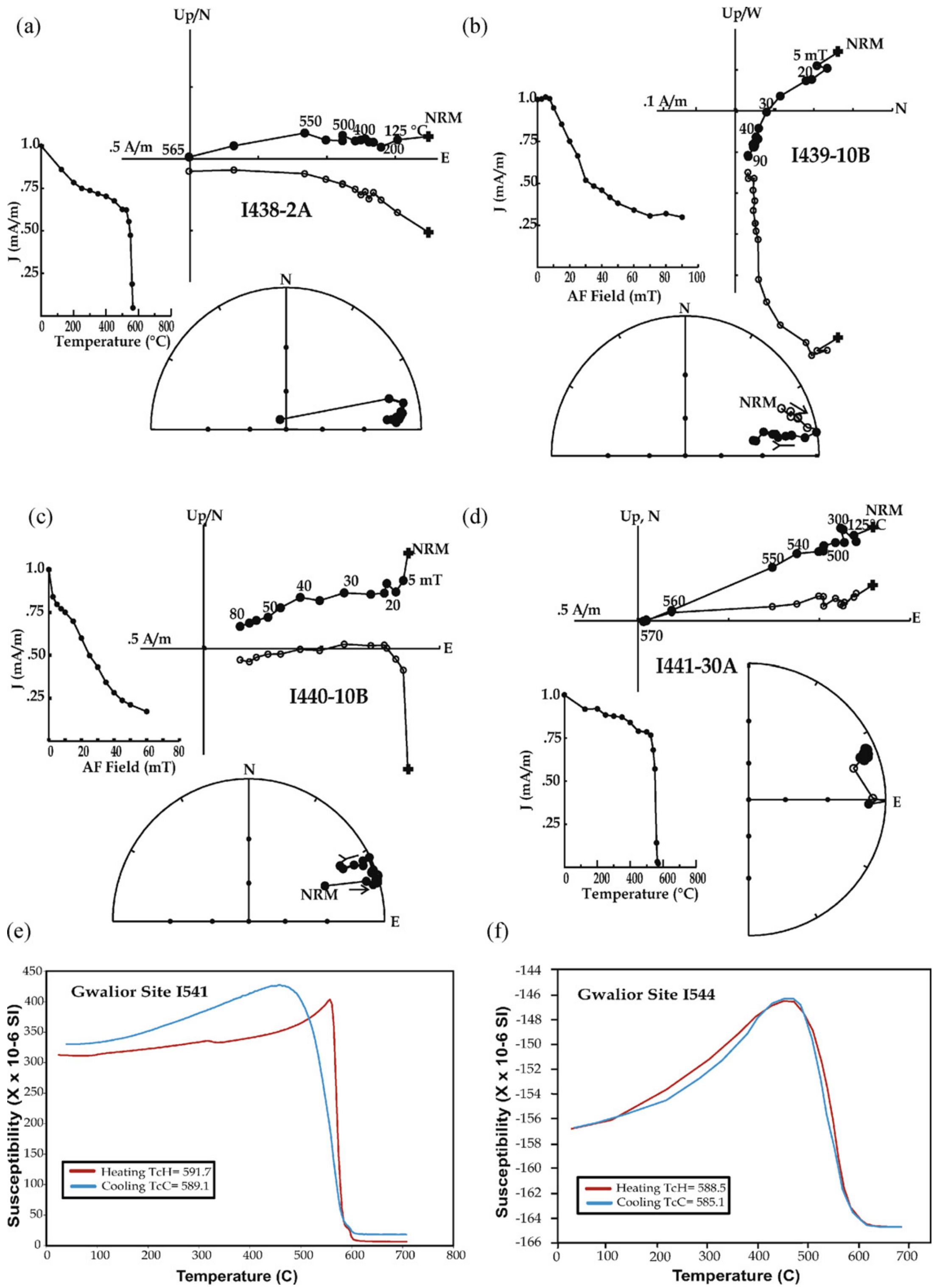

Fig. 4. Paleomagnetic data of the Gwalior volcanics showing (a) thermal demagnetization behavior at the site 38. (b) Alternating field demagnetization behavior at the site 39. This sample shows a great circle trajectory toward the East and down. (c) Alternating field demagnetization behavior at the site 40. (d) Thermal demagnetization behavior at the site 41. Curie temperature runs for selected samples in this study. (e) Dyke sample I541 showing a heating Curie temperature of 591.7 °C and a cooling Curie temperature of 589.1 °C; (f) Dyke sample I544 with a heating Curie temperature of 588.5 °C and a cooling Curie temperature of 585.1 °C.

Table 1
Gwalior results.

Site/study	N	Dec	Inc	k	α95
Athavale et al. (1963)	7	70°	3°		18°
Klootwijk (1974)	23	78°	34°	369	5°
McElhinny et al. (1978)	12	78.5°	25.8°	48	6.3°
Site 38—this study	13	81.3°	11.7°	89.4	4.4°
Site 39—this study	8	73.5°	10.8°	44	8.5°
Site 40—this study	12	71.8°	0.0°	195	3.1°
Site 41A—this study	10	71.2°	−10.3	52	6.7°
Site 41B—this study	5	72.5°	−19.3	588	3.2°
Site 41C—this study	6	72.9°	−3.8	79	7.6°
Lower trap mean	21	72.2°	−11.1	107.2	12°
Upper trap mean	75	75.4°	14.2°	34.9	11.6°
Overall mean	96	74.3°	5.8°	22	11.2°
Tilt-corrected mean	96	73.9°	4.4°	22	11.2°

N = number of samples used; k = kappa precision parameter; α95 = cone of 95% confidence about the mean direction. Site 41A, B and C are from the lower traps all other are from the upper traps.

4. Paleomagnetic and geochronologic results

4.1. Gwalior traps region

The Gwalior traps of the Bundelkhand craton are exposed near the city of Gwalior (Fig. 3) and are assigned to the Morar Subgroup (Gwalior Group). The traps are found at two levels within the Morar Subgroup and are separated by sedimentary rocks. The lower part of the traps consists of two or more eruptions and the upper zone of the traps consists of a 160-m-thick sequence of multiple flows. The rocks have experienced little deformation and have a low 3–5° northerly dip. The Gwalior traps are correlated with the Bijawar traps (Athavale et al., 1963; Chakrabarti et al., 2004). Crawford and Compston (1969) reported a Rb–Sr age of 1798 ± 120 Ma (using the revised ^{87}Rb decay constant of 1.42×10^{-11} year^{-1}) for the upper traps. Mafic sills in the Gwalior basin have Rb and K–Ar ages of 1775–1790 Ma (Ramakrishnan and Vaidyanadhan, 2008). While none of these ages are robust estimates, we also note that some preliminary paleomagnetic data from 1883 Ma dykes (dated by French et al., 2008) indicate slightly higher paleolatitudes and suggest that the northern cratons of India may have undergone slow rotational and latitudinal motion between 1883 and 1780 Ma.

4.1.1. Paleomagnetic results

We resampled the Gwalior traps in the Bundelkhand craton. Previous studies on the Gwalior traps were based on a limited number of samples from the upper traps in the Gwalior Fort region (Athavale et al., 1963; Klootwijk, 1974; McElhinny et al., 1978). Both Klootwijk (1974) and McElhinny et al. (1978) described a shallow low-coercivity component and a slightly steeper high-coercivity component directed toward the east and down. These authors used blanket demagnetization rather than vector analysis.

We sampled four new sites of the trap volcanics (see Table 1) and applied stepwise demagnetization techniques. One of these sites (41) was a recently opened quarry that contained 3 distinct flow horizons in the lower traps (A–C). Fig. 4 shows typical demagnetization results from the Gwalior volcanic rocks.

The mean results from all studies are shown in Fig. 5. Our results largely confirm the previous studies although our directions are somewhat shallower than the high-coercivity components reported by Klootwijk (1974) and McElhinny et al. (1978). The Gwalior traps are all of a single polarity and our combined tilt-corrected mean result has a declination = 73.9° and an inclination of +4.4° (k = 22, α95 = 11·2°). The paleomagnetic pole was calculated using a site location of 26°N, 78°E and is located at 15.4°N, 173.2°E (dp = 5.6°, dm = 11.2°; see Table 1).

