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Remagnetization of Mesozoic limestones from the Jaisalmer basin, NW India

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SUMMARY

High coercivity but low unblocking (LB) temperature components (∼80–100 °C) demonstrate that goethite is the principal carrier of the natural remanent magnetization (NRM) in Jurassic and Cretaceous limestone from the Jaisalmer basin (Rajasthan, NW India). Goethite-bearing components (declination = 359.9°, inclination = 46.0°, α_{95} = 4.0°, N = 10 sites) plot close to the present day field direction. High unblocking (HB) components (declination = 172.0°, inclination = −45.6°, α_{95} = 9.1°, N = 7 sites) are carried by haematite, mostly with reverse polarity directions, but undoubtedly not primary. This remagnetization event, mostly within a period of reverse magnetic polarity, occurred after 35 Ma and before 780 000 yr (the last known reversal). Only palaeomagnetic data from a single Cretaceous site (declination = 302.0°, inclination = −47.2°, α_{95} = 14.0°, N = 10 samples) has potentially preserved a primary magnetization (carried by normal polarity magnetite); if correct, this site substantiates a mid-southerly palaeolatitude for India during mid-Aptian times (∼117 Ma).

Key words: India, Jaisalmer basin, Mesozoic, palaeomagnetism, remagnetization.

1 RATIONALE

Our interest in India and other continental fragments, such as Madagascar and Seychelles, relates to efforts in defining apparent polar wander (APW) paths, refining Rodinia–Gondwana–Pangea reconstructions and increasing our general knowledge of supercontinental assembly and break-up. For that reason, we have extensively studied rocks in the Indian ocean realm for detailed palaeomagnetic, geochronological and geochemical analysis.

The Phanerozoic APW path for India (Torsvik & Van der Voo 2002) is not very robust and palaeomagnetic data of reasonable to good quality are essentially derived from Neoproterozoic—Early Cambrian (?) sediments, Late Permian—Early Triassic sediments (251–243 Ma; international commission on stratigraphy timescale, `http://micropress.org/stratigraphy/`), Cretaceous volcanics (∼118 and 91 Ma) and abundant results from Deccan volcanic rocks (∼65 Ma). Aiming to fill the relatively large gaps in the palaeomagnetic record we sampled Jurassic, Cretaceous and Tertiary sedimentary sequences from the Jaisalmer basin in Rajasthan (Fig. 1). Unfortunately our initial aspirations to refine the Indian APW path and to improve Pangea break-up and palaeogeography were compromised by chemical remagnetization problems.

2 INTRODUCTION

The termination of sedimentation in the Neoproterozoic—Early Cambrian (?) Marwar basin (Marwar supergroup in Fig. 1) marked the end of protracted Precambrian geological evolution of the Rajasthan region in NW India. The Phanerozoic geological evolution of this region has largely centred around formation of rift basins in response to global tectonic processes that resulted in separation of the Indian Plate from Gondwanan crustal elements during Jurassic and Cretaceous times (Fig. 2). The growth, evolution and geometry of Mesozoic–Tertiary basins have largely been controlled by NW–SE and NE–SW trending fracture systems. Differential movement resulted in formation of the Jaisalmer basin during the Mid-Jurassic and Bikaner–Nagaur basins (Figs 1 and 3) in Early Tertiary times (Misra *et al.* 1993). The evolution of the Jaisalmer basin was controlled by the NW–SE fracture system while the development of the roughly N–S trending Barmer basin has been ascribed to underplating associated with the drift of the Indian Plate over the buoyant Reunion plume at K–T boundary time. This also led to the separation of India–Seychelles (Plummer & Belle 1995).

The Mesozoic evolution of the Jaisalmer basin began after a prominent hiatus and commenced with fluviodeltic (continental) deposits of the Liassic–Bathonian Lathi formation (Fm.). In the Upper Lathi Fm., a marine transgression is documented, conformably overlain by the marine Jaisalmer Fm. (Callovian–Oxfordian). The ∼165 Ma break-up of East Gondwana (Coffin & Rabinowitz 1988) and subsequent opening of the Mozambique ocean (Fig. 2) was synchronous with the formation of Jurassic rift systems. The pronounced effect of Gondwana break-up on Indian lithosphere is manifested in the development of a number of fracture systems. Marine deposition in the Jaisalmer basin ceased during the Late Cretaceous

