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Paleomagnetic analysis of the Marwar Supergroup, Rajasthan, India and proposed interbasinal correlations

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ABSTRACT

The Marwar Supergroup refers to a 1000–2000 m thick marine and coastal sequence that covers a vast area of Rajasthan in NW–India. The Marwar Basin uncomformably overlies the ~750–770 Ma rocks of the Malani Igneous Suite and is therefore considered Late Neoproterozoic to Early Cambrian in age. Upper Vindhyan basinal sediments (Bhander and Rewa Groups), exposed in the east and separated by the Aravalli–Delhi Fold Belt, have long been assumed to coeval with the Marwar Supergroup. Recent studies based on detrital zircon populations of the Marwar and Upper Vindhyan sequences show some similarity in the older populations, but the Vindhyan sequence shows no zircons younger than 1000 Ma whereas samples taken from the Marwar Basin show distinctly younger zircons. This observation led to speculation that the Upper Vindhyan and Marwar sequences did not develop coevally.

While there are alternative explanations for why the two basins may differ in their detrital zircon populations, paleomagnetic studies may provide independent evidence for differences/similarities between the assumed coeval basins. We have collected samples in the Marwar Basin and present the paleomagnetic results. Previous paleomagnetic studies of Marwar basinal sediments were misinterpreted as being indistinguishable from the Upper Vindhyan sequence. The vast majority of our samples show directional characteristics similar to the previously published studies. We interpret these results to be a recent overprint. A small subset of hematite-bearing rocks from the Jodhpur Formation (basal Marwar) exhibit directional data (Dec = 89° Inc = −1° α95 = 9°) that are distinct from the Upper Vindhyan pole and may offer additional support for temporally distinct episodes of sedimentation in these proximal regions. A VGP based upon our directional data is reported at 1°S 344°E (dp = 5°, dm = 9°). We conclude that the Marwar Supergroup developed near the close of the Ediacaran Period and is part of a larger group of sedimentary basins that include the Huqf Supergroup (Oman), the Salt-Range (Pakistan), the Krol–Tal belt (Himalayas) and perhaps the Molo Supergroup (Madagascar).

1. Introduction

The Neoproterozioc Era (1000–541 Ma) is marked by rapid changes in continental configurations (Meert et al., 1993, 2003; Kirschvink et al., 1997; Evans, 1998; Meert, 1999; Meert and Tamrat, 2004). Paleogeographic reconstructions for cratonic nuclei are highly contested, particularly for the periods following the breakup of the supercontinent Rodinia at 750 Ma and during the amalgamation of the southern supercontinent of Gondwana at 530 Ma (Torsvik et al., 1996; Weil et al., 1998; Li et al., 2008; Meert, 2003; Meert et al., 1995, Meert and Van der Voo, 1996; Meert and Lieberman, 2008; Meert and Torsvik, 2003; Collins and Pisarevsky, 2005). These two intervals of plate reorganization provide an important backdrop for the biological changes that took place during the Cambrian and are often cited as external triggers for the stimulation and proliferation of multicellular organisms (Hoffman et al., 1998; McCall, 2006; Meert and Lieberman, 2004, 2008; Lieberman and Meert, 2004; Santosh et al., 2013). Accordingly, knowledge of the distribution of the continents during the Neoproterozoic and more specifically, the Ediacaran (635–541 Ma) is salient for those attempting to understand the paleogeographic setting for the dawn of complex life. The sequence of events that led to the ultimate coalescence of the East Gondwana elements (India, East Antarctica, Australia, Madagascar, Sri Lanka, and the Seychelles) during the Ediacaran is a subject of considerable dispute with two competing hypotheses. The first asserts that the aforementioned cratons were fused together around 1300 Ma as "East Gondwana" and remained united throughout the breakup of Rodinia (Yoshida et al., 2003; Yoshida, 1995; Yoshida and Upreti, 2006; Squire et al., 2006). A

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united East Gondwana coalesced with West Gondwana around 530 Ma, and remained intact until the Mesozoic. The alternative view (espoused by Meert and Van der Voo, 1997; Meert et al., 1995; Meert, 2003; Gray et al., 2008; Pisarevsky et al., 2008) maintains that these cratons rifted separately during Rodinia breakup and were later assembled during several temporally distinct orogenic events along the eastern margin of Africa and interior regions of East Antarctica. A comparison of high quality paleomagnetic and geochronologic data from the different cratons will ultimately provide the means for resolving this debate.

Peninsular India is located in the central part of the Gondwana supercontinent and contains numerous exposures of Proterozoic-Early Cambrian sedimentary and igneous rocks that show great potential for paleomagnetic studies. In this study, we provide new paleomagnetic data from the Marwar Supergroup (NW India) and show that the Marwar is significantly younger than the Upper Bhander and Rewa Groups in the Vindhyan Basin.

2. Geologic setting of the Marwar Supergroup

Bhowmik et al. (2009) suggested that the pre-1.0 Ga Indian landmass consisted of at least three micro-continental blocks, the North Indian block, the South Indian Block and the Marwar block that were united by ~1.0 Ga (Fig. 1; Meert et al., 2010). Peak and retrograde stages of metamorphism are recorded in schistose rocks from the central domain of the Central Indian Sausar Mobile Belt at 1062 ± 13 Ma and 993 ± 19 Ma monazite ages (Bhowmik et al., 2012). The Aravalli/Delhi region is also characterized by granitic intrusions with ages of ~0.9–1.1 Ga (Deb et al., 2001; Pandit et al., 2003; Buick et al., 2006, 2010; Just et al., 2011; Meert et al., 2013). Ages of ~1.1 – 0.9 were obtained on zircons from granitoid plutons in the northern part of the Delhi Fold Belt (Biju-Sekhar et al., 2003; Meert et al., 2013). A number of other granitic bodies in the Aravalli region were dated to ~1.0–0.9 Ga (Volpe and Macdougall, 1990; Deb et al., 2001; Lescuyer et al., 1993; Sivaraman and Raval, 1995; Pandit et al., 2003). These early Neoproterozoic magmatic bodies were emplaced during collision of the Marwar and Mewar cratons at the end of the Delhi orogeny (Roy and Jakhar, 2002; de Wall et al., 2012). This magmatic event is manifested in the 968. Ma (U–Pb zircon) calc-alkaline Sendra granitoids (Pandit et al., 2003) along with 987 Ma (U–Pb zircon) rhyolites of the Sendra–Ambaji–Ajmer sector (Deb et al., 2001).

The Erinpura and related intrusions represent a younger and more widespread thermal event in the Marwar region (Heron, 1953). The 'Erinpura Granites' of Heron (1953;best exposed in the Sirohi– Jawai Dam region) are a group of variably deformed granitoids (including granite, granodiorite and banded gneisses) exposed between the Ajmer in the north and northern part of Gujarat State in the south. The age of the Erinpura granites was first determined by Choudhary et al. (1984; Rb–Sr) at ~830 Ma. More recently, robust geochronologic data (U–Pb; U–Th–Pb) have shown that these granites were emplaced over a longer time