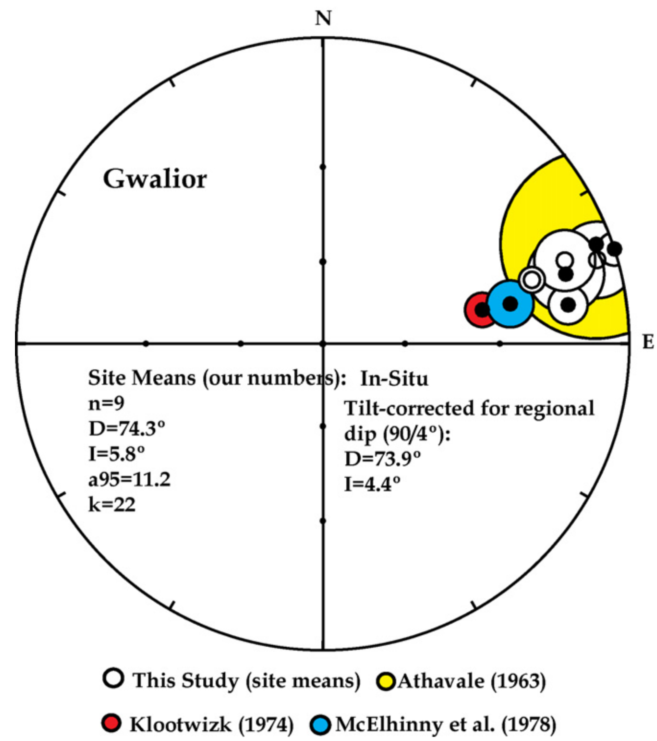

Fig. 5. Stereoplot of site mean directions from our study (white shading), the mean of Athavale et al. (1963, yellow shading), Klootwijk (1974, red shading), and McElhinny et al. (1978, blue shading). The overall mean based on nine sites yields an in situ declination of 74.3° and an inclination of 5.8°. Correction for regional tilt (strike: 90, dip: 4) yields a tilt-corrected mean of 73.9°/4.4°. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Rock magnetic studies were also performed to constrain the magnetic mineralogy of the dyke samples. Most of the sites show unblocking temperatures ranging between 550 and 590 °C (Fig. 4a–d) indicative of titano-magnetite. A sharp drop in susceptibility occurred in most of the samples during heating at temperatures between 550 and 580 °C; suggests the presence of magnetite (Fig. 4e and f).

Unfortunately, exposures of the Gwalior volcanics are limited and there are no field tests that can be conducted to ascertain whether or not the remanence is primary, so the results should be viewed with caution. In addition, the age cited above by Crawford and Compston (1969) has a large error (120 Ma). Our best estimate for the age of the Gwalior pole is thus ∼1.8 Ga.

4.2. Anantapur dykes region

The Anantapur district lies to the west of the Cuddapah basin (Fig. 6a and b). Granitoids, gniesses and schists of Archaean to Paleoproterozoic age (2.9–2.1 Ga) constitute the basement lithogies in the area. The basement is intruded by a number of dyke swarms of different ages (1.9–1.7 Ga, 1.5–1.3 Ga and 1.2–1.0 Ga) and directions (NE–SW, ENE–WSW or NW–SE). Some of these dykes are over 150 m wide and tens of kilometers in length. The larger dykes can be seen as persistent linear ridges, surrounding the Paleo-Mesoproterozoic intracratonic Cuddapah basin (Karunakaran, 1971; Halls, 1982; Drury, 1984; Murthy et al., 1987; Poornachandra Rao, 2005). Most of these dykes abruptly terminate at the boundary of the Cuddapah basin and are thus thought to be older than the basin (Kumar and Bhalla, 1983; Balakrishna et al., 1979; Bhattacharji and Singh, 1981). A close scrutiny of the field, petrographic, geochemical and radiometric data on these dykes suggest three major phases of dyke emplacement (all poorly dated) between Paleo-Neoproterozoic (1900–1700, 1500–1300 and 1200–1000 Ma) around the Cuddapah basin (Chalapathi Rao et al., 2005). The majority of these dyke swarms are dolerite and gabbro along with a few intrusions of peridotite, syenite and granophyres. The dykes are fine to coarse-grained with subophitic to ophitic or granular textures and tholeiitic to alkaline in compositions (Balakrishna et al., 1979; Kumar and Bhalla, 1983; Halls, 1982; Murthy, 1987; Murthy et al., 1987; Chalapathi Rao et al., 2005). The Anantapur gneissic basement is also intruded by a diamondiferous kimberlitic and lamproitic cluster at ∼1100 Ma (Chalapathi Rao et al., 2004). The older (∼1900 Ma) of the igneous intrusions are thought to coincide with the thermal events responsible for the initiation and development of intracratonic Cuddapah basin of the Peninsular India.

We sampled the E–W to ENE trending granular to coarse-grained, alkaline to tholeiite dykes from the southwestern region of Anantapur for zircon dating (site I595) and paleomagnetic studies (site I589, I594 and I5103; Fig. 6). Kumar and Bhalla (1983) also conducted a paleomagnetic study on ENE–WSW and NE–SW trending doleritic dykes in the region.

4.2.1. Geochronologic results

U–Pb ages from the zircon were determined for the E–W trending alkaline dolerite dyke sample I595 (Fig. 6). Only one of the two

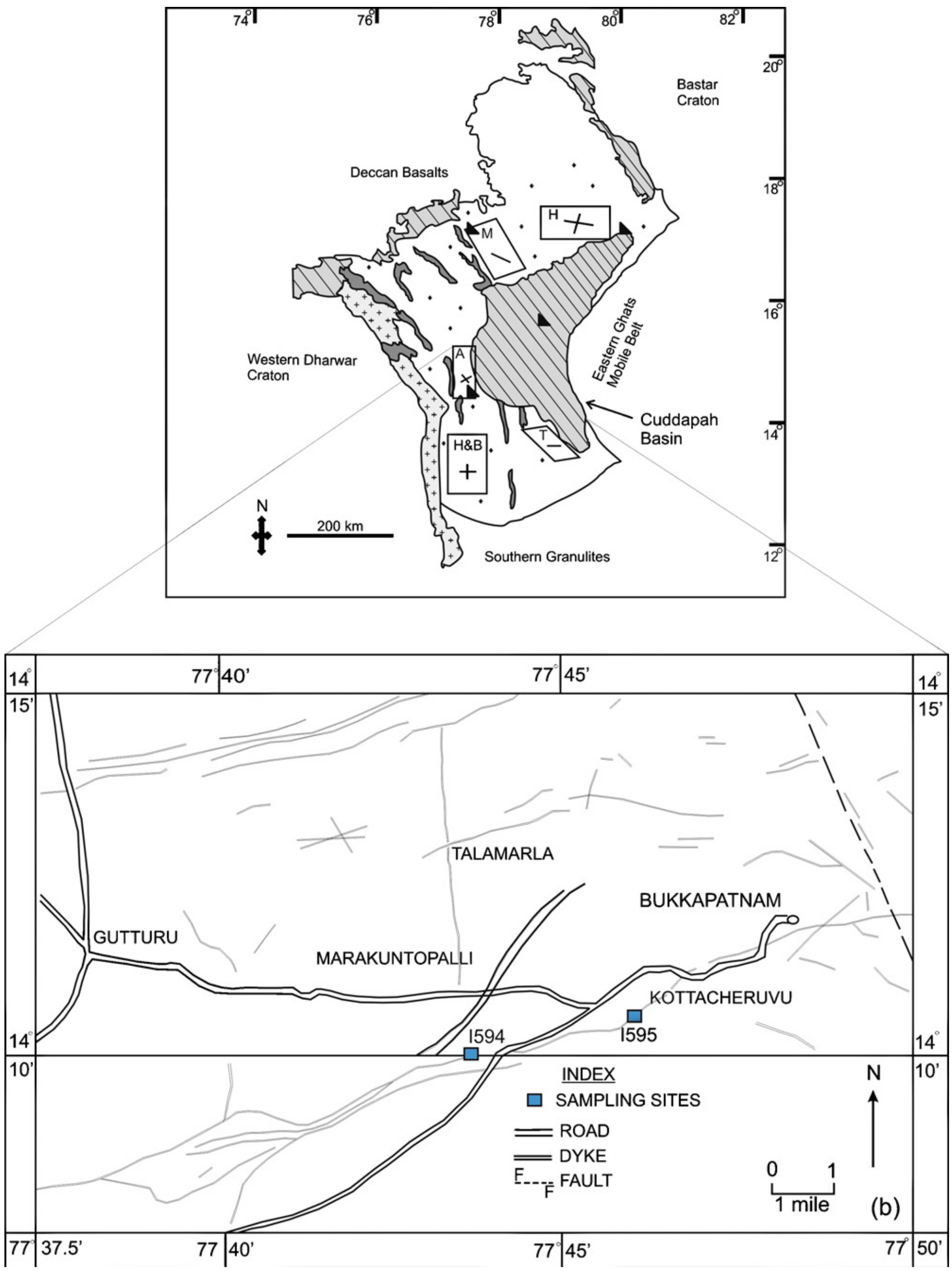

Fig. 6. (a) Sketch map of the Eastern Dharwar craton. Archaen assemblages associated with cratonization are shown here. Abbreviations for schist belts are as follows: Sa = Sandur, KKJH = Kolar–Kadiri = Jonnagiri–Hutti, RPSH = Ramagiri–(Penakacheria–Sirigeri)–Hungund, and VPG = Veligallu–Raichur–Gadwal superbelt. The dotted and dashed line indicates possible location under the basin. Dashed lines represent Paleozoic to more recent sedimentary cover (modified from Naqvi and Rogers, 1987). Dyke intrusions into the EDC are H&B = Harohalli and Bangalore swarm; A = Anantapur swarm; M = Mahbubnagar swarm; H = Hyderabad swarm. (b) Enlarged sketch map of the Anantapur region in Andhra Pradesh showing the location of dikes used in this study including the Great dyke of Bukkapatnam (after Murthy, 1995). Geochronologic sample that yielded zircons is I595 (blue box). Sites I594 and I595 (blue boxes) are also studied for paleomagnetic analyses. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