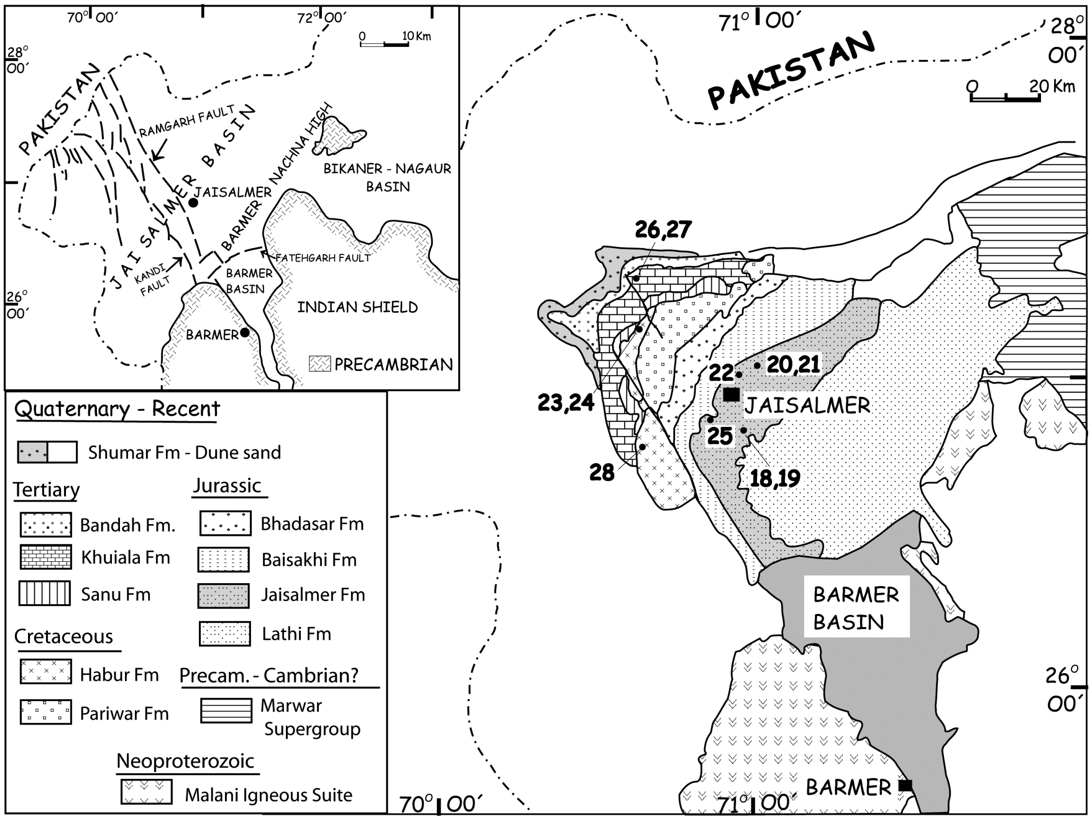

Figure 1. Geological map of Jaisalmer basin in western Rajasthan (adapted from Das Gupta 1975; Singh 1999; Roy & Jakhar 2002) showing locations of palaeomagnetic sampling sites. Stratigraphic details are listed in Fig. 3. Inset map shows major tectonic elements of western Rajasthan (adapted from Misra *et al.* 1993).

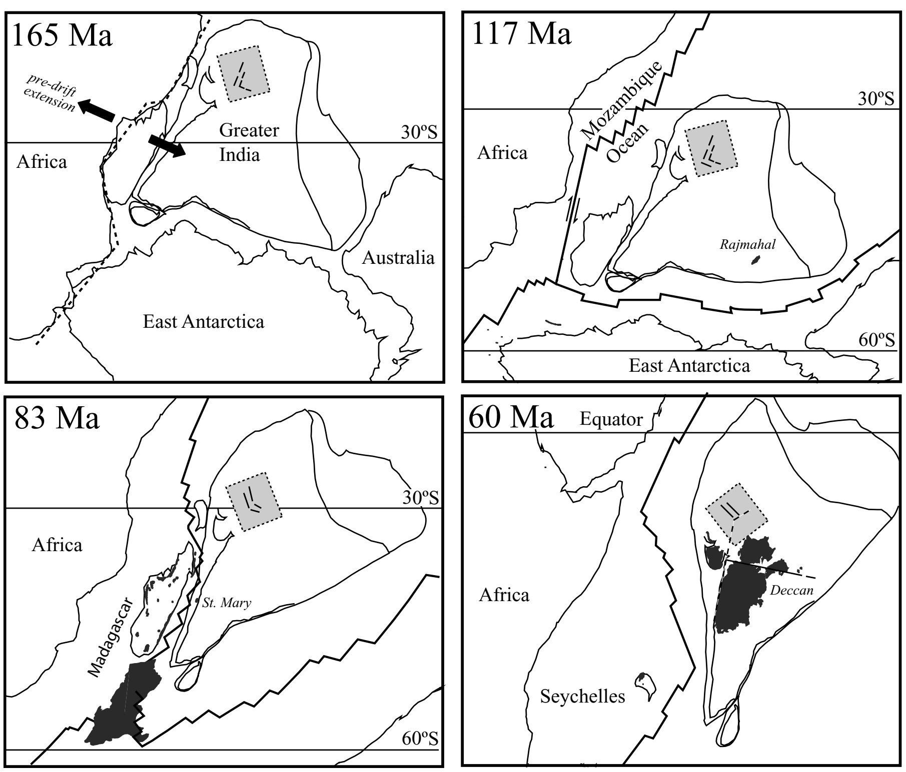

Figure 2. Palaeomagnetic reconstructions (geocentric axial dipole, GAD, based model of Torsvik & Van der Voo 2002) of some East Gondwana continents and microcontinents from 165 Myr (∼initiation of seafloor spreading in the Mozambique ocean after a long period of continental rifting) to 60 Myr (shortly after separation of India and the Seychelles). Large igneous provinces (LIPs) are shown in black (Madagascar, Rajmahal and Deccan) and commonly linked to the Marion, Kerguelen and Reunion hotspots. The grey-shaded region on the maps approximately corresponds to the outlines of Fig. 1.