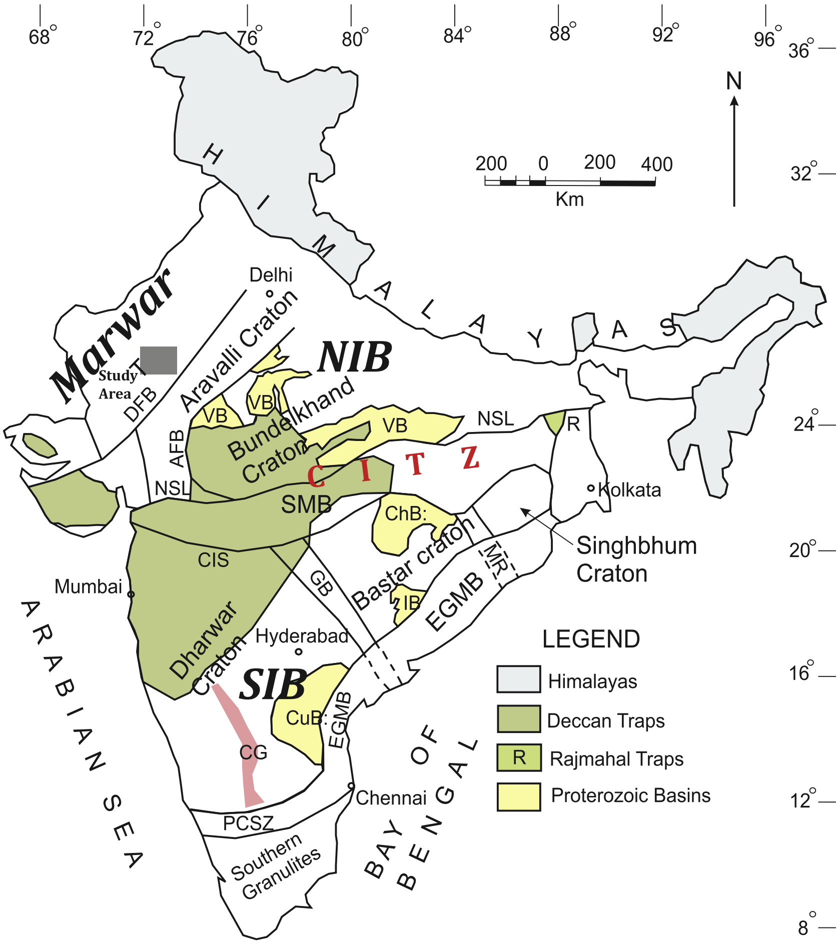

Fig. 1. Generalized cratonic map of Peninsular India. The study area is located in the Marwar terrain of NW India (shaded rectangle). Abbreviations in the map NIB = North Indian Block, SIB = South Indian Block; DFB = Delhi Fold Belt; AFB = Aravalli Fold Belt; NSL = Narmada-Son Lineament; CIS = Central Indian Suture; CITZ = Central Indian Tectonic Zone; SMB = Satpura Mobile Belt; EGMB = Eastern Ghats Mobile Belt; GB = Prahnita-Godavari Basin; MR = Mahandi Rift; PCSZ = Palghat-Cauvery Shear Zone; VB = Vindhyan Basin; ChB = Chhattisgarh Basin; IB = Indravati Basin; CuB = Cuddapah Basin; CG = Closepet Granite.

span, between 860 and 820 Ma (Deb et al., 2001; van Lente et al., 2009; Just et al., 2011; Ashwal et al., 2013). Sediments of the Sirohi Group were deposited over the Erinpura Granite. Both the Erinpura Granite and the Sirohi Group metasediments are overlain by the 770–750 Ma Malani Igneous Suite (Torsvik et al., 2001a,b; Gregory et al., 2009; Meert et al., 2013). Recent geochemical, deformation and geochronologic studies show that the Mt. Abu granitoids, traditionally considered as late kinematic in relation to Delhi orogeny, are much younger and part of the Malani magmatic episode (de Wall et al., 2012; Ashwal et al., 2013).

The Malani Igneous Suite (MIS) is a broad term used to denote Neoproterozoic felsic volcanics, felsic intrusives, minor basaltic flows and mafic dykes that are exposed over an area of 54,000 km^2 in SW Rajasthan, India (Bhushan, 2000; Torsvik et al., 2001a; Gregory et al., 2009; Meert et al., 2013). The initial phase of igneous activity associated with the MIS was characterized by major felsic and minor mafic flows and was followed by the emplacement of granitic bodies. The intrusion of volumetrically minor felsic and mafic dykes represent the final phase of Malani activity. Age constraints for the MIS range from ~750 Ma to ~770 Ma (Torsvik et al., 2001a,b; Gregory et al., 2009; van Lente et al., 2009; Pradhan et al., 2010; Meert et al., 2013). The Marwar Supergroup unconformably overlies the MIS.

The basin containing the Marwar Supergroup is one of several Proterozoic-aged intracratonic basins found in Peninsular India. Collectively, these basins are referred to as the "Purana" (Hindi for 'ancient') basins. Sedimentary units within the Marwar Basin, like many Neoproterozoic-Cambrian units in the regions formerly adjacent to India in the Ediacaran, developed during a complex interval of Gondwana assembly that included some post-collisional extension (Husseini and Husseini, 1990; Chaudhuri et al., 2002). The Marwar Supergroup is located in the Rajasthan sector of West Peninsular India and covers ~51,000 km^2 in the Jodhpur–Nagaur–Khatu region of Rajasthan (Fig. 2; Pareek, 1984).

The Marwar Supergroup is composed of a two-kilometer thick section of un-metamorphosed and relatively un-deformed succession of sandstones, shales, carbonates, and evaporites. Lithostratigraphically, the sediments are divided into three groups; the lowermost Jodhpur Group, the middle Bilara Group, and the uppermost Nagaur Group (Fig. 3; Khan, 1971; Pareek, 1984). The youngest sedimentary unit of the Nagaur Group is the Tunklian Sandstone. The Tunklian sandstone is unconformably overlain by the Permo-Carboniferous Bap boulder bed (Pandey and Bahadur, 2009). The oldest unit of the Jodhpur Group (Pokaran Boulder Bed or Sonia sandstone) unconformably overlies the Neoproterozoic Malani Igneous Suite (Figs. 3 and 4a). The Pokaran boulder bed was interpreted as a glacial till by Chauhan et al. (2001) and correlated to the Marinoan glaciation (see also Bhatt et al., 2005). As noted by Cozzi et al. (2012) the evidence for a glacial origin is based on presumed 'glacial striations' on boulders of the Marwar Supergroup observed near Sankra. Similar striations are observed on the Sankra mafic dyke and are known to be ventifacts. Due to our field observations and those of Cozzi et al. (2012), a glacial origin for the Pokaran Boulder Bed is rejected (Fig. 4b). The Jodhpur Group is a fluvio-marine succession of cross-bedded, white to reddish sandstone and maroon shale (Fig. 4c). The Bilara Group consists of dolomitic and stromatalitic limestone that conformably overlie the Jodhpur Group (Khilnani, 1968; Barman, 1987; Pandit et al., 2001). In a somewhat confusing nomenclature, the Hanseran Evaporite Group is included within the Bilara Group; however, as noted by Mazumdar and Strauss (2006), these are coeval facies variants within the basin. The so-called Hanseran Group is characterized by seven evaporitic cycles of dolomite, magnesite, anhydrite, halite, polyhalite, and clay bands (Das Gupta, 1996; Kumar, 1999; Mazumdar and Strauss, 2006). To avoid confusion, we refer to this sequence as the Bilara Group in the manuscript. Unconformably overlying the Bilara Group is a sequence of fine to coarse grained, cross-bedded, reddish brown, sandstone and siltstone of the Nagaur Group (Pandey and Bahadur, 2009; Fig. 3).

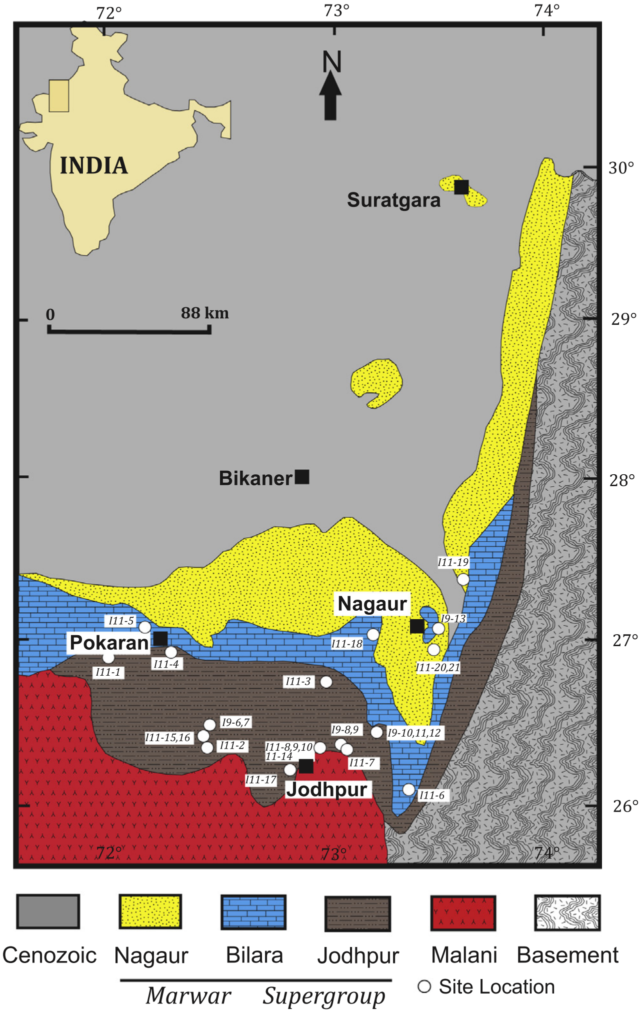

Fig. 2. Generalized geological map of the study area and the Marwar Supergroup. Paleomagnetic sampling locations are denoted by white circles with the corresponding site numbers (see also Table 1 for paleomagnetic results). Major cities are denoted by black squares (modified from Pareek, 1981).