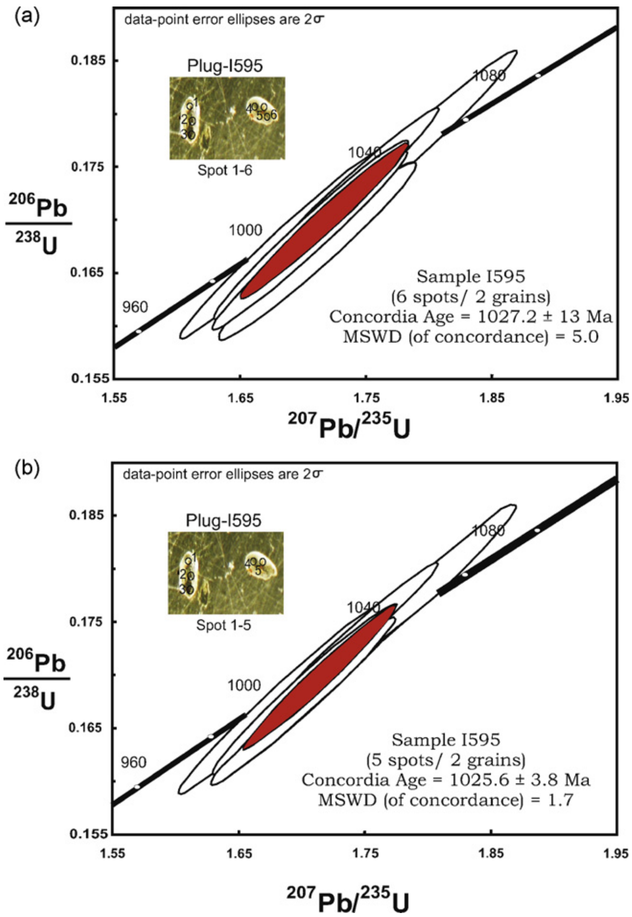

Fig. 7. (a) U–Pb concordia diagram for the six spots from the concordant zircons from sample I595 yielding an age of 1027.2 ± 13 Ma (2σ; MSWD = 5.0). Photo of zircon grains from plug I595 grains 1–6 (Appendix A). (b) U–Pb concordia diagram for the five spots from the concordant zircons from sample I595 yielding an age of 1025.6 ± 3.8 Ma (2σ; MSWD = 1.7). Photo of zircon grains from plug I595 grains 1–5 (Appendix B).

samples yielded two well-faceted zircon and several fragments/tips of zircon (Fig. 7).

Six laser spots from the two euhedral zircons (sample I595) yielded a concordant U–Pb age of 1027.2 ± 13 Ma (2σ; MSWD = 5.0; Fig. 7a). One of the six spots was slightly more discordant (3%) than the other five (all less than 1% discordant) and an age calculated from these five spots yielded a more precise age of 1025.6 ± 3.8 Ma (2σ; MSWD = 1.7; Fig. 7b; Table 2).

4.2.2. Paleomagnetic results

The NRM of most of the Anantapur dykes formed well grouped clusters and yielded fairly consistent paleomagnetic directions that further improved with cleaning. Our sites yielded intermediate to shallow inclination that are similar to those obtained by previous workers from the area (Kumar and Bhalla, 1983; Rao, 2005; Table 3). Dyke I595 that yielded a concordant U–Pb age of 1025.6 ± 3.8 Ma

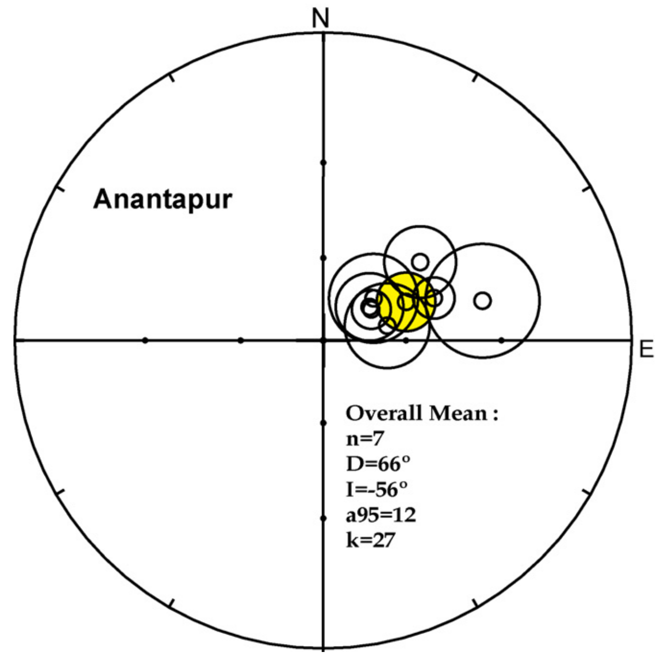

Fig. 8. Stereoplot of site mean directions from our study (Anantapur site I595), the mean of Kumar and Bhalla (1983) and Poornachandra Rao (2005). The best overall mean based on 8 sites yields an in situ declination of 66° and an inclination of −56° ($\alpha95$ = 12; k = 27; shaded yellow).

also yielded a mean declination = 76.9° and inclination = −50.6° (k = 19.23, $\alpha95$ = 12°; N = 9; Fig. 8).

Previous paleomagnetic, geochemical and petrologic characteristics studies indicated at least three phases of dyke emplacement in the region (Murthy, 1987; Kumar and Bhalla, 1983; Chalapathi Rao et al., 1996; Poornachandra Rao, 2005). The combined mean direction of site I595 and dyke (ii) of Kumar and Bhalla (1983) is intermediate and up to the east with a declination = 77° and inclination = −66° (k = 35, $\alpha95$ = 15°; N = 4). Paleomagnetic results on the E–W to N–E trending dykes reported by Poornachandra Rao (2005) from the vicinity of Anantapur district also yielded consistent intermediate up directions to the east (Fig. 9, Table 3). The overall mean from eight of these sites including ours (I595) gave a VGP at 10°N and 211°E with a mean declination = 65° and inclination = −57° (k = 31, $\alpha95$ = 10°; Fig. 8, Table 3).

The older set of E–W trending dykes yielded an overall mean VGP at 28°N and 176°E with a mean declination = 61° and inclination = −0.5° (k = 33, $\alpha95$ = 14°; Fig. 8, Table 3).

Thermal demagnetization on our samples indicated unblocking temperatures between 580 and 590 °C, consistent with low-Ti magnetite as the main carrier of magnetization (Fig. 9a–d). This was confirmed in the Curie temperature runs (Fig. 9e and f) that show a sharp loss in magnetic susceptibility at temperature ranges of 570–590 °C that is characteristic of magnetite. In the absence of any robust field tests to confirm a primary magnetization, we note that the results presented in this paper should be considered preliminary.

Table 2
Anantapur geochronologic results.

Grain	$^{207}Pb/^{206}Pb$	1σ error	$^{206}Pb/^{238}U$	1σ error	$^{*207}Pb/^{235}U$	1σ error	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	% Disc	RHO
I595_1	0.0677124	0.0001	0.14783	0.00087	1.40979	0.0820	1002	19	1013	13	1039	7.9	1	0.982355
I595_2	0.0673486	0.0002	0.14872	0.00083	1.27409	0.1000	1008	19	1013	13	1028	8.4	1	0.979570
I595_3	0.0668359	0.0001	0.14760	0.00140	1.70992	0.1900	1001	20	1004	14	1012	7.8	0	0.984771
I595_4	0.0677586	0.0001	0.15586	0.00088	1.45505	0.0230	1052	20	1048	13	1040	7.7	0	0.982914
I595_5	0.0672164	0.0001	0.15135	0.00078	1.35673	0.0240	1024	19	1023	13	1024	7.4	0	0.984055
I595_15	0.0683800	0.0002	0.14698	0.00089	1.75198	0.1400	997	19	1015	13	1058	10	2	0.972800

Table 3
Anantapur results.