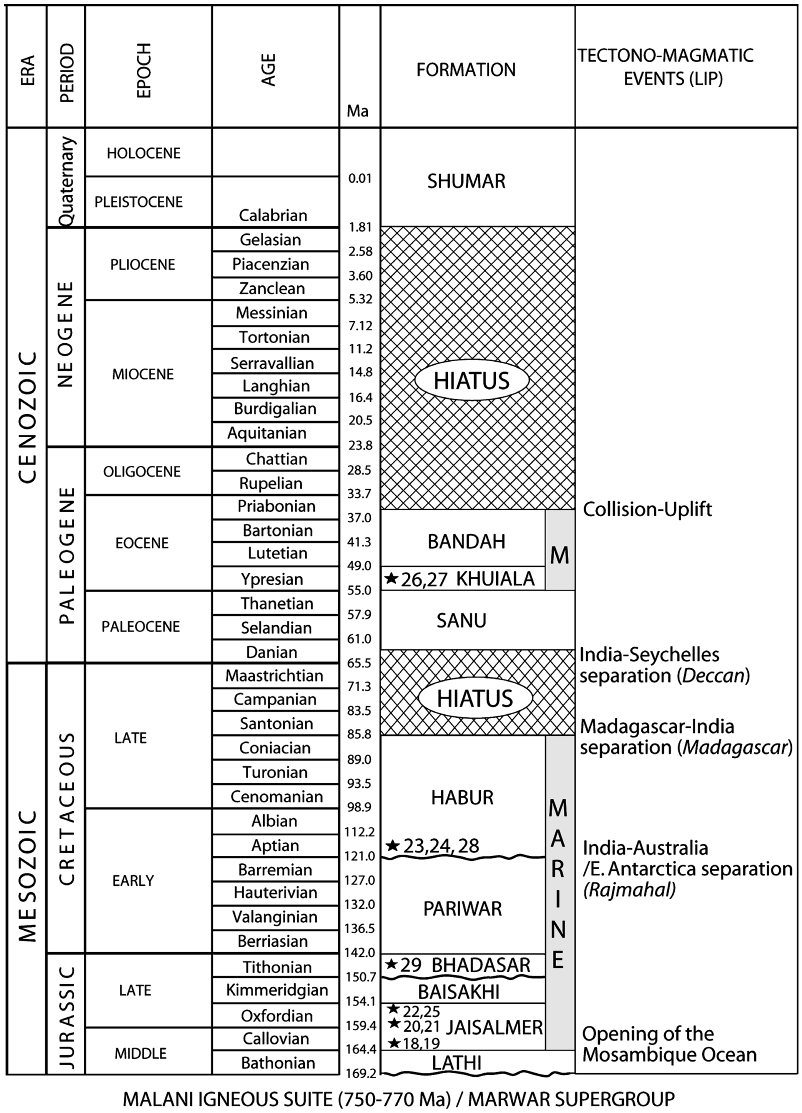

Figure 3. International commission on stratigraphy timescale (`http://micropress.org/stratigraphy/`), lithostratigraphy of the Jaisalmer basin (modified from Misra *et al.* 1993) and tectonomagmatic events relating to India and adjacent continents; LIP = large igneous province. Stratigraphic sampling levels are shown as black stars and denoted with the site number (see Fig. 1).

(∼85 Ma); the marine regression can be linked with the separation of India and Madagascar (Fig. 2) at that time (Storey *et al.* 1995; Torsvik *et al.* 2000). The Jaisalmer basin was renewed during the Palaeocene (∼65 Ma), simultaneous with the initial formation of the Barmer and Bikaner–Nagaur basins. The Mesozoic geological succession of the Jaisalmer basin has been illustrated in Fig. 3.

3 GEOLOGY OF THE JAISALMER BASIN AND SAMPLING LOCATIONS

The Jaisalmer basin shows a general younging and deepening trend towards the west (Fig. 1). The Liassic–Bathonian Lathi Fm. (Lathi Sandstone) unconformably overlies the 770–750 Ma Malani igneous suite (Torsvik *et al.* 2001) and the Marwar supergroup (Neoproterozoic—Early Cambrian?), and is recognized as the oldest Mesozoic unit in the Jaisalmer basin (Pareek 1984; Singh 1999). In the lower part, the Lathi sandstone (sequence of conglomerate, arkose, lithic arenite and coarse-grained sandstone with abundant gymnospermous fossil tree trunks, leaf impressions and silicified gastropod shells) is suggestive of deposition under stable delta conditions (GSI 2001). The Upper Lathi Fm. sequence includes bands of sandstone and siltstone grading into limestone, indicative of shallow marine shelf sedimentation.

The NW–SE trending rifted graben enabled a marine transgression in the Jaisalmer region, causing the end of shallow marine deposition. The Callovian–Oxfordian Jaisalmer Fm. consists predominantly of fossiliferous limestone (sampling sites 18–22, 25). The thickness of the Jaisalmer Fm. varies from 120 to 170 m (Das Gupta 1975). The limestone beds are generally horizontal (Table 1), but occasional steeper dips (∼30°) are observed close to some fault contacts.

The Jaisalmer Fm. is conformably overlain by the Baisakhi Fm. (Fig. 3), a 10–12 km wide semi-arcuate belt to the north and west of Jaisalmer. The main lithological units are grey and black gypsum-bearing shales, argillaceous sandstone and intraformational conglomerate. The Baisakhi Fm. is overlain by the Bhadasar Fm. (65 m in thickness), the latter representing a sequence of ferruginous sandstone with intercalations of thin shale beds (sampling site 29).

Table 1. Site mean directions (*in situ*) for Jurassic–Cretaceous limestones from the Jaisalmer basin (mean sampling location: 27°N, 70.75°E).

Site	Age	Strike/dip	Low unblocking (LB)				High unblocking (HB)			
		(°)	Dec.	Inc.	N	α_{95}	Dec.	Inc.	N	α_{95}
24	Cretaceous (Aptian)	0/0	5	51.8	19	3.9	302	−47.2*	10	14
23	Cretaceous (Aptian)	0/0	359.9	41.2	16	4.4	188.9	−47.1	13	5.5
28	Cretaceous (Aptian)	220/18	0.9	43.5	7	4.2	172.1	−34.7	10	11.6
29	Jurassic (Tithonian)	290/5	4	43.4	10	3.4	177.2	−46.7	8	6
25	Jurassic (Oxfordian)	0/0	354.1	58.7	6	9.7	343.1	29.9	6	14.6
22	Jurassic (Oxfordian)	15/3	2.3	41.3	13	2.3	162.5	−49.6	8	9.4
21	Jurassic (Oxfordian)	0/0	2.9	40.8	9	4.3	Irregular directional behaviour			
20	Jurassic (Oxfordian)	0/0	352.1	52	5	14.5	Irregular directional behaviour			
19	Jurassic (Callovian)	219/17	0.8	43.6	7	4.2	183.9	−54.7	6	10
18	Jurassic (Callovian)	49/23	355.2	42.9	7	4.1	158.7	−52.3	5	29.2
MEAN (except HB site 24):			359.9	46	10#	4.0	172	−45.5	7#&	9.1
Pole (except HB site 24):			90°S–237° E $dp/dm = 3/5°$				83°S–162° E $dp/dm = 7/12°$			