3. Age constraints on Marwar sedimentation

The Malani Igneous Suite is well dated to between 750 and 770 Ma (Torsvik et al., 2001a,b; Gregory et al., 2009; van Lente et al., 2009; Pradhan et al., 2010; Meert et al., 2013) and therefore provides a maximum age for the overlying Marwar sediments. The Marwar Supergroup was historically classified as Neoproterozoic based upon the relatively un-deformed stratigraphy and the absence of index fossils within the sequence. Assuming the Neoproterozoic Snowball Earth event was globally distributed, the absence of glacial deposits within the Marwar Supergroup suggests a post-Marinoan age of deposition (i.e.<635 Ma). Ediacaran fossils collected from the Jodhpur group, including *Arumberia*, *Beltanelliformis*, *Aspidella*, and *Hiemalora*, support a late-Neoproterozoic age for the Jodhpur (<570 Ma; Kumar and Pandey, 2008, 2009; Raghav et al., 2005; Kumar, 2012).

Malone et al. (2008) recently studied detrital zircon populations from the Girbhakar and Sonia sandstones of the Jodhpur Group.

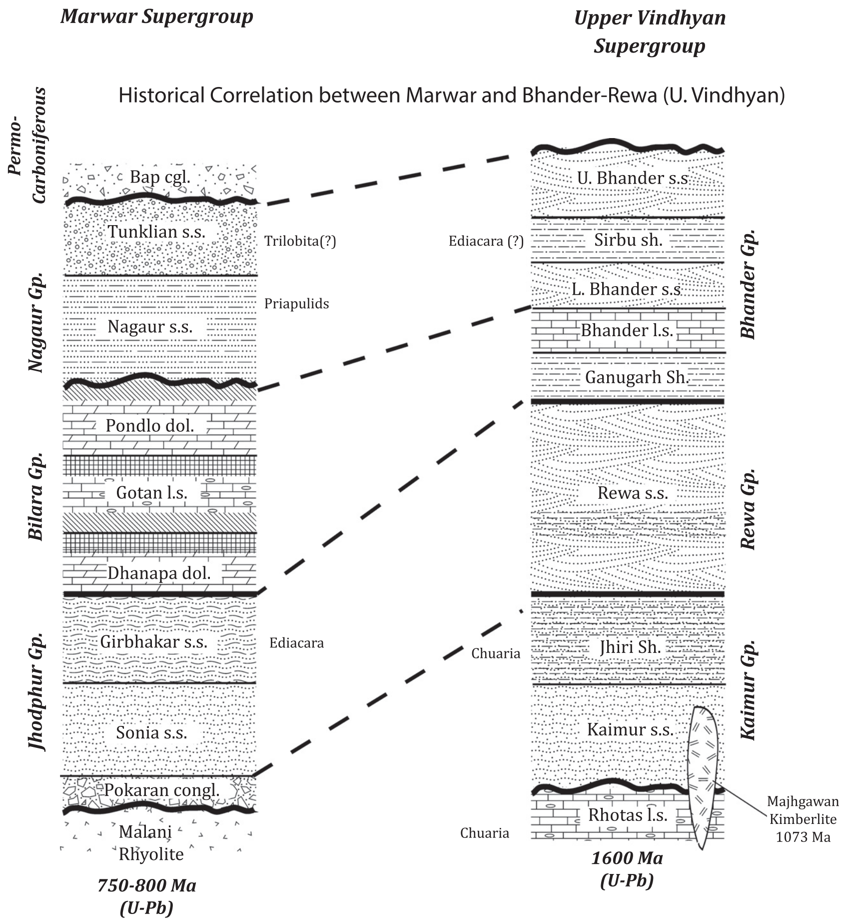

Fig. 3. Generalized stratigraphic columns for the Marwar Supergroup and the Upper Vindhyan Supergroup. The historical correlations between these two sequences are also shown for illustrative purposes. Most recent data from the Vindhyan basin adjacent to the Aravalli sequence indicates this historical correlation is not valid (Malone et al., 2008; Gopalan et al., 2013; Turner et al., 2013).

The results yielded a peak detrital zircon age range between 800 and 900 Ma along with a smaller subset of 780 Ma zircons. The carbonates of the Bilara Groupwere the focus of several chemostratigraphic attempts to constrain the age of the Marwar Supergroup. Carbon isotope studies suggest that the Precambrian–Cambrian boundary lies within the Bilara Group based upon negative δ^{13}C anomalies (<-4.3‰ PDB & <-6.5‰ PDB) that correlate with the Nemakit-Daldynian carbon isotopic evolution curve (Pandit et al., 2001; Mazumdar and Bhattacharya, 2004).

Mazumdar and Strauss (2006) analyzed the δ^{34}S concentrations within trace sulfates from Bilara Group carbonates and calcium sulfates from the Hanseran evaporites and concluded that the data (33.8 ± 3.1‰ & 32.4 ± 3‰) closely matched sulfate enrichment patterns from the end-Neoproterozoic. Mazumdar and Strauss (2006) also examined the strontium isotopic composition from the Bilara carbonates and evaporites and determined the relatively high ratios (^{87}Sr/^{86}Sr = 0.70832 ± 0.000354) are comparable to post-Gaskiers ^{87}Sr/^{86}Sr global seawater curves. The Nagaur Group, the uppermost unit of the Marwar Supergroup, yielded trace fossils of *Rusophycus*, *Dimorphichnus*, and *Cruziana*, suggesting an early-Cambrian age for the unit (Kumar and Pandey, 2008, 2009). A study of acritarch fossils from the Nagaur sandstones also support a Cambrian age for the uppermost Marwar Supergroup (Prasad et al., 2010).

McKenzie et al. (2011) studied detrital zircon populations from Nagaur sandstone and Turner et al. (2013) summarized all detrital zircon populations from the Marwar Supergroup (Fig. 5). The results of this study demonstrate a large concentration of grains between 700 Ma and 1000 Ma and a small population of young grains with a peak at 540 Ma. Based on the aforementioned studies our best estimate for the age of the Marwar Supergroup is between 521 and 570 Ma with the Ediacaran–Cambrian boundary (541 Ma) located within the Bilara Group.

3.1. Marwar – Upper Vindhyan (non)Correlation

The Marwar Supergroup, also referred to as the ‘Trans-Aravallli Vindhyans’, was historically considered as a westward basin correlative of the upper part of the Vindhyan sedimentary basin (Fig. 3; Heron, 1932; Heron, 1936; Verma, 1991). The historical correlation between the Marwar and Upper Vindhyan (Bhander and Rewa Groups) was based primarily on lithologic similarities, lack of fossils and a lack of penetrative deformation in both the basins (Fig. 3). Subsequent studies also argue that the sedimentary facies similarities between the Upper Vindhyan and Marwar sequence suggest a contemporaneity while ignoring any data that do not fit this correlation (see Poornachandra Rao et al., 2007; Azmi et al., 2008; Kumar, 2012; Srivastava, 2012a,b). We argue that the two basins are separated in time by up to 400 million years, as discussed below.