Site	N	Dec	Inc	k	α95	Plat	Plong	Reference
Younger Dykes (E–W)								
DT2	5	76°	−34	14.8	16.3°	8°N	189°E	Poornachandra Rao (2005)
D8	6	69°	−48	72.4	6.7°	10°N	201°E	Poornachandra Rao (2005)
D29	5	50°	−66	19.9	15.7°	13°N	226°E	Poornachandra Rao (2005)
D30A	5	51°	−46	30.1	11.4°	25°N	208°E	Poornachandra Rao (2005)
DT1	5	54°	−69	27	12.1°	8°N	228°E	Poornachandra Rao (2005)
D32	5	258°	57	10	20°	0°N	27°E	Poornachandra Rao (2005)
Dyke (ii) + I5145	4 sites	76.7°	−66.4	35	15°	2°S	217°E	Kumar and Bhalla (1983) + this study
Dyke (i)	5	57°	−69	52	7°	8°N	225°E	Kumar and Bhalla (1983)
Older Dykes E–W								
Dyke (iii)	12	64°	−7	142	8°	24°N	178°E	Kumar and Bhalla (1983)
Dyke (iv)	6	53°	−8	142	6°	34°N	183°E	Kumar and Bhalla (1983)
I594	14	46°	5.1°	27.9	7.6°	45°N	177°E	This study
I5103	7	79°	1.3°	12.12	18.1°	11°N	169°E	This study
I589	8	241°	−6.4	36.03	9.4°	29°N	171°E	This study
Overall mean-younger	8 dykes	65.2°	−57	31	10°	10°N	211.4°E	This study
Overall Mean-Older	5 dykes	61°	−0.5	33	14°	28°N	176° E	This study

Dec = declination; Inc = inclination; k = kappa precision parameter; α95 = cone of 95% confidence about the mean direction; Plat = Pole Latitude; Plong = Pole Longitude.

4.3. Malani Igneous Suite basement and early Plutonism

The Malani Igneous Suite (MIS) is exposed over a large area in NW India (Fig. 10); however, most of the region is covered by alluvial sands and the outcrop density is very low. The MIS felsic volcanics and granites are seen as isolated tors, ridges and hills. The mutual relationships between different phases of MIS magmatism are unclear due to the cover and not much is known about

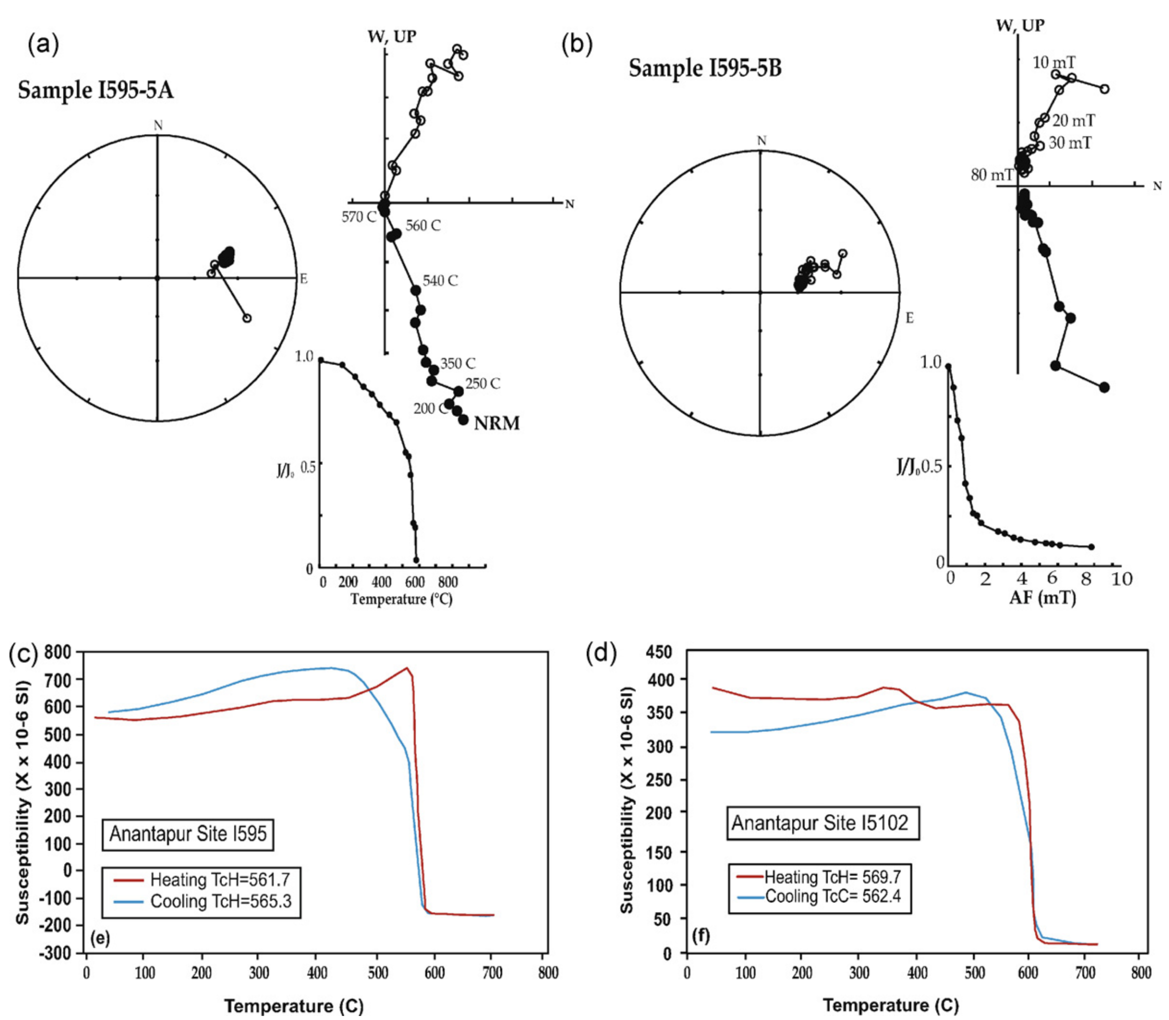

Fig. 9. (a) Thermal demagnetization behavior of Anantapur dyke sample I590-9b. (b) Alternating field demagnetization behavior of the dyke sample I590-8. (c) Thermal demagnetization behavior of the dyke sample I595-5A. (d) Alternating field demagnetization behavior of the dyke sample I595-5B. Curie temperature runs for selected samples in this study (e) Anantapur dyke sample I595 showing a heating Curie temperature of 561.7 °C and a cooling Curie temperature of 565.1 °C; (f) Anantapur dyke sample I5102 with a heating Curie temperature of 569.7 °C and a cooling Curie temperature of 562.4 °C. In all the stereoplots open/closed circles represent up(−)/down(+) inclinations.

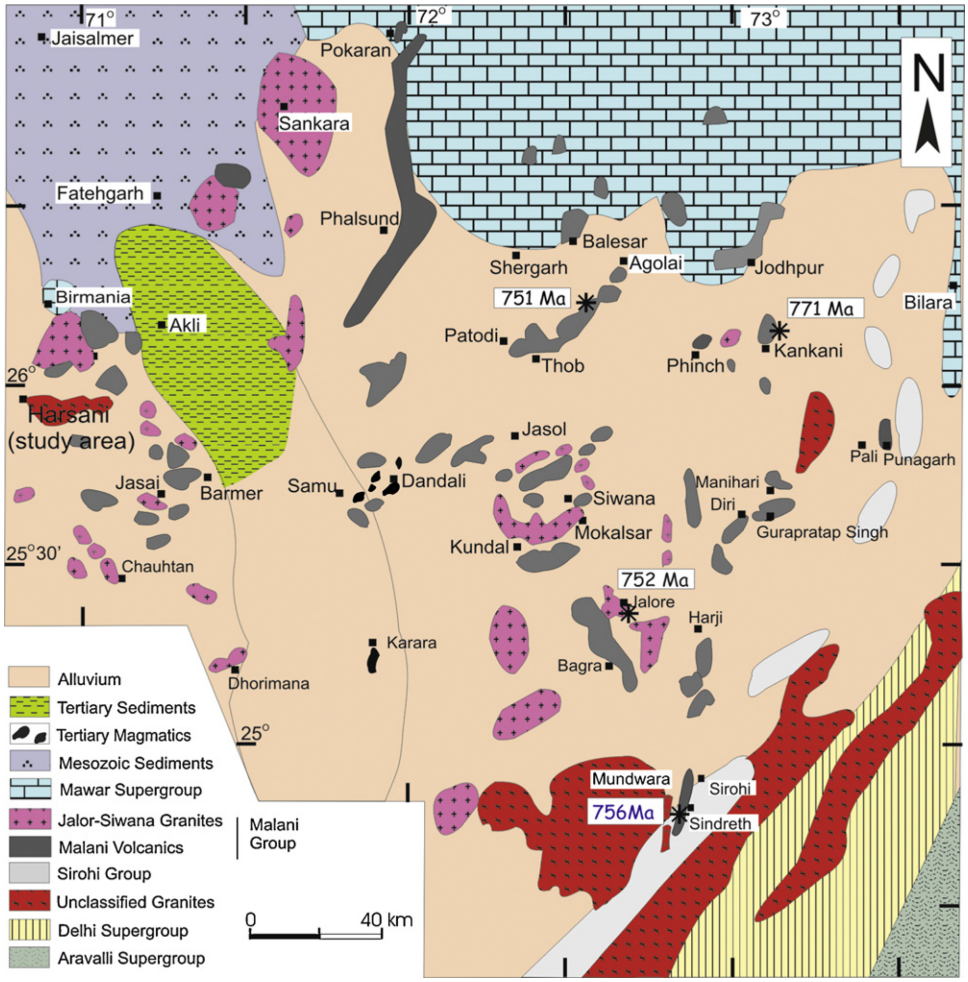

Fig. 10. Sketch map showing Precambrian stratigraphic units of the western part of the Aravalli mountain region and in NW India with sampling area of Harsani granodiorite (adapted from GSI publications and other published work).