Dec., Inc. = mean declination, inclination; N = number of samples (#sites; &HB site 25 site mean inverted prior to calculation); α_{95} = 95 per cent confidence circle; dp/dm = semi-axis around the mean pole. *Site 24 pole: 12° S, 120° E, $dp/dm = 12/18°$.

Kimmeridgian and Tithonian ages have been assigned to these formations (Das Gupta 1975; Singh 1996).

A poorly exposed sequence of sandstone with intercalations of shale has been described as the Pariwar Fm. (Swami Nath *et al.* 1959). The rocks are largely devoid of faunal assemblages, however, on the basis of abundant angiospermic plant fossils, a Lower Cretaceous (Neocomian) age and continental intermittent shallow neritic depositional environments have been suggested (Das Gupta 1975; Lukose 1977). The overlying Habur Fm. consists of yellowish arenaceous limestone (sites 23, 24 and 28) with marl bands and coquinoidal limestone. The Habur succession represents a strand line facies environment marking the second major marine transgression and the fossil assemblage points to an Aptian age (Das Gupta 1975).

After a major hiatus (Fig. 3), the sedimentation in Jaisalmer basin commenced during the Palaeocene with deposition of glauconitic and silty sandstone of the Sanu Fm. The sedimentary attributes and lithological characters of the Sanu Fm. indicate a continental environment grading into inner to outer shelf marine conditions, inferred from the planktonic foraminiferal assemblage recorded in the younger sequences of the Sanu Fm. (Singh 1996). The Sanu Fm. is overlain by a 100-m-thick, predominantly calcareous Khuiala Fm. comprising horizontal, calcareous shale and limestone (sites 26, 27) of Late Palaeocene—Early Eocene age. The Khuiala Fm. is disconformably overlain by the Bandah Fm., which is the youngest Tertiary sequence in the Jaisalmer basin. It comprises bentonitic clay, argillaceous and chalky limestone.

4 PALAEOMAGNETIC EXPERIMENTS

The natural remanent magnetization (NRM) was measured on a JR6A spinner magnetometer in a magnetically shielded environment at the Geological Survey of Norway, Trondheim. Thermal demagnetization was carried out with an MMTD furnace and alternating field (AF) with an in-house two-axis tumbler demagnetiser. Bulk susceptibility was measured on a Barthington MS2 system. Characteristic remanence components were calculated with least-square algorithms using the SIAPD software of Torsvik, Briden and Smethurst (http://www.geodynamics.no/IAPD).

Samples from the Tertiary sites (26 and 27) have low NRM intensities (~0.1 mA M^{-1}) and the NRM directions are scattered. The demagnetization experiments are characterized by irregular directional behaviour and the Tertiary sites are therefore not discussed.

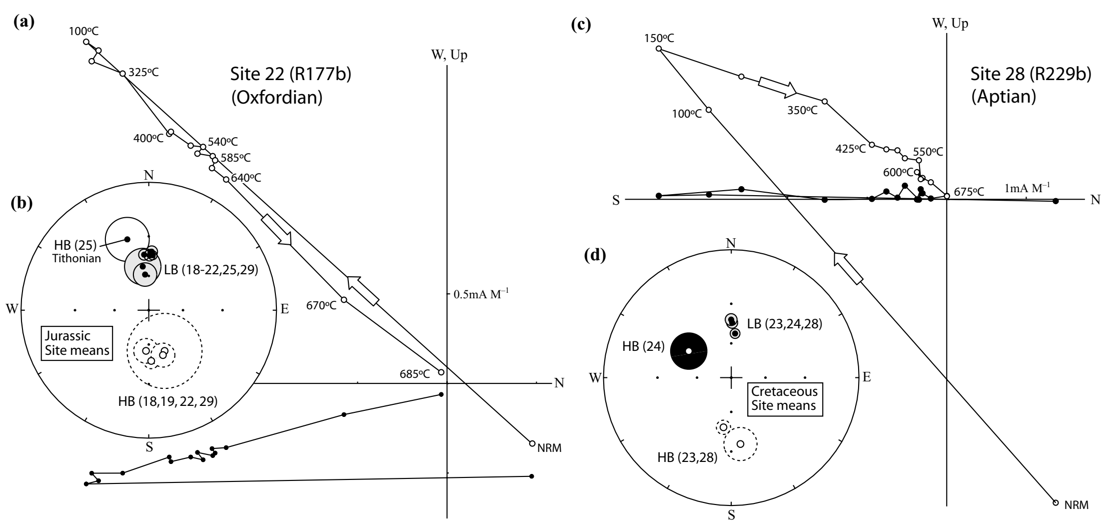

Figure 4. Typical examples of thermal demagnetization of Jurassic (a) and Cretaceous (c) samples from the Jaisalmer basin. Steroplots (b, d) show *in situ* site mean directions with 95 per cent confidence circles (Table 1). LB/HB = high/low unblocking components. In orthogonal vector plots (a, c), open (closed) symbols represent points in the vertical (horizontal) plane. In stereoplots (b, d), open (closed) symbols represent negative (positive) inclinations.