Recent geochronologic/paleomagnetic findings from a number of “Purana” basins considerably weaken support for the correlation between the Marwar Supergroup and the Upper Vindhyan Bhander–Rewa sequences. A paleomagnetic and detrital zircon analysis of the Bhander and Rewa Groups led Malone et al. (2008) to postulate that sedimentation in the Upper Vindhyan basinceased around

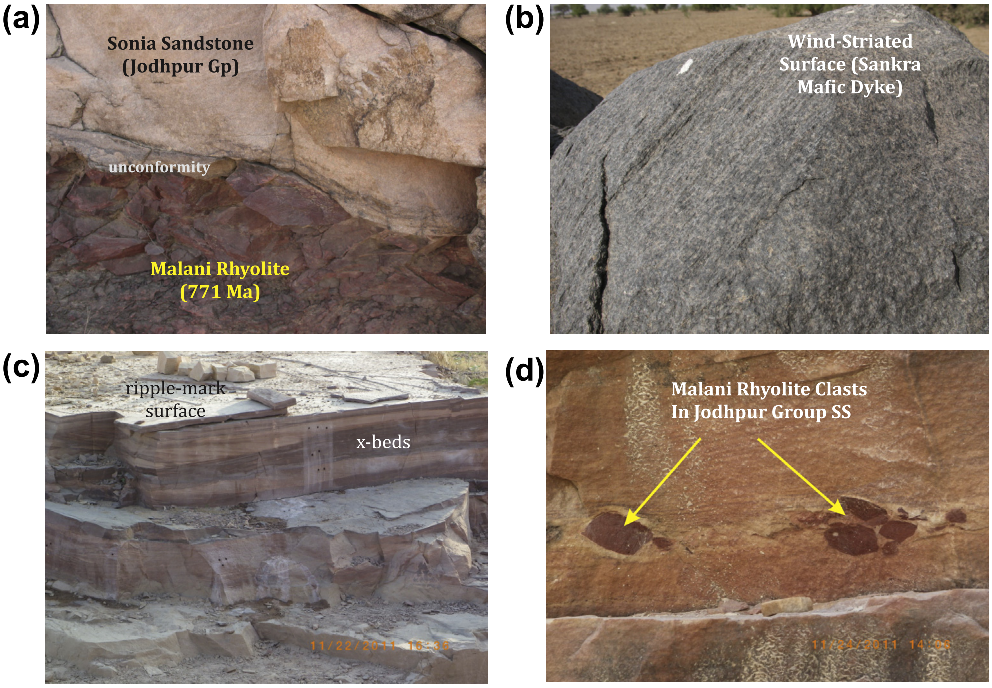

Fig. 4. (a) Contact between the Malani rhyolites and the Sonia sandstone of the Jodhpur Group (lower Marwar Supergroup); (b) striated surface (ventifact) on an exposure of the Sankra mafic dyke. These striated surfaces were previously thought to be glacial in originin boulders of the Pokaran boulder bed nearby (Chauhan et al., 2001); (c) Purple-red cross-bedded sandstones of the Jodhpur Group. Bedding surfaces are typically ripple marked; (d) Clasts of the Malani rhyolite in the Jodhpur sandstones. These clasts were drilled for a conglomerate test.

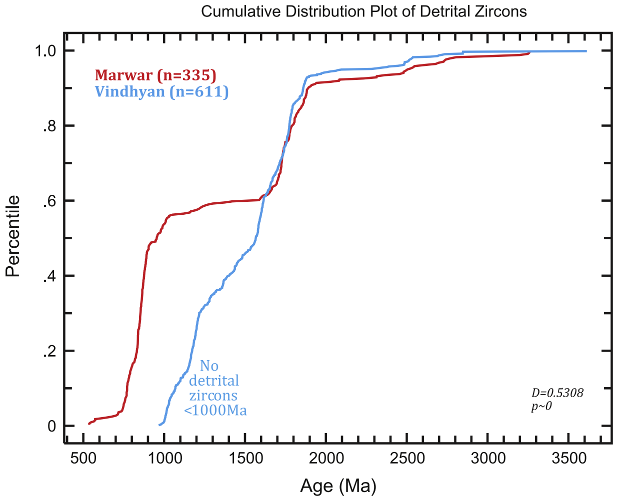

Fig. 5. Cumulative distribution plot of all detrital zircon studies from the Marwar Supergroup and the Upper Vindhyan Supergroup (after Turner et al., 2013; Malone et al., 2008; McKenzie et al., 2011). Note the absence of any detrital zircons in the Vindhyan Supergroup <1000 Ma. A statistical comparison of the two distributions shows no correlation.

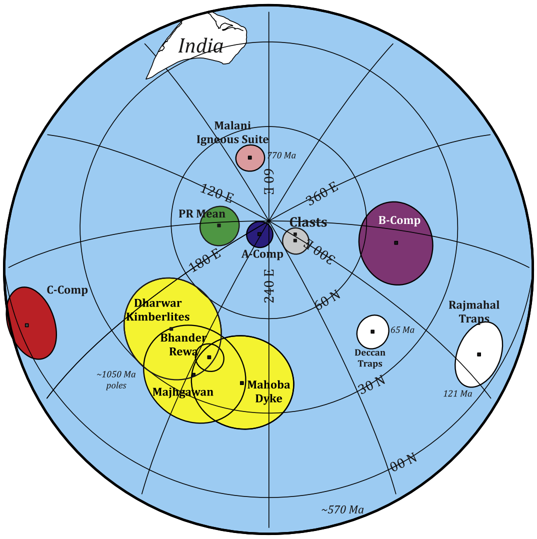

Fig. 6. Paleomagnetic poles discussed in the text. 1050–1100 Ma poles include the Mahoba dyke pole (Pradhan et al., 2012); Majhgawan kimberlite pole (Gregory et al., 2006); Dharwar Kimberlites pole (Venkateshwarlu and Chalapathi Rao, 2013). The Bhander–Rewa pole is also shown in this cluster (Malone et al., 2008). The mean pole from the Marwar Supergroup obtained by Poornachandra Rao et al. (2007) is shown (pole PR; after correcting for the sign of the inclination). The corrected pole falls very close to our mean A-component pole from this study. Other poles shown include the Malani Igneous Suite pole (Meert et al., 2013; Gregory et al., 2009; Torsvik et al., 2001a; Klootwijk, 1975); poles from the Rajmahal and Deccan traps and the B and C mean poles from this study. Clasts represent VGP calculated from clasts of Malani rhyolites within the Jodhpur sandstone.

~1000 Ma. Gregory et al. (2006) first pointed out the similarity between paleomagnetic directions in the 1073 Ma Majhgawan kimberlite and published poles from the Bhander–Rewa Groups. The Majhgawan kimberlite intrudes the Baghain Sandstone of the Kaimur Group. Malone et al. (2008) performed a comprehensive paleomagnetic study on the Bhander–Rewa Groups and confirmed the directional similarity noted by Gregory et al. (2006). Pradhan et al. (2012) conducted a paleomagnetic study on the ~1100 Ma Great Dyke of Mahoba (Bundelkhand craton). The VGP from the Great Dyke of Mahoba overlaps with the Majhgawan VGP and the Bhander–Rewa pole providing additional support for a >1000 Ma age for the Upper Vindhyan. Venkateshwarlu and Chalapathi Rao (2013) cited paleomagnetic evidence from 1.1 Ga

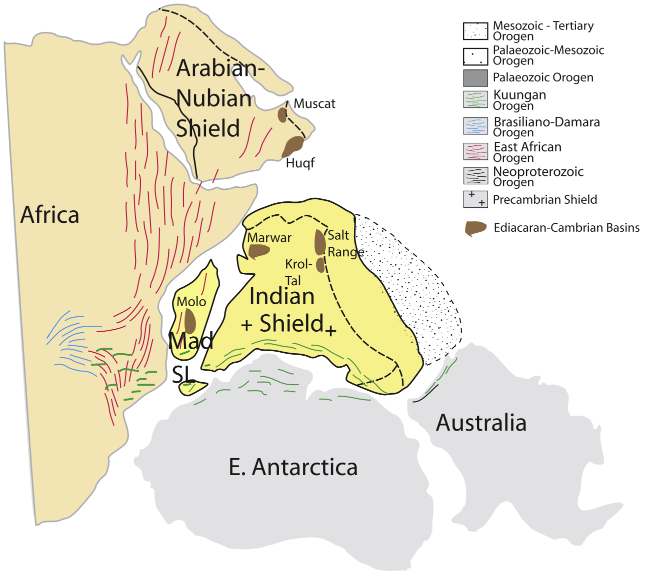

Fig. 7. Possible correlative basins to the Marwar Basin shown in a Gondwana configuration. Fig. 8 shows idealized stratigraphic correlations between the Marwar, Krol–Tal, Salt-Range and Huqf Supergroup.

kimberlites and lamproites in the Dharwar craton in support of the conclusions made by Malone et al. (2008) regarding the Mesoproterozoic age for the Upper Vindhyan sedimentary sequence (Fig. 6). Lastly, Gopalan et al. (2013) provided Pb–Pb ages for the Bhander, Lakheri and Balwan limestones of the Upper Vindhyan. Although errors on individual age determinations were large, the ages ranged from ∼900–1075 Ma supporting a Late Mesoproterozoic (Stenian) to Early Neoproterozoic (Tonian) age for these rocks.