the 'basement' for the MIS. Geochronologic results on the rhyolitic phase of Malani activity is taken from a 771 ± 5 Ma U–Pb age (Gregory et al., 2009). The duration of magmatism is unclear though Gregory et al. (2009) suggested that it lasted from ∼771 to 751 Ma on the basis of correlation (and U–Pb ages) with igneous activity in the Seychelles (Torsvik et al., 2001b). Van Lente et al. (2009) suggested a connection between the coeval Sindreth and Punagarh felsic volcanism of southwestern Aravalli craton and MIS on the basis of the U–Pb isotopic ages of 767–761 Ma reported from the Sindreth rhyolites. The closing age of Malani magmatism is less clear. Granitic bodies such as the Jalore and Siwana are considered to be a part of the MIS on the basis of reported Rb–Sr ages (727–698 Ma; Rathore et al., 1996, 1999), geological and geochemical considerations (Eby and Kochhar, 1990; Pandit and Amar Deep, 1997). Laul and Balakrishnan (2007) reported a Sm–Nd isochron age of 813 ± 13 Ma from the Siwana granite, which is approximately 90 million years older than the previously reported Rb–Sr whole rock ages (see Dhar et al., 1996; Rathore et al., 1996). Recently, Just et al. (submitted for publication) have argued for a time interval of ∼50 million years between Erinpura Granite (pre-Malani) and the MIS, on the basis of monazite ages of Erinpura granite.

The basement rocks for MIS in the southwestern part are represented by ground level outcrops ∼50 km west of Barmer town (Fig. 10). These rocks can be described in terms of three temporal assemblages, trondhjemitic gneiss, migmatized diorite and granodiorite (Pandit et al., 1999). The oldest unit is a well-foliated trondhjemitic gneiss (quartz, biotite, oligoclase–andesine and subordinate K-feldspar). The trondhjemitic gneiss is characterized by high silica (>73%), moderate alumina (13.6–14.4%), low to moderate MgO (0.5–0.74%) and CaO (1.54–2.23%) and a high Na_2O/K_2O ratio (1.76–2.23). The migmatized diorites are exposed only within depressions and streambeds and include a fine-grained amphibole rich mafic component and a plagioclase-rich relatively coarse-grained neosome.

The youngest assemblage of the supposed pre-Malani basement, the Harsani granodiorite, is exposed as minor NE-trending knolls to the east of village Harsani. The Harsani granodiorite is a medium grained and crudely foliated rock with predominant plagioclase (oligoclase), quartz, perthite and hornblende. The granodiorites are geochemically distinct from the trondhjemitic gneisses in terms of relatively lower silica (61.24–67.4%), moderate to high alumina (15.42–15.84%), higher MgO (1.26 to 1.56%) and CaO (2.75–3.06%) and lower Na_2O/K_2O ratios (1.16–1.81). However, both are clearly distinct from the undeformed, highly siliceous, alkali-rich, CaO- and MgO-poor Malani rhyolites (including felsic tuffs) and granites.

The trondhjemitic gneiss is cut by Malani rhyolite dykes. Although no direct relationship between trondhjemitic gneisses and granodiorites could be observed due to extensive sand cover, some indirect field relations have been utilized by Pandit et al. (1999) to assign an older Archean age to the trondhjemitic gneiss and a pre-Malani age to the granodiorite.

We analyzed zircons from the Harsani granodiorite for U–Pb geochronology to further constrain the lower age limit of MIS activity.

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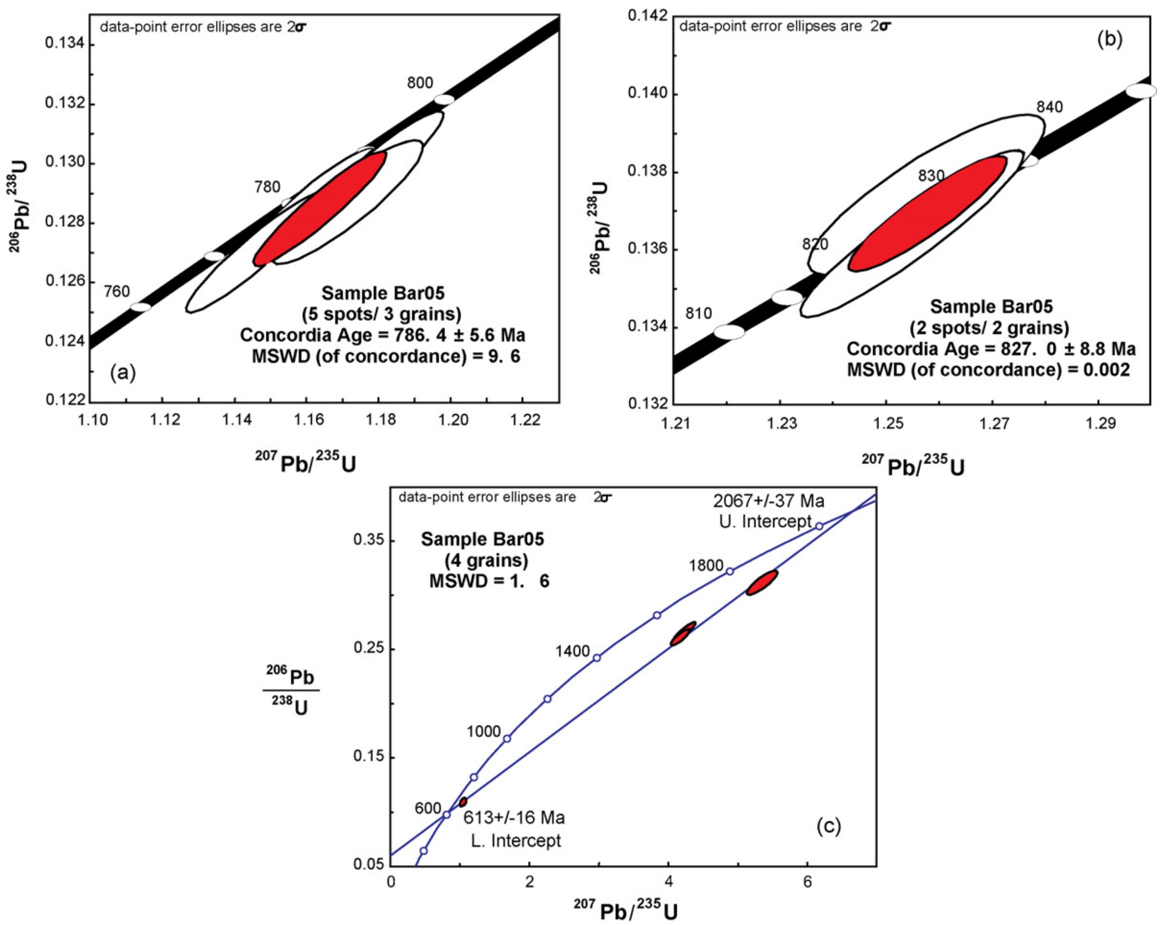

Fig. 11. (a) U–Pb concordia diagram for the five spots from three concordant zircon fragments and tips from sample Bar05 yielding an age of 786.4 ± 5.6 Ma (2σ) with a relatively large MSWD = 9.6. (b) U–Pb concordia diagram for the two spots from two concordant zircons from sample Bar05 yielding an age of 827.0 ± 8.8 Ma (2σ; 0.96 probability of concordance). (c) Discordia plot using other four fragmentary zircons from Bar05. The lower intercept age is 613 ± 16 Ma and the upper intercept age is 2060 + 37/−38 Ma (MSWD = 1.6).

4.3.1. New geochronologic results

A total of 10 zircon grains/pieces were recovered from the Harsani granodiorite (Fig. 11). Only one of the grains was euhedral and well-faceted and we were able to obtain two laser spots on this zircon. These two spots yielded a concordant age of 827.0 ± 8.8 Ma (2σ; 0.96 probability of concordance). Five other grains (tips) yielded a concordant age of 786.4 ± 5.6 Ma (2σ) with a relatively large MSWD = 9.6. In addition, four other grains yielded highly discordant ages with a lower intercept of 613 ± 16 Ma and an upper intercept age of 2060 + 37/−38 Ma (MSWD = 1.6; Table 4).

Our interpretation of these data is that the 827.0 ± 8.8 Ma age closely approximates the time of intrusion of the granodiorite and the 786.4 ± 5.6 Ma may relate to a disturbance of the U–Pb system at the onset of Malani volcanism. This is consistent with the reported ages of the coeval intermediate granitoid rocks (tonalites) forming the basement of Punagarh volcanics (Van Lente et al., 2009) that are correlated with the Erinpura granites (Choudhary et al., 1984;

Table 4
Barmer geochronologic results.