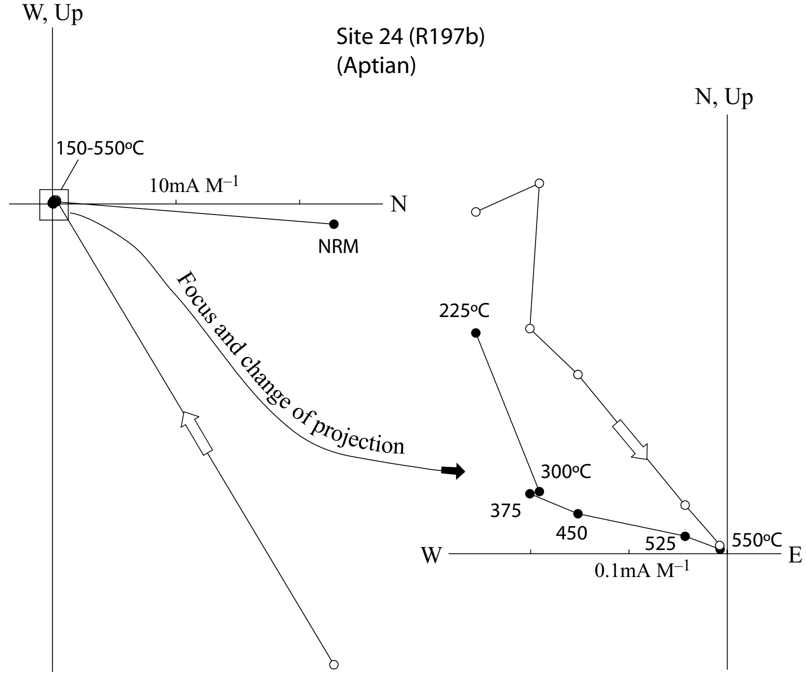

Figure 5. Example of thermal demagnetization of a site 24 (Cretaceous) sample. Note the large intensity drop at low temperatures (goethite) and that HB components from this site appear to be carried by magnetite (and not haematite observed from all other sites).

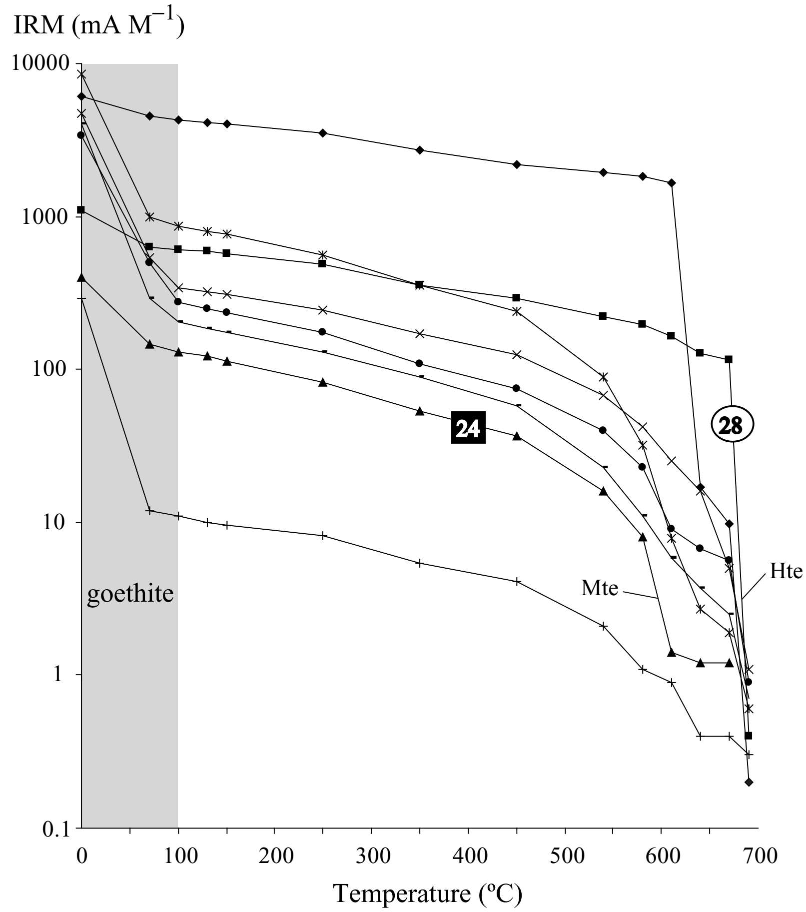

Figure 6. Example of thermal demagnetization of isothermal remanent magnetizations (IRMs; 1.3 T). IRM curves for sites 24 are 28 samples are annotated. Mte = magnetite; Hte = haematite. Note the logarithmic vertical scale.

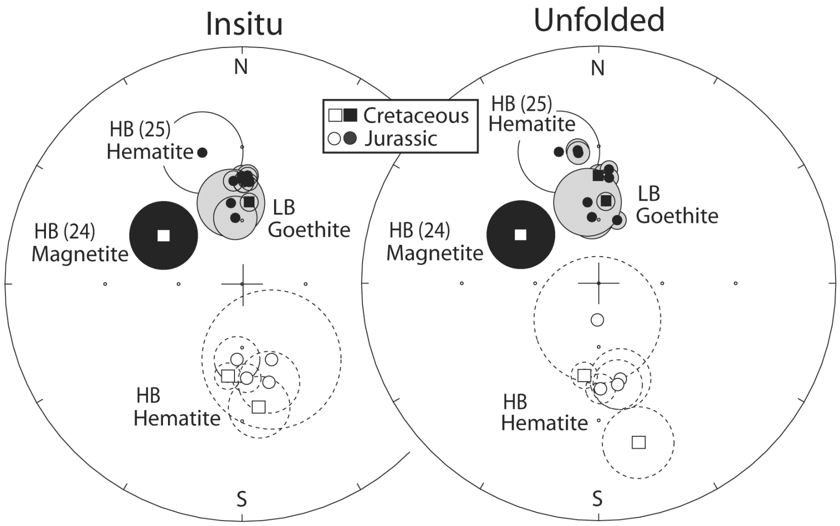

Figure 7. Summary of all site mean directions plotted in *in situ* and unfolded (100 per cent) coordinates. LB components (grey shaded 95 per cent confidence circles) fail a fold test whereas HB haematite components marginally fail a statistically valid negative fold test.