Geochronologic studies from the Chhattisgarh and Indravati Basins along with the Vindhyan Basin support the notion that the larger Purana Basins (Vindhyan, Chhattisgarh and Indravati) are older than ∼1000 Ma whereas the Marwar Basin is part of a sequence of younger (Neoproterozoic to Cambrian) basins found in the Middle East and the Himalayas (Husseini and Husseini, 1990;Patranabis-Deb et al., 2007; Malone et al., 2008; Basu et al., 2008; McKenzie et al., 2011; Bickford et al., 2011; Mukherjee et al., 2012; Turner et al., 2013).

3.2. Correlations to regional neoproterozoic basins

In addition to being correlated with the Upper Vindhyan Bhander–Rewa sediments, the Marwar Supergroup was correlated with sedimentary sequences in the Salt Range of Pakistan, the Ara Formation (Huqf Supergroup) of Oman, the Krol–Tal succession of the Himalayas and perhaps the Molo Supergroup of Madagascar (Fig. 7). These units all contain Ediacaran–Cambrian aged sedimentary rocks and are believed to have developed in a rift setting (Hughes et al., 2005; Jiang et al., 2002, 2003; Kaufman et al., 2006; Maithy and Kumar, 2007; Mazumdar and Bhattacharya, 2004; Cozzi and Rea, 2006; Husseini and Husseini, 1990). Correlations between the Marwar Supergroup and the Krol–Tal (Himalayas) is supported by nearly identical detrital zircon population variations (McKenzie et al., 2011). Lithologically, the Marwar Supergroup, the Salt Range sequence, and the Ara Formation (Oman) show 6–7 nearly identical cycles of carbonate–evaporite deposits (Fig. 8; Cozzi and Rea, 2006); whereas the Vindhyan is devoid of evaporite deposits. Based on similarities of Ediacaran–Cambrian fossils from the Upper Nagaur Sandstone (Marwar Supergroup) to Cambrian-aged fossils from the Salt

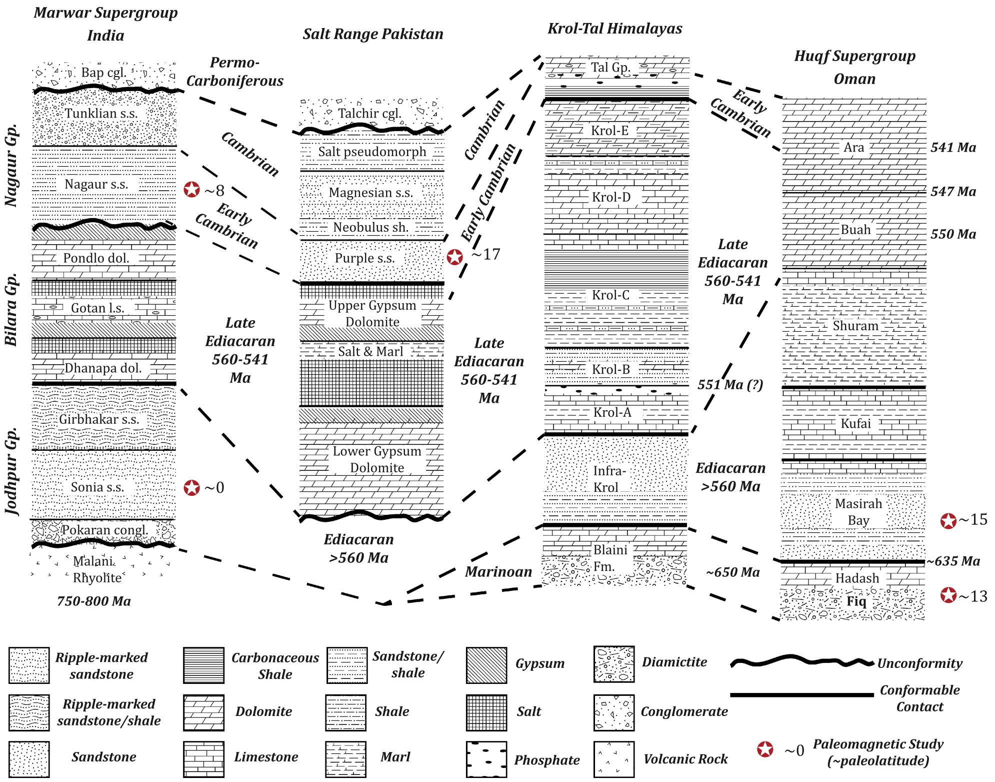

Fig. 8. Comparative stratigraphy (idealized) and proposed correlations between the Marwar Supergroup, the Salt Range (Pakistan), the Krol–Tal (Himalayas) and the Huqf Supergroup (Oman). The key correlative sequences are the evaporitic-carbonate sequences (Bilara Group-Marwar; Gypsum-salt and marls of the Salt Range; Krol sequence (Himalayas) and the Buah–Ara sequences (Huqf Supergroup). Red stars show sequences where paleomagnetic data are available and the approximate paleolatitude for that sequence (Kilner et al., 2005; Wensink, 1972; McElhinny, 1970; Kempf et al., 2000; this study).

Table 1
Paleomagnetic results from the Marwar Supergroup.

Site #	Component	Unit	n/N	Dec (°)	Inc (°)	K	A95 (°)	Plat	Plong	dp (°)	dm (°)
I96-L	B	Jodhpur	4/11	328	−8	39	15	46°S	123°E	8	15
I96-H	C	Jodhpur	3/11	274	+3	27	24	05°N	342°E	12	24
I97-H1	B	Jodhpur	5/8	332	+10	17	19	56°N	309°E	10	19
I97-H2	C	Jodhpur	4/8	81	−1	23	20	07°S	347°E	10	20
I98-L	A	Jodhpur	1/10	2	33	–	–	82°N	240°E	–	–
I98-M	B	Jodhpur	2/10	306	+31	–	–	39°N	344°E	–	–
I99-H	B	Jodhpur	2/13	312	+20	–	–	42°N	333°E	–	–
I910-H	A	Jodhpur	11/12	6	+34	31	8	80°N	217°E	6	10
I911-H	A	Jodhpur	9/14	357	+37	128	5	83°N	282°E	3	5
I912-H	A	Jodhpur	10/18	359	+37	78	6	84°N	264°E	4	6
I12-L	A	Jodhpur	11/30	007	+40	44	7	83°N	192°E	5	8
I12-M	B	Jodhpur	2/30	324	+1	–	–	46°S	131°E	–	–
I12-H	C	Jodhour	2/30	66	−11	–	–	19°S	359°E	–	–
I14-H	C	Jodhpur	7/16	96	+10	12	18	03°S	155°E	9	18
I17-L	A	Jodhpur	10/12	6	+47	26	10	84°N	140°E	8	13
I17-H	C	Jodhpur	3/12	83	−17	15	33	03°S	354°E	17	34
I18-M	B	Jodhpur	4/11	319	+39	24	19	53°N	345°E	13	24
I18-H	C	Jodhpur	1/11	279	+9	–	–	10°N	343°E	–	–
I19-L	A	Jodhpur	4/7	357	+38	55	13	84°N	285°E	9	15
I19-M	B	Jodhpur	2/7	321	+19	–	–	50°N	326°E	–	–
I19-H	C	Jodhpur	1/7	108	−2	–	–	16°N	336°E	–	–
I117-L	A	Jodhpur	8/13	1	+46	17	14	89°N	124°E	11	17
I117-H	B	Jodhpur	5/13	332	+20	14	21	56°N	185°E	12	22
I913-L	A	Bilara	3/13	2	+36	36	21	82°N	241°E	14	24
I118-l	A	Bilara	4/10	12	+46	22	20	79°N	161°E	16	25
I119-L	A	Nagaur	8/27	15	+44	14	15	77°N	164°E	17	19
I119-H	C	Nagaur	3/27	88	+28	21	27	09°N	151°E	16	29
I120	C	Nagaur	2/12	290	2	–	–	18°N	335°E	–	–

Notes: Comp = Component of magnetization (see text) n/N = samples used/samples; Dec = Declination; Inc = Inclination; *k* = kappa precision parameter; *a*95 = circle of 95% confidence; Plat = Latitude of the paleomagnetic pole; plong = longitudeof the paleomagnetic pole; dp = cone of confidence along site latitude; dm = cone of confidence orthogonal to site latitude.