Grain	$^{207}Pb/^{206}Pb$	1σ error	$^{206}Pb/^{238}U$	1σ error	$*^{207}Pb/^{235}U$	1σ error	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	$^{207}Pb/^{206}Pb$	1σ	% Disc	RHO (error corr.)
Concordant (830 Ma)														
Bar05_14	0.104559	0.0004	0.796001	0.007	0.053964	0.0003	830	8	827	10	819	13	0	0.85
Bar05_17	0.103866	0.0005	0.758269	0.021	0.054239	0.0001	824	9	826	9	830	8	0	0.94
Concordant (786 Ma)														
Bar05_2	0.098418	0.0007	0.723274	0.012	0.053568	0.0001	784	9	789	10	804	8	1	0.95
Bar05_3	0.098691	0.0006	0.763438	0.011	0.053557	0.0001	786	9	790	9	803	9	1	0.94
Bar05_4	0.097705	0.0007	0.718155	0.009	0.053207	0.0001	778	9	781	9	789	8	0	0.95
Bar05_11	0.098071	0.0005	0.844853	0.034	0.053664	0.0002	781	8	788	9	807	11	1	0.9
Bar05_19	0.096751	0.0005	0.713415	0.011	0.053189	0.0001	771	8	776	9	789	8	1	0.94
Discordant grains														
Bar05_1	0.083196	0.0004	0.638326	0.011	0.055020	0.0001	669	7	714	8	859	8	6	0.94
Bar05_8	0.206235	0.0049	2.68271	0.095	0.093854	0.0010	1545	39	1696	47	1887	20	9	0.92
Bar05_9	0.203406	0.0033	2.66302	0.076	0.094257	0.0010	1526	28	1688	37	1895	20	10	0.86
Bar05_10	0.241246	0.0052	3.36606	0.120	0.101459	0.0014	1774	42	1893	52	2027	25	6	0.85

Deb et al., 2001; Laul and Balakrishnan, 2007) and preceded the outpouring of Malani rhyolites at around 771 Ma (Gregory et al., 2009). The discordant zircons reflect inheritance of an older basement component of Paleoproterozoic age. We place less significance on the lower intercept age but do note that others have suggested an Ediacaran-age thermal disturbance in the region (Rathore et al., 1999). Thus, it is thought that the main phase of rhyolitic magmatism in the Malani province occurred over a relatively short interval (∼20–30 Ma) and therefore the paleomagnetic pole derived from the Malani sequence should show very little latitudinal scatter (assuming normal plate motion speeds). Indeed, Gregory et al. (2009) show that data from mafic dykes are identical to that observed in the rhyolites. Additional paleomagnetic studies on the older phases of magmatism may help constrain motions between ∼800 and 771 Ma.

5. Discussion

The new paleomagnetic and geochronologic results outlined above are combined with the results from previous studies to provide a summary of the Proterozoic paleogeographic history of India.

5.1. Paleoproterozoic results (2.5–1.6 Ga)

A combined result for the poorly dated Paleoproterozoic Gwalior traps yields a paleomagnetic pole for India at 15.4°N, 173.2°E (dp = 5.6°, dm = 11.2°) using the reported age of ∼1.8 Ga (Crawford and Compston, 1969; Ramakrishnan and Vaidyanadhan, 2008). Our reconstruction using the new Gwalior paleomagnetic pole places Indian subcontinent at equatorial position with a paleolatitude of 2.2 ± 5.5°N. The other Paleoproterozoic poles used for our ∼1.8 Ga reconstruction come from Laurentia, Baltica, Amazonia, Australia and Kalahari (Fig. 12). Our reconstruction follows the paleogeographic configuration of Laurentia, Baltica and Amazonia at 1.83 Ga in the proposed model of "Hudsonland" (Pesonen et al., 2003; Williams et al., 1991). The intermediate latitudinal position of Laurentia in our reconstruction is defined by a mean VGP from the Sparrow dykes, Churchill Province and the Coronation Geosyncline (Pesonen et al., 2003). Meert (2002) places Laurentia at polar latitudes in his "closest approach" paleomagnetic model for the Paleo-Mesoproterozoic supercontinent "Columbia" at ∼1.7–1.5 Ga based on the paleomagnetic data from the Trans Hudson Orogenic belt (THO) of the Canadian Shield (Symons and MacKay, 1999). The absence of any rigorous field tests from THO makes the data less reliable. Our intermediate latitude position for Laurentia at ∼1.8 Ga is in accord with the paleomagnetically consistent paleogeography for Columbia proposed by Bispo-Santos et al. (2008) using the ∼1.8 Ga Dubawnt Group paleomagnetic pole of the Churchill Province. Although we do note that other interpretations are also possible for the position of Laurentia within Columbia configuration for this time period, in the absence of more robust data from the THO, we prefer the intermediate latitude position for Laurentia. The position of Baltica is constrained to be close to Laurentia by the well-defined paleomagnetic pole from the Haukivesi lamprophyres of Finland (Neuvonen et al., 1981). The Amazonian craton was located in the southern hemisphere within the Columbia supercontinent adjacent to Baltica and its position is defined by the mean VGP given in Pesonen et al. (2003). The position is also supported by a later configuration of Amazonia using the results obtained from the 1790 Ma Colider Suite (CS Pole) by Bispo-Santos et al. (2008). A Paleoproterozoic (∼1.8–1.85 Ga) connection between India, North China and Laurentia was proposed on the basis of the presence of contiguous unmetamorphosed and undeformed radiating mafic dyke swarms within Southern peninsular India, North China and Canadian Shield of North America (Hou et al., 2008; French et al., 2008). In their classic Columbia model, Zhao et al. (2004, 2005, 2006) also placed India and North China adjacent to each other, based on geologic similarities between the two cratons. The presence of similar aged orogenic belts in India and North China further reinforces the argument of their contiguity although, detailed geologic arguments favoring their proximity are lacking during Mesoproterozoic (Rogers, 1996; Rogers and Santosh, 2002; Zhao et al., 2002, 2004, 2006; Santosh et al., 2003, 2007, 2009a,b).

We do not include North China in our ∼1.8 Ga reconstruction due to the paucity of paleomagnetic data from North China at ∼1.8–1.9 Ga. Lastly, we do note that our Gwalior pole for India lacks robust age determination and while making any paleogeographic reconstruction using this pole, our interpretation relies upon the U–Pb age of 1798 ± 120 (Crawford and Compston, 1969). It is interesting to note that the VGPs from the older (∼1.9 Ga) mafic dykes of the southern Bastar craton and nearby Cuddapah basin from the adjacent Dharwar craton, India (French et al., 2008; Clark, 1983; and our own work) and our ∼1.8 Ga Gwalior traps do show a similar near-equatorial position for Indian subcontinent although the declinations differ by ∼60°.

The paleoconfiguration of Australia is not well defined during Paleoproterozoic. The paleopole position at 1.82 Ga for the Plum Tree Creek volcanics in the Pine Creek Orogen of northwestern Australia used in our reconstruction, falls at 29°S, 195°E and yields a low to intermediate paleolatitudinal position for northwestern Australia block (Idnurm and Giddings, 1988; Kruse et al., 1994; Idnurm, 2004). The low latitudinal position for Australia during Paleoproterozoic is also supported by the paleomagnetic data obtained by Schmidt and Williams (2008) from the Elgee siltstone and Pentecost sandstone of Kimberley Group. Pesonen et al. (2003) speculated that Australia was a part of "Hudsonland" (Columbia) at 1.77 Ga.

Paleomagnetic data from the Kalahari craton is sparse for the Paleoproterozoic like many other continental blocks. At ∼1.8 Ga, the Kalahari craton was undergoing prolonged crustal accretion to form the proto-Kalahari craton by 1750 Ma according to the model by Jacobs et al. (2008). We use the only available 1.8–1.85 Ga

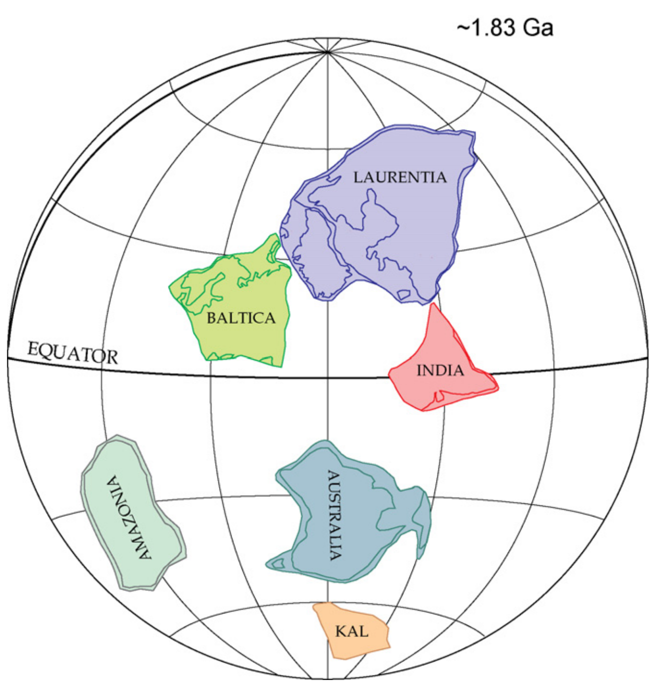

Fig. 12. Paleomagnetically based reconstruction at 1.83 Ga after (Pesonen et al., 2003). The Bundelkhand craton is positioned according to paleomagnetic data from the Gwalior volcanics reported in this paper (paleolongitudes are unconstrained). The reconstruction places India at equatorial positions with mid latitudinally located Laurentia within the Columbia supercontinent.