Jurassic and Cretaceous samples show a wide range of NRM intensities (typically 2–100 mA M^{-}) but low susceptibilities ($\sim 75^{*}10^{-6}$ SI units). All samples show a pronounced NRM intensity drop at low temperatures (Fig. 4) and the intensity is often reduced to less than 1 per cent at 100–150 °C. Goethite is therefore an important NRM carrier and the mean NRM direction for all samples (declination = 005°, inclination = 48°, $\alpha_{95} = 6°$) overlaps with the present earth field (PEF; declination = 0.5°, inclination = +41°) direction for the sampling location. Goethite is most commonly chemical in origin and Néel temperatures (blocking temperatures) have reported between 55 and 130 °C (Dekkers 1989 for overview). It is extremely resistant to AF demagnetization and most of the samples were therefore exposed to thermal demagnetization.

Most Jurassic samples show a two-component magnetization structure, i.e. a normal polarity low unblocking (LB) component (close to the PEF) and a high temperature (HB) component of reverse polarity with southerly declinations and negative inclinations (Figs 4a and b). The HB components are almost antipodal to the LB components and remanence stability up to 670–685 °C indicates haematite as the remanence carrier. HB directions from site 25 (Late Oxfordian; Fig. 3) differ from the other sites because HB components from this site (also carried by haematite) are of normal polarity (Fig. 4b).

HB components from the Cretaceous sites 23 and 28 are characterized by southerly declinations with negative inclinations of ∼45° (reverse polarity) and almost antipodal to goethite-bearing normal polarity direction (Figs 4c and d). HB components are carried by haematite with unblocking temperatures of up to 670–680 °C; site means are very similar to the Jurassic sites. Site 24 differs in that the HB components show northwest declinations with negative inclinations (Figs 4d and 5). Site 24 HB components are probably carried by magnetite as maximum unblocking temperatures vary between 540 and 575 °C (Fig. 5).

Isothermal remanent magnetization (IRM) curves demonstrate the influence of high-coercivity phases. No samples were saturated in the maximum available field of 1.3 T. Thermal demagnetization of the IRM induced samples reveals a large intensity drop (40–96 per cent) below 70–100 °C (Fig. 6) and demonstrates the dominance of goethite. In addition, most curves show pronounced unblocking above 650–670 °C (e.g. site 28 sample), indicative of haematite, whilst for example a sample from site 24 shows maximum unblocking below 600 °C (magnetite) in accordance with thermal demagnetization of the NRM (Fig. 5).

Table 2. Global apparent polar wander (APW) path in Indian coordinates (geocentric axial dipole (GAD) model of Torsvik & Van der Voo 2002). Running mean path with 10-Ma window length. A95 = 95 per cent confidence circle around mean pole; N = number of poles.

Age ± 10 Ma	A95	N	Pole Lat.	Pole Long.
0	4.8	11	−85.6	338.3
5	4.1	13	−87.1	23.0
10	3.8	15	−87.2	70.2
15	4.4	13	−85.2	95.8
20	4.3	18	−84.0	57.3
25	4.3	20	−83.4	67.0
30	4.2	20	−81.8	83.3
35	4.4	18	−80.8	97.4
40	3.8	18	−76.4	102.9
45	3.0	20	−72.9	101.6
50	2.9	28	−68.5	94.9
55	2.6	33	−63.3	95.4
60	2.8	37	−54.8	94.8
65	2.6	34	−45.3	95.8
70	2.9	31	−35.2	98.0
75	2.7	30	−30.3	100.1
80	2.9	33	−28.9	100.5
85	2.8	33	−25.6	103.8
90	3.0	31	−25.0	108.5
95	3.5	25	−23.9	111.1
100	5.0	11	−20.5	117.0
105	6.4	9	−14.7	117.2
110	3.9	16	−8.3	116.3
115	3.2	22	−3.4	115.6
120	3.2	24	−2.3	116.7
125	3.3	22	0.1	118.3
130	3.3	16	4.4	118.1