Table 2
Summary Results.

Component	Unit	N	Dec (°)	Inc (°)	K	a95 (°)	Plat	Plong	dp (°)	dm (°)
A-Component-Directional	All	79	004	+40	144	4	85°N	206°E	3	5
A-Component- Site Mean	All	11				4	85°N	211°E		
B-Component-Site Mean	Jodhpur	8	311	+07	22	12	50°N	324°E	7	13
C-Component-Site Means Normal	Jodhpur+ Nagaur	3	281	+05	81	14				
C-Component-Site Means Reverse	Jodhpur+ Nagaur	6	087	+01	15	18				
C-Component-Directional Normal Samples	Jodphur+ Nagaur	6	286	+01	54	9	14°N	336°E	5	9
C-Component-Directional Reverse Samples	Jodphur+ Nagaur	20	086	+03	12	10	05°N	164°E	5	10
C-component-Directional All Samples	Jodhpur ONLY	21	089	−01	14	9	01°S	344°E	5	9
Site 16-Clasts		19	353	+34	68	4°	80°N	294°E	3	5
Site 16-Sandstones		5	353	+36	9	27°	81°N	304°E	18	32

Notes: *N* = number of samples/sites used; Dec = Declination; Inc = Inclination; *k* = kappa precision parameter; *a*95 = circle of 95% confidence; Plat = Latitude of the paleomagnetic pole; plong = longitude of the paleomagnetic pole; dp = cone of confidence along site latitude; dm = cone of confidence orthogonal to site latitude.

Range and Himalayas, Kumar and Pandey (2010) postulated a Cambrian aged marine link between these regions.

4. Paleomagnetic methods

A total of 267 samples were collected and analyzed from 17 separate sites within the Marwar Supergroup (Fig. 2). Most of the samples were taken from redbed units in the Jodhpur and Nagaur Groups. We collected a few samples from the limestone units in the Bilara Group, but these were weakly- to non-magnetic and did not yield meaningful results (other than presumed present-day field). All samples were collected using a water-cooled portable drill. Sample orientation was performed in the field using sun compass readings and a Brunton magnetic compass. Local magnetic declination was <1°. Samples were cut into uniform cylindrical specimens in the laboratory. Pilot samples were selected for preliminary demagnetization and a sequence of thermal demagnetization steps was chosen based on these preliminary results. Thermal demagnetization was performed on all samples using an ASC TD-48 thermal demagnetizer. Measurements were carried out on a 2G 77R Cryogenic Magnetometer at the University of Florida. The resulting data were analyzed using principle component analysis of a best-fit line on Super IAPD software. Sample fragments not used in thermal demagnetization 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 from each site.

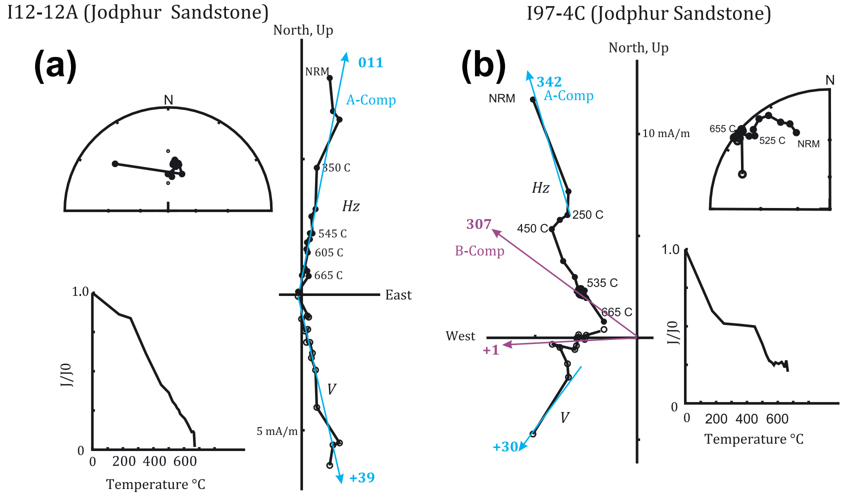

Fig. 9. (a) Zijderveld diagram, stereoplot and intensity decay diagram for sample I12-12a showing a univectorial decay for the A-component of magnetization; Closed (open) circles (stereonet) represent positive (negative) inclinations; Hz = horizontal vector; V = vertical vector (b) Zijderveld diagram, stereoplot and intensity decay diagram for sample I97-4c. This sample shows a low-temperature A-component overprint (blue colors) followed by removal of the B-component (purple colors) at higher temperatures. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

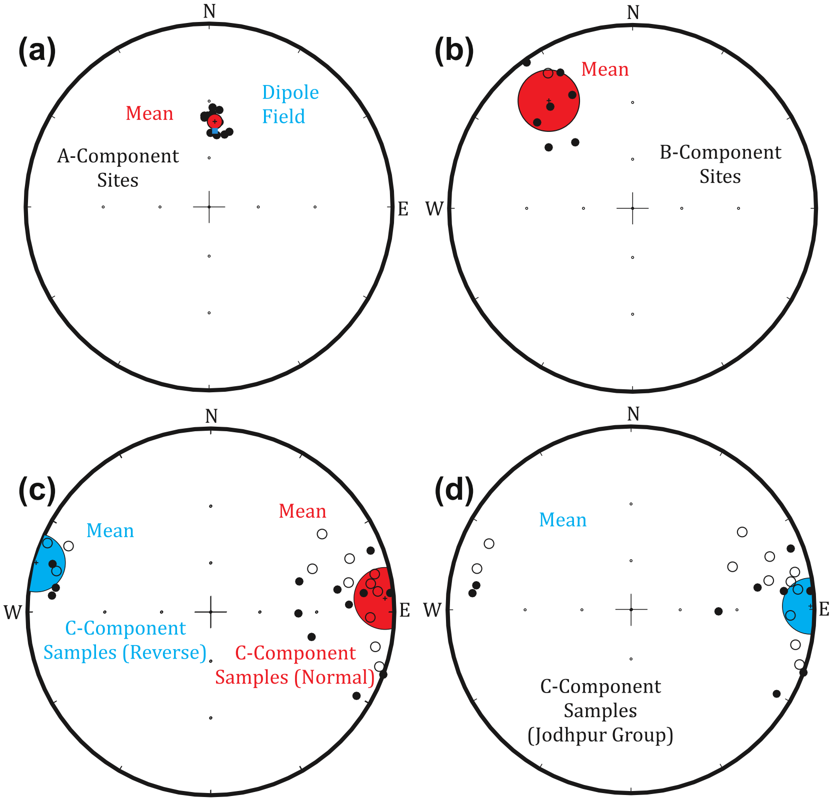

Fig. 10. (a) Mean direction for the A-component, the present-day dipole field direction is represented by a blue square; closed (open) circles represent positive (negative) inclinations (b) Mean direction for the B-component, symbols as in 8a; (c) mean direction for the 'normal' polarity C-component (red), and mean direction for the 'reverse' polarity C-component (blue), symbols as in 8a; (d) overall mean direction for the C-component in this study calculated from Jodhpur samples only, symbols as in 8a. Results are also tabulated in Tables 1 and 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Paleomagnetic results

Paleomagnetic analysis of the Marwar Supergroup specimens yielded evidence of multiple components and overprinting. Three distinct paleomagnetic components were isolated and the results are presented in Tables 1 and 2.