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Fig. 13. Reconstruction at ~1.2 Ga based on our new age from Harohalli Paleomagnetic pole and data reported in Pesonen et al. (2003) that places India at polar latitudes contiguous to Australia as compared to mid latitudinal positions of Laurentia, Siberia and Amazonia with North China at the equatorial positions (paleolongitudes are unconstrained).

Sebanga Poort dyke pole of Jones et al. (1976) in our reconstruction that position proto-Kalahari at intermediate to high latitudes. However, we are aware that this pole is not paleomagnetically well constrained.

5.2. Mesoproterozoic results (1.6–1.1 Ga)

The Mesoproterozoic period witnessed the disintegration of the Paleoproterozoic supercontinent Columbia and the subsequent amalgamation of the Early Neoproterozoic landmass Rodinia (Moores, 1991; Dalziel, 1991; Hoffman, 1991; Rino et al., 2008). The position of the Indian subcontinent in Rodinia configuration is debated. In archetypal Rodinia, India was attached to Australia and East Antarctica, similar to its Gondwanan configuration (Dalziel, 1991; Hoffman, 1991; Moores, 1991; Li et al., 1996; Torsvik et al., 1996; Weil et al., 1998). Later workers challenged this configuration on paleomagnetic and geological grounds and suggest that India was never a part of Rodinia supercontinent (Fitzsimons, 2000; Meert, 2003; Powell and Pisarevsky, 2002; Torsvik et al., 2001a,b). In this paper, we review our updated ~1.2 Ga paleomagnetic pole from the Harohalli alkaline dyke swarm at 24.9°S, 258°E ($\alpha95 = 15°$; Pradhan et al., 2008) in an attempt to better constrain the position of India during this period. Pradhan et al. (2008) reported concordant U–Pb age of 1192 ± 10 Ma that is far older than all previously published ages on the Harohalli and supposedly correlative dykes (Ikramuddin and Stuber, 1976; Anil Kumar et al., 1989; Devaraju et al., 1995). Discordant ages ranging from 580 to 1139 Ma was also calculated the zircon fragments of sample I5143 (Pradhan et al., 2008). Slightly discordant zircons form a tight grouping near 580–600 Ma region of concordia (Pradhan et al., 2008).

This new U–Pb radiometric age necessitates an almost 400 Ma revision in age of the Harohalli alkaline dykes. Fig. 13 shows 1.2 Ga reconstruction using our new Harohalli pole for India and other key paleomagnetic poles from Laurentia, Amazonia, North China and Australia. Laurentia is positioned at intermediate latitudes following the mean paleomagnetic pole calculated at ~1156 Ma (Pesonen et al., 2003). Amazonia is juxtaposed with the Llano segment of Laurentia's Grenville orogen using the recently dated ~1200 Ma Nova Floresta mafic sills pole reported by Tohver et al., 2002 (also see Cordani et al., 2009; Elming et al., 2009). Tohver et al. (2004a,b, 2005a,b, 2006) suggested a common Rodinian paleogeography for Amazonia and southern Laurentia at least since 1.2 Ga with Amazonian craton undergoing lengthy sinistral strike slip motion along the Grenville margin (i.e. present-day eastern North America). The North China (NC) craton occupies equatorial latitudes in our reconstruction using the mean BCP (Baicaoping Formation) pole at 1.2 Ga (Zhang et al., 2006). Within their APWP matching of NC with Laurentia during 1250–750 Ma, the 1200 Ma BCP pole falls between 1270 and 1100 Ma Laurentian poles (Zhang et al., 2006). However, these authors do suggest that the distantly located paleopoles from North China and Laurentia for 1200–1400 Ma periods imply non-coherence between them at 1.2 Ga. The combined paleomagnetic data from the mafic and metamorphic intrusive rocks of the Albany-Fraser orogen (Mt. Barren Group, Bremer Bay and Whalebone Plateau and Fraser dyke) place Australia at higher latitudes in ca 1.2 Ga configuration (Pisarevsky et al., 2003). An interesting observation from the paleomagnetic data of the ~1.2 Ga Harohalli dykes of the Dharwar craton is that it places India at polar latitudes adjacent to Australia although not in a traditional 'East Gondwana' configuration.

5.2.1. ~1.1–1.0 Ga reconstructions

The end of Mesoproterozoic and beginning of the Neoproterozoic era is recognized as the significant time period for the initiation of the breakup of the proposed Rodinia supercontinent followed by the assembly of Gondwana. We review our previously reported paleomagnetic and geochronologic results from the Upper Vindhyan sediments (Malone et al., 2008) and the Majhgawan kimberlite (Gregory et al., 2006) of Central India along with the newly reported geochronologic and paleomagnetic data from the Anantapur mafic dyke swarms, and the possible ~580 Ma paleomagnetic overprint of the Harohalli dykes of the Dharwar craton of the peninsular India to evaluate the paleogeographic configuration of Indian subcontinent during Neoproterozoic (~1.0 Ga to ~580 Ma).

The Vindhyan Basin in central Peninsular India is a large intracratonic sedimentary basin that provides target area to conduct the necessary paleomagnetic and geochronologic studies for Meso-Neoproetrozoic. In our efforts to constrain the depositional history of the basin and provide key paleomagnetic poles from India for the Neoproterozoic, we considered analyzed contemporaneous geochronologic and paleomagnetic results from the Upper Vindhyan sediments and the Majhgawan kimberlite that intrudes the lower part of the Upper Vindhyan sedimentary rocks (Gregory et al., 2006; Malone et al., 2008).

Malone et al. (2008) studied detrital zircon populations from the Bhander and Rewa Groups in the Vindhyan rocks of Rajasthan sector along with samples from the Lower Marwar Supergroup in Rajasthan to constrain the age of the Upper Vindhyan. Malone et al. (2008) noted that the youngest population of zircons from the Upper Bhander is older than 1000 Ma. This observation, coupled with the similarity in paleomagnetic directions from the Upper Vindhyan and the 1073.5 ± 13.7 Ma age of the Majhgawan kimberlite (Gregory et al., 2006), it is concluded that the Upper Vindhyan sedimentation was completed by ~1000 Ma, a result consistent with recent geochronologic data from the Chhattisgarh basin to the south (Patranabis-Deb et al., 2008; Basu et al., 2008). The paleomagnetic data from the Bhander and Rewa Groups of the Upper Vindhyan sequence yield pole positions that overlap with the Majhgawan kimberlitic pole (Gregory et al., 2006).

Our new geochronologic results of the tholeiitic to alkaline Anantapur dykes (1025.6 ± 3.8 Ma; Fig. 7b) fall into a similar age

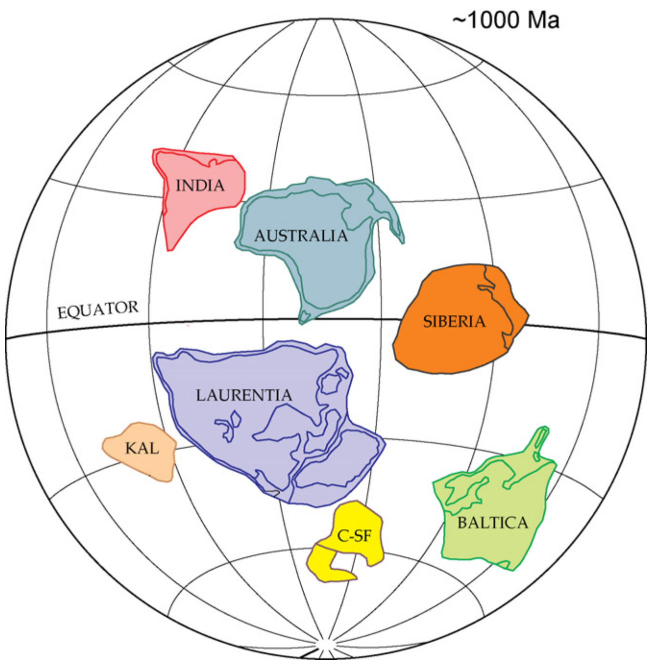

Fig. 14. Reconstruction at ~1.0 Ga using our new paleomagnetic data from the ~1.0 Ga dated Anantapur dykes of the Dharwar craton, India. The paleomagnetic poles for other continental blocks are taken from Pesonen et al. (2003). Our reconstruction places India (Anantapur dyke pole) and Australia (Bangemall sill pole) in contiguous positions.

bracket as those of magmatic events around Cuddapah basin. The overall mean of paleomagnetic directions from eight sites including ours (I595) from the Anantapur region gave a VGP at 10°N and 211°E (α95 = 10°; Fig. 9, Table 2).