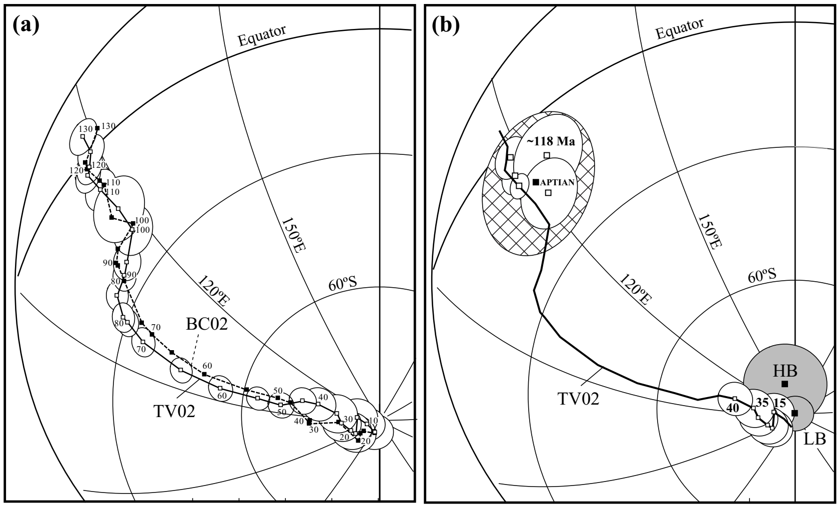

Figure 8. (a) Example of two global apparent polar wander (APW) paths plotted in Indian coordinates (TV02 = Torsvik & Van der Voo 2002, Table 2; BC02 = Besse & Courtillot 2002). BC02 running mean paths are not drawn with A95 confidence circles for diagram simplicity. (b) ∼118-Ma poles from India (listed in Torsvik & Van der Voo 2002) compared with the site 24 pole (Aptian; ∼ 117 Ma), the LB goethite poles and the HB haematite pole. TV02 running mean path (Table 2) is only shown with A95 confidence circles for the youngest sections.

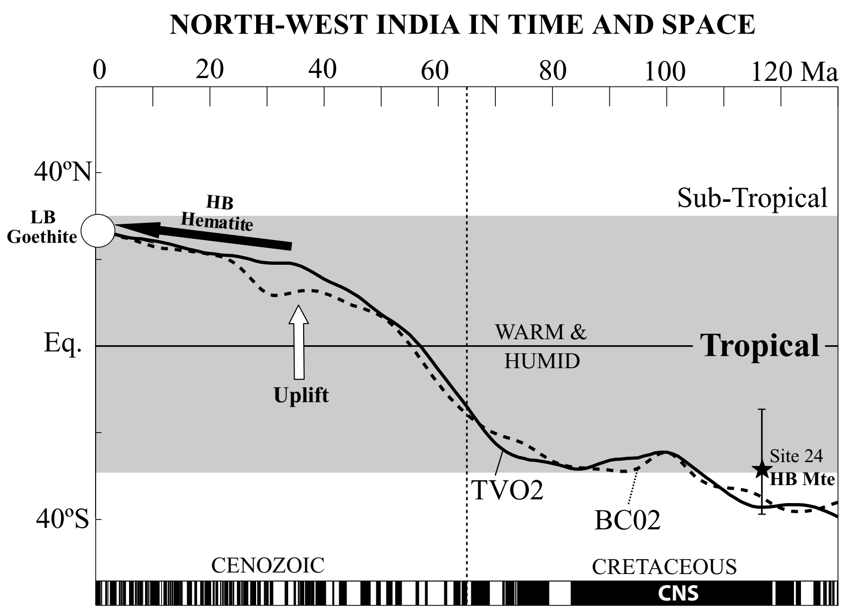

Figure 9. Latitudinal drift for NW India (27°N, 70.75°E) based on two different apparent polar wander (APW) models (see Fig. 8 caption). Geomagnetic polarity scale after Cande & Kent (1995); black = normal and white = reverse polarity; CNS = Cretaceous normal superchron, ∼118–83 Myr. Currently, subtropical high-pressure zones are located between 20 and 30° but in most palaeoclimatic modelling the subtropical high is placed at 30° latitude. See text for details.

5 INTERPERETATION AND CONCLUSION

Sampling sites are flat-lying or weakly folded/tilted with a NE–SW fold axis (Table 1) and LB site means fail fold tests (McFadden & McElhinny 1990) at the 95 per cent confidence. HB (reverse polarity) site means also become more dispersed during unfolding (Fig. 7) but the fold test is not statistically significant at the 95 per cent level. LB and HB components are not statistically different (positive reversal test—classification B of McFadden & McElhinny 1990) and they overlap with the geocentric axial dipole (GAD) direction (declination = 0°, inclination = +45.5°) and the PEF.

Only HB components from a single Early Cretaceous site (24) provide some hints of primary magnetization. This site embraces only 60 cm of Aptian stratigraphy (∼117 Ma) and may therefore represent a spot reading of the magnetic field of the Earth. The palaeomagnetic pole falls on the expected Early Cretaceous segment of global APW paths (e.g. Torsvik & Van der Voo 2002; Table 2; Besse & Courtillot 2002; Fig. 8a) and matches poles from, for example, the ∼118 Ma Rajmahal and Sylhet traps (Fig. 8b) in Eastern India (Fig. 2). In addition, site 24 is of normal magnetic polarity, which is expected for Aptian-aged rocks (within the Cretaceous normal superchron; Fig. 9). We therefore suggest that site 24 records an Early Cretaceous magnetization, but not conclusively of primary Aptian origin. If correct, this confirms the intermediate southerly palaeolatitude of India in Aptian times (Fig. 2). All remaining sites record a PEF component carried by goethite (LB) and a young HB remagnetization component of mostly reverse polarity (Fig. 7) carried by haematite. The HB component is obviously older than 780 000 yr (the last known reversal) but could be as old as 35 Ma when compared with global APW paths (Fig. 8b).

Weathering and erosion of rocks are primarily controlled by climatic factors, especially temperature and humidity. In the Late Eocene (∼35 Ma; Fig. 3), the sedimentary sequences in NW India were uplifted as a result of the ongoing India–Asia collision. NW India was located within the warm and humid tropics (Fig. 9), and thus uplift and subsequent erosion would have exposed Mesozoic strata to conditions of intense chemical weathering. Subsequently, NW India drifted into more arid or transitional latitudes (say $>20°$N) at ∼20 Ma (Fig. 9). Goethite is a common secondary iron oxide and extensively formed in humid environments. The view that goethite would more or less always dehydrate to haematite is commonly argued in the literature (e.g. Lowrie & Heller 1982; Özdemir & Dunlop 2000). However, goethite is a thermodynamically stable phase with respect to haematite plus water under a wide range of conditions (Grygar *et al.* 2003; Dekkers, private communication, 2004). It is therefore likely that haematite is a direct product of chemical weathering, depending on pH and availability of water, rather than representing dehydration of goethite.