Component A was by far the most common direction and was identified in 79 samples from 11 sites (Tables 1 and 2). Component

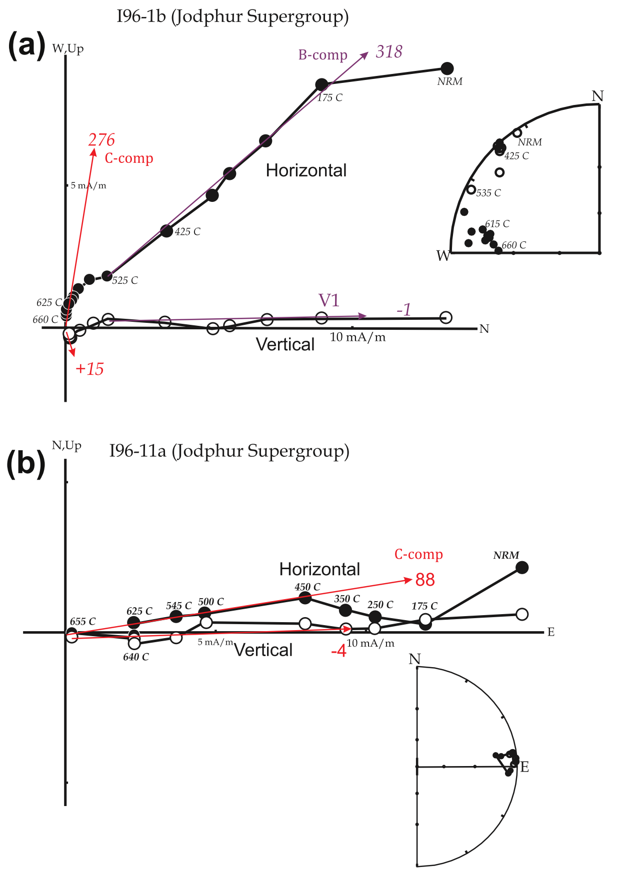

Fig. 11. (a) Zijderveld diagram and stereoplot for sample I96-1b that shows a B-component overprint and a high-temperature ‘normal’ polarity C-component, symbols as in Fig. 7; (b) Zijderveld diagram and stereoplot for sample I96-11a showing a univectorial ‘reverse’ C-component magnetization, symbols as in Fig. 7.

A was unblocked over a large range of temperatures, from as low as 250 °C in magnetite-bearing samples and up to 695 °C in hematite-bearing samples (Fig. 9). The mean direction for component A has a Declination = 4° and an Inclination = +40° ($k = 144$, $\alpha_{95} = 4°$; Fig. 10a and Table 2).

Component B was identified within 26 samples from 8 sites (Figs. 9 and 11a and Tables 1 and 2). Component B was carried mainly within hematite-bearing samples up to 695 °C and yielded a mean direction of Dec = 311° and Inc = +7° ($k = 22$, $\alpha_{95} = 12°$; Fig. 10b).

Component C was identified within 26 samples from 9 sites and was of dual-polarity (Figs. 10c and d and 11a and b). The majority of the samples exhibiting the C-direction were collected within the lowermost Jodhpur Group (21 samples, Tables 1 and 2) with only a few samples from the Nagaur showing a similar direction. After reversing the ‘normal’ polarity (nominally westerly declinations) samples a mean direction was obtained from the Jodhpur Group with a Dec = 89° and Inc = −1° ($k = 14$, $\alpha_{95} = 9°$; Fig. 10d).

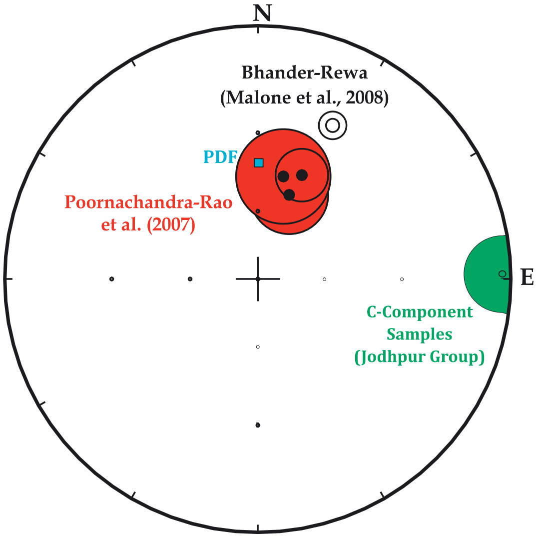

Fig. 12. Stereoplot showing Poornachandra Rao et al.’s (2007) ‘primary’ remanence from the Marwar Supergroup as compared to the mean direction obtained by Malone et al. (2008) for the Bhander–Rewa Groups of the Upper Vindhyan sequence and the C-component pole from the Jodhpur Group samples in this study. Note that closed circles represent positive inclinations in the Marwar Supergroup and open circles represent negative inclinations in the Bhander–Rewa. PDF = present dipole field direction for sampling locality.

6. Discussion

Only a single component was identified in the Marwar Basin in a previous paleomagnetic study (Poornachandra Rao et al., 2007). That study was concentrated on the basal units of the Marwar Supergroup and utilized 19 hand samples from 3 sites within the Jodhpur Group. Poornachandra Rao et al. (2007) reported a mean paleomagnetic direction with a declination = 20° and an inclination = +46° (Fig. 12). Apparently during the calculation of the paleomagnetic pole, these authors erroneously changed the sign of the inclination value (i.e. to −46°). This error in sign resulted in Poornachandra Rao et al. (2007) correlating previously published results from the Bhander–Rewa with their study (see Athavale et al., 1972; McElhinny et al., 1978; Malone et al., 2008).

We have recalculated the pole of Poornachandra Rao et al. (2007) at 76°N and 155°E ($\alpha_{95} = 6°$). The corrected VGP differs significantly from the mean Bhander–Rewa VGP of 43.1°N, 213.8°E ($\alpha_{95} = 6°$;Malone et al., 2008) and negates using the Jodhpur directions in support of a Bhander–Rewa and Marwar Supergroup correlation (Figs. 6 and 12).

As noted in Section 5, three distinct magnetic components were identified in the Marwar Supergroup. For convenience, we label these components A, B and C in order of our interpreted age progression (A = youngest, C = oldest). The A-Component appeared most frequently in our collection. The mean direction of Dec = 4° and Inc = +40° ($k = 144$, $\alpha_{95} = 4°$) was calculated based on a more robust sample (compared to Poornachandra Rao et al., 2007) using 79 samples collected from 11 sites. The paleomagnetic pole calculated from this directional data falls at 85°N, 211°E (Fig. 6 and Table 2). The A-component was present either as a single vector or as a low-temperature overprint on the B and C directions.

Due to the fact that both our A-component magnetization and that identified in the study by Poornachandra Rao et al. (2007) both closely resemble the Earth’s present magnetic field (Figs. 10a and 12), we sought an independent test to verify/refute the primary nature of this direction. To that end, we performed a conglomerate test utilizing Malani rhyolite clasts suspended within sandstones of the Jodhpur Group (Fig. 4d). The outcrop was discovered just above the Malani rhyolites near the city of Jodhpur.