Within the archetypal Rodinia configuration at around 1.1–1.0 Ga, Laurentia formed the core of the supercontinent with East Gondwana components lying at its present-day western margin while Baltica and Amazonia occupy its present-day eastern margin (Moores, 1991; Dalziel, 1991; Hoffman, 1991). However, the lack of reliable paleomagnetic data from the East Gondwana blocks prevents its precise placement within Rodinia. The paleogeographic reconstruction using our newly dated ~1.0 Ga Anantapur dyke pole places India at a paleolatitude of 37.6° N (Fig. 14). The other key paleomagnetic poles used for this configuration come from Laurentia, Siberia, Baltica, Australia, Congo-Sao Francisco and Kalahari. The occurrence of Grenvillian age collisional features in NW Baltica, NW Amazonia and NW Congo indicate the final docking of these blocks to Laurentia at 1.05 Ga (Pesonen et al., 2003). We used the Bangemall sills paleopole for Australia that is close to the AUSMEX fit of Wingate et al. (2002) at 1.05 Ma (Fitzsimons, 2002). Although India can be placed in close proximity to Australia due to longitudinal uncertainties, it is clear that the configuration does not favor an East Gondwanan configuration for these two blocks. The position and orientation of Siberia is considered controversial within Rodinia. Siberia is placed either adjacent to the northern margin of Laurentia (Hoffman, 1991; Condie and Rosen, 1994; Rainbird et al., 1998) or within Australia–Siberia–Laurentia fit along the western margin of Laurentia (Sears and Price, 2000).

5.3. *Neoproterozoic results (1000–570 Ma)*

The end of the Neoproterozoic era witnessed the breakup of the Rodinia supercontinent and nearly synchronous amalgamation of Gondwana around 530 Ma (Meert, 2001, 2003; Powell and Pisarevsky, 2002; Meert and Lieberman, 2004; Torsvik et al., 1996).

There are several competing models for the assembly of Gondwana that are reviewed in Meert and Lieberman (2008). East Gondwana is widely assumed to have been a single coherent entity since the end of the Mesoproterozoic (Powell et al., 1993; Dalziel, 1997; Weil et al., 1998; Yoshida, 1995; Yoshida et al., 2003). The apparent continuity of a Grenville-age (1100–1000 Ma) metamorphic belt along the Greater India–East Antarctica–Australia margin has generally been taken as evidence for no substantial movements of these cratonic blocks from their East Gondwana fit since 1.0 Ga. Meert and Van der Voo (1997) and Meert (2003) challenged the assumption of a coherent East Gondwana and suggested a multiphase amalgamation of the various cratonic blocks through a series of orogenic events spanning the interval from ~750 to ~530 Ma. Fitzsimons (2000) demonstrated that the proposed hypothesis of a single continuous late Mesoproterozoic orogenic belt along the African, Indian and Australian margins of Antarctica in Gondwana was incorrect and showed that there are three distinct late Mesoproterozoic–early Neoproterozoic orogenic belts.

Paleomagnetic data from the coeval Malani Igneous Suite (MIS) of India and Mundine well dyke swarms of Australia–Mawson continental blocks also indicates that these were not united until after 750 Ma (Torsvik et al., 2001a,b; Malone et al., 2008; Gregory et al., 2009; Wingate and Giddings, 2000). Our paleomagnetic data from the Malani dykes (Gregory et al., 2009) 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 dykes) argue strongly against a coherent East Gondwana at 750 Ma and explain the younger Pan-African belts between these cratons as the result of a final Ediacaran-age collision.

We also report a paleogeographic reconstruction at ~580 Ma. Paleogeographic reconstructions for this interval of time are highly controversial (Meert et al., 1994; Torsvik et al., 1996; Kirschvink et al., 1997) in part due to the apparent rapid motion of several cratonic blocks. Whether or not this rapid motion is due to plate motion, true polar wander or inertial interchange true polar wander is beyond the scope of this review; however, discussions regarding each of these mechanisms can be found in Kirschvink et al. (1997), Torsvik et al. (1998), Evans (1998), Meert (1999) and Meert and Tamrat (2004).

We use the average of our new paleomagnetic pole 76.5°S, 68.8°E (α95 = 15°) obtained from the overprint of the Harohalli dykes (Pradhan et al., 2008; Halls et al., 2007) and the mean Banganapalli paleomagnetic pole 73.48°N, 233.63°E (α95 = 5.2°) from the Kurnool Group (Goutham et al., 2006) to position India. The paleoconfiguration using this new Indian pole and other key paleomagnetic poles from the constituent cratonic nuclei of East Gondwana at 580 Ma (Fig. 15) places India at equatorial latitudes. We follow the model of Meert (2003) and place part of East Antarctica (Rayner Complex and Prince Charles Mtns.) adjacent to the Eastern Ghats margin of India. The other paleomagnetic poles used in our reconstruction at ~580 Ma come from Laurentia and the West Gondwanan blocks including Amazonia, West Africa, Congo-Sao Fansisco, Rio de-Plata and Kalahari (as in Tohver et al., 2006; Gray et al., 2006; Cordani et al., 2009).

On the basis of the paleomagnetic data from Australia–Mawson continental blocks, Powell and Pisarevsky (2002) suggest that these were not united until after 750 Ma. India and Western Australia could be in contact as early as 610 Ma, supported by the existence of Darling mobile belt, a sinistral shear that is consistent with an oblique collision of Greater India along the Western Australia margin (Powell et al., 1993). If our new pole is correct (and indeed ~580 Ma), then it is possible that

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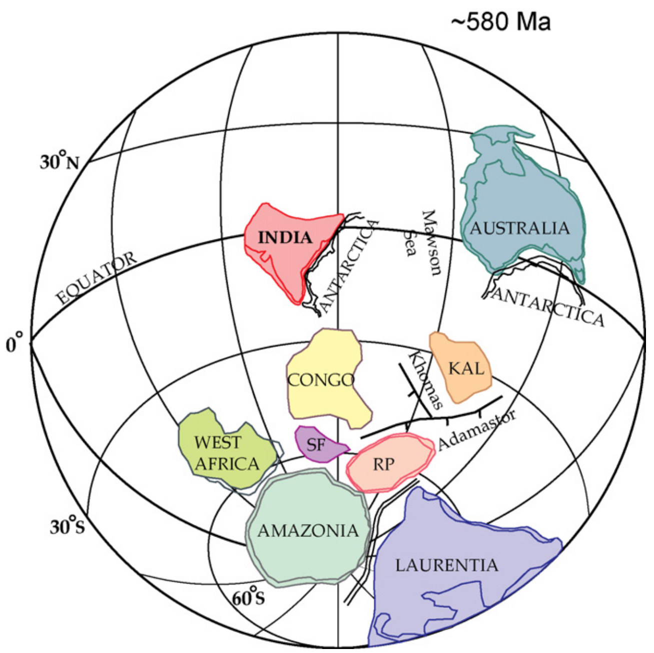

Fig. 15. Paleogeographic reconstruction based on the combined paleomagnetic poles from the younger discordant 580 Ma Harohalli overprint (Pradhan et al., 2008) and the coeval Banganapalli Quartzite of the Kurnool Group (Goutham et al., 2006). It places India at shallow equatorial latitude in close proximity to a part of Antarctica but separated from Australia via Mawson Sea. The other half of the East Antarctica microcontinent is attached to Australia based on its Elatina dyke paleomagnetic pole. The cratonic blocks within West Gondwana with Laurentia rifting away from Amazonia and Rio Plata (RP). Kalahari is separated from Congo-SF and Amazonia via Adamastor and Khomas oceans (modified from Gray et al., 2006).

India and Australia were either in contact or very close to one another by this time. Constraints on the positions of the western Gondwana blocks in our reconstruction are not based on paleomagnetic data and so the apparent discordance between the eastern Gondwana blocks and those from western Gondwana is an artifact of our placing the western blocks adjacent to present-day eastern Laurentia during the opening of the Iapetus Ocean (Fig. 15).

6. Conclusion

The new results reported in this paper from the Gwalior traps, the Anantapur dykes and the Harsani granodiorite, coupled with the previous studies done by our group emphasize that revisions in the Precambrian paleogeographic history of the Indian subcontinent are still in the early stages. We have presented some possible paleoreconstructions of India at ~1.8 Ga, 1.2 Ga, 1.0 Ga and 580 Ma. With the exception of the 580 Ma reconstruction, support for a traditional East Gondwana configuration with Himalayan margin of India adjacent to western Australia is precluded. Although most of our newer data need additional support, they are consistent with the model of Gregory et al. (2009) wherein the assembly of “East Gondwana” is coincident with the assembly of greater Gondwana during the Ediacaran–Early Cambrian time.

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