6 IMPLICATIONS

Stratigraphically linked reversals in a sedimentary sequence are usually considered as the definitive evidence for primary remanence. However, our study demonstrates that secondary HB components carried by haematite can have dual polarity. Fortunately, the drift history for India during the Mesozoic is reasonably well constrained and these HB components should not be mistaken as primary. Furthermore, HB components are more dispersed after unfolding and indicate a post-fold origin. However, when dealing with old rocks where reference data are poor to non-existent and fold tests are not available, dual polarity remagnetization may well result in a conclusion that HB components were primary. Hence, we call for caution in interpreting all sedimentary sequences with dual polarity magnetizations as primary.

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REFERENCES

Besse, J. & Courtilliot, V., 2002. Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 Myr, *J. geophys. Res.,* **107**(B11), 2300, doi:10.1029/2000JB000050.

Cande, S.C. & Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic, *J. geophys. Res.,* **100,** 6093–6095.

Coffin, M.F. & Rabinowitz, P.D., 1988. Evolution of the conjugate East African-Madagascan margins and the western Somali Basin, *Geol. Soc. Am. Special Paper,* **226,** 78 pp.

Das Gupta, S.K., 1975. Revision of the Mesozoic—Tertiary stratigraphy of the Jaisalmer Basin, Rajasthan, *Ind. J. Earth Sci.,* **2,** 77–94.

Dekkers, M.J., 1989. Magnetic properties of natural goethite-I. Grain-size dependence of some low- and high-field related rockmagnetic parameters measured at room temperatures, *Geophys. J.,* **97,** 323–340.

Grygar, T., Dědeček, J., Kruiver, P.P., Dekkers, M.J., Bezdička, P. & Schneeweiss, O., 2003. Iron oxide mineralogy in late Miocene red beds from La Gloria, Spain: rock-magnetic, voltammetric and Vis spectroscopy analyses., *Catena,* **53,** 115–132.

Geological Survey of India (GSI), 2001. Geology and Mineral Resources of Rajasthan, *Geological Survey of India Miscellaneous Publication,* **30**(12), 113 pp.

Lowrie, W. & Heller, F., 1982. Magnetic properties of marine limestones, *Rev. Geophys. Space Phys.,* **20,** 171–192.

Lukose, N.G., 1977. Palynological evidence on climatic changes in Jaisalmer Basin, Rajasthan, *Desertification and its Control,* Vol. 5, pp. 31–41 ICAR, New Delhi.

McFadden, P.L. & McElhinny, M.W., 1990. Classification of the reversal test in palaeomagnetism, *Geophys. J. Int.,* **103,** 725–729.

Misra, P.C., Singh, N.P., Sharma, D.C., Upadhyay, H., Kakroo, A.K. & Saini, M.L., 1993. *Lithostratigraphy of west Rajasthan basins,* Oil and Natural Gas Commission, Dehradun, unpublished report.

Özdemir, Ö. & Dunlop, D.J., 2000. Intermediate magnetite formation during dehydration of goethite, *Earth planet. Sci. Lett.,* **177,** 59–67.

Pareek, H.S., 1984. Pre-quaternary geology and mineral resources of norhtwestern India, *Geol. Surv. of India Mem.,* **115,** 91 pp.

Plummer, Ph.S. & Belle, E.R., 1995. Mesozoic tectono-stratigraphic evolution of the Seychelles microcontinent, *Sed. Geol.,* **96,** 73–91.

Roy, A.B. & Jakhar, S.R., 2002. *Geology of Rajasthan (Northwest India): Precambrian to Recent,* Scientific Publishers (India), Jodhpur, p. 421.

Singh, N.P., 1996. Mesozoic—Tertiary biostratigraphy and biogeochronological datum planes in Jaisalmer Basin, Rajasthan, in *Contributions to XV Indian Colloquium on Micropaleontology and Stratigraphy,* pp. 63–89, eds Pandey, J., Azmi, R.J., Bhandari, A. & Dave, A., KDMIPE and WIHG, Dehradun.

Singh, N.P., 1999. *Relevance of laboratory studies in geological modelling and field geology; Jaisalmer field guide,* ONGC, Dehradun, pp. 1–14.

Storey, M., Mahoney, J.J., Saunders, A.D., Duncan, R.A., Kelley, S.P. & Coffin, M.F., 1995. Timing of hot spot-related volcanism and the break-up of Madagascar and India, *Science,* **267,** 852–855.

Swami Nath, J., Krishnamurthy, J.G., Verma, K.K. & Chandak, G.J., 1959. General Geology of Jaisalmer area, Rajasthan. In: *ECAFE symposium on Mineral Research and Development,* pp. 154–155. ONGC, Dehradun.

Torsvik, T.H. & Van der Voo, R., 2002. Refining Gondwana and Pangea Palaeogeography: Estimates of Phanerozoic (octupole) non-dipole fields, Geophys, *J. Int.,* **151,** 771–794.

Torsvik, T.H., Tucker, R.D., Ashwal, L.D., Carter, L.M., Jamtveit, B., Vidyadharan, K.T. & Venkataramana, P., 2000. Late Cretaceous India-Madagascar fit and timing of break-up related magmatism, *TerraNova,* **12,** 220–224.

Torsvik, T.H., Carter, L.M., Ashwal, L.D., Bhushan, S.K., Pandit, M.K. & Jamtveit, B., 2001. Rodinia refined or obscured: Palaeomagnetism of the Malani Igneous Suite (NW India), *Prec. Res.,* **108,** 319–333.