Clasts of the rhyolite within the Jodhpur sandstone exhibited stable (and largely uni-vectorial) behavior with directions that were of dual-polarity and remarkably well-grouped (Fig. 13a and b). The ‘normal-polarity’ direction (equivalent to our A component) yielded a mean of Dec = 354° and I = +33° (Fig. 14; $k = 44$, $\alpha_{95} = 5.4°$) and a ‘reverse polarity’ direction of Dec = 170° and I = −38° (Fig. 14; $k = 53$, $\alpha_{95} = 9.3°$). The remarkable coincidence of all directions within the clasts suggests that the northerly (down) directed

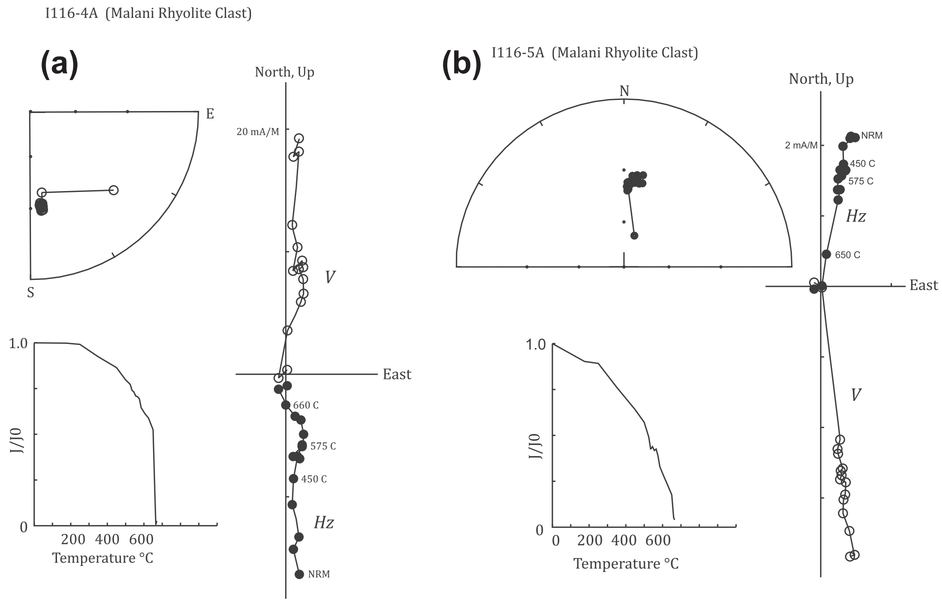

Fig. 13. (a) Zijderveld diagram, stereoplot and intensity decay diagram for conglomerate sample I116-4a showing a univectorial decay for the A-component of magnetization (reverse polarity); Closed (open) circles (stereonet) represent positive (negative) inclinations; Hz = horizontal vector; V = vertical vector (b) Zijderveld diagram, stereoplot and intensity decay diagram for conglomerate sample I116-5a showing a univectorial decay of the A-component of magnetization (normal polarity).

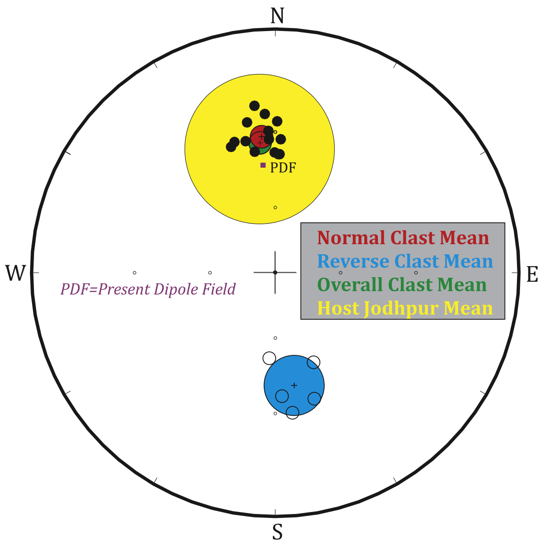

Fig. 14. Stereoplot of directional data obtained from the conglomerate test. Closed (open) circles represent positive (negative) inclinations.

component observed in our study and Poornachandra Rao et al. (2007) is a viscous remanence of relatively recent origin. A similar dual-polarity remagnetization was noted by Torsvik et al. (2005) in the Jaisalmer Basin of Rajasthan (Cretaceous age). Torsvik et al. (2005) also argued that the remagnetization in the Jaisalmer Basin was the result of post-Eocene uplift, erosion and weathering associated with the Indo-Asian collision. We assert that our A-component along with the 'primary component' reported in the Poornachandra Rao et al. (2007) study are recent overprints.

Component B was less commonly observed in our samples. The mean direction for the B-component was calculated with a Dec = 334° and Inc = +10° from 25 samples collected from 10 sites. A VGP calculated from the mean B-direction yielded a pole at 57°N and 306°E (Fig. 6; α95 = 6°). The B-Component VGP falls near, but statistically distinct from a very well-defined paleomagnetic pole from the Deccan Traps that falls at 37°N and 281°E (α95 = 3°; Vandamme et al., 1991; Fig. 6). There are several outliers of Deccan Trap age magmatic rocks in western Rajasthan and the thermal influence of the Deccan Traps is widespread throughout India (Sen et al., 2012). We note that our directions are from a limited number of samples that likely do not average secular variation, but we feel confident that this direction is most likely a thermo-chemical manifestation of the Deccan Traps volcanism. Our conclusion is supported by the fact that Component B is sometimes observed as a low temperature overprint in samples that also record the C-Component (see below). Alternatively, the direction may also represent an early Tertiary overprint associated with the initial phase of Indian–Asian collision.

Component C is a high temperature component observed in 21 samples from 10 sites. Although the C-component is less commonly observed in the samples, it does exhibit both polarities. When we invert the westerly directed polarity (for the Jodhpur Group samples), we obtain an overall mean direction of Dec = 89° and Inc = −1°. A VGP calculated from our mean direction plots at 1°S and 344°E (dp = 5°dm = 9°; Fig. 6). A comparison of the C-component to known Phanerozoic poles from India shows that it is distinct from all previously published works. Although the Phanerozoic paleomagnetic database from India is sparsely populated (both spatially and temporally), we feel that this component should be evaluated as a potential primary magnetization recorded in the Marwar Supergroup. A reversal test was performed comparing sites that exhibited Component C. The reversal test was inconclusive most likely due to the relatively small number of samples.

7. Conclusions

Our paleomagnetic study of the Marwar Supergroup isolated 3 distinct components of magnetization. Component A closely resembles Poornachandra Rao et al.'s (2007) observed direction and is believed to be a recent field overprint based on a negative conglomerate test. Component B may represent a partial thermal overprint from the Cretaceous-aged Deccan Traps based on gross similarities between the Deccan Traps pole and the VGP calculated from the B-Component. Component C (Dec = 89° Inc = −1°;

$\alpha95 = 9°$) is distinct from any Phanerozoic poles from this region of India and likely represents the primary magnetic direction for the Marwar Supergroup.

The virtual geomagnetic pole (VGP) generated from our C-Component does not correlate with the paleomagnetic poles from the Bhander–Rewa Groups of the Upper Vindhyan basin (Fig. 6; Malone et al., 2008) and provides additional evidence that the two basins evolved at different times in India's history. It should also be noted that our VGP does not correspond to poorly defined Ediacaran APWP for Gondwana except along the younger ~500–520 Ma portion of the path (Trindade et al., 2006). It is therefore possible that the C-component represents an early Cambrian remagnetization, but at present we cannot fully assess this possibility. Complex remagnetizations are also found in Ediacaran–Cambrian red bed and carbonate sequences of the Nama Group in Africa (Meert et al., 1997).

The Marwar Basin was active during the time of final Gondwana assembly. In Gondwana reconstructions (Fig. 7), the Marwar Basin is located in proximity to basins in Oman, Pakistan, Madagascar and northern India (Krol–Tal region). Many of these sedimentary sequences show remarkable similarities and we show possible correlations between these basins in Fig. 8. There are limited paleomagnetic data from Oman and Pakistan (Salt Range). Comparing paleomagnetic poles from the Marwar, Huqf Supergroup and the Salt Range is problematic due to age differences between the studied units. The sampled sections in the Huqf Supergroup were mostly derived from the Hadash and Fiq Formations (Cryogenian age) and thus are significantly older than the units sampled in this study. Kilner et al. (2005) did report data from two sites (7 samples) in the overlying Masirah Bay sandstones (Fig. 8). The mean paleolatitude from that very limited study is ~15°.

If our conclusions are correct, then the Upper Vindhyan Sequence is temporally distinct from the Marwar Supergroup. This would include a rejection of the assertion made by Kumar (2012) who suggested that the Maihar sandstone (Bhander Group) could be correlated with the Jodhpur sandstones of the Marwar Supergroup. Kumar (2012) rejected all paleomagnetic and geochronological data by Malone et al. (2008) in reaching that conclusion. We note here that directional data from the Maihar is identical to the Bhander–Rewa directions in both the Son Valley region and Rajasthan and distinct from the directions observed in the Jodhpur Group. Therefore, Maihar–Jodphur correlations should be rejected.

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