Polarity inversion in the Rajmahal lavas, north-east India: trap emplacement near commencement of the Cretaceous Normal Superchron

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SUMMARY
To evaluate suggestions from earlier work that a reversal of magnetization is present in the Rajmahal Traps of mid-Cretaceous (probable Aptian) age in north-eastern India, we have sampled a 140 m thick section comprising a minimum of nine flow units at 25 sites in the north-western part of the outcrop. A coherent N→R→N magnetostratigraphy is identified, with evidence for transitional behaviour at the top and bottom of the succession.

The mean characteristic remanence direction of the reversed sites (D/I = 145.7°/63.5°, \(x_\alpha = 6.0°\)) is approximately antiparallel to that of the normal polarity sites (D/I = 300.2°/-55.7°, \(x_\alpha = 12.4°\)), and the group mean confirms a palaeomagnetic pole position near 125°E, 9°s (\(x_\alpha = 10.5°\)) for the time of eruption of the traps. From \(^{40}\)Ar/\(^{39}\)Ar evidence that the Rajmahal–Bengal Traps were emplaced over a short interval at ca. 117 Ma, we interpret the brief reversed episode identified near the base of the succession as a record of the ISEA event. The polarity evidence therefore supports the view that the Rajmahal Traps were fed by the Crozet Hotspot at the beginning of the Cretaceous Normal Superchron (-119–83 Ma).

Key words: magnetostratigraphy, palaeomagnetism, Rajmahal Traps.

1 INTRODUCTION
The Rajmahal volcanic episode of NE India comprises a suite of tholeiitic lavas with occasional flows of pitchstone, andesite and trachytic composition. The lavas are intercalated with sediments assigned to the Upper Gondwana system (Ball 1876; Pascoe 1959; Sarkar, Nag & Mallik 1989). They dip gently to the east beneath Gangetic deposits and appear to be an exposed component of a large eruptive episode comprising the Bengal Traps (now only preserved as subcrop) and the Sylhet Traps, lying some 400 km to the north-east (Mahoney et al. 1983).

Palaeomagnetic study of Rajmahal lavas commenced in the 1950s with results reported by Clegg, Radhakrishnamurty & Sahasrabudhe (1958; mean declination/inclination (D/I) = 328°/−64°). These data were not progressively demagnetized but subsequent studies by Radhakrishnamurty (1963, 1970; D/I = 322°/−64°), McDougall & McElhinny (1970; D/I = 310°/−67°) and by Athavale et al. (1970) of the correlative Sylhet Traps (D/I = 332°/−59°) based on alternating field (a.f.) cleaned data, yielded closely similar directions of characteristic remanence. These studies were all concentrated in the eastern part of the Rajmahal Hills and identified remanence of uniform normal polarity acquired when India lay in the southern hemisphere.

Subsequently, Klootwijk (1971) reported results from 27 sites distributed across the Rajmahal outcrop; the majority were of normal polarity, but two sites appeared to record a reversed magnetization. Further studies by members of Jadavpur University (Ghosh 1979; Bagchi 1991) also identified reversed magnetized sites, whilst Sherwood, Baer & Mallik (1993) recorded two sites with transitional and reversed directions at Pakur and Gandheswari, although it was unclear whether the sampled exposures were in situ.

This collective evidence suggests that at least one reversal of the geomagnetic field is recorded by the Rajmahal Traps. However, the lavas were dated as 103–108 Ma using the K–Ar method (McDougall & McElhinny 1970; recalculated using decay constants recommended by Steiger & Jager 1977), and Dalrymple & Lanphere (1974) reported a \(^{40}\)Ar/\(^{39}\)Ar isochron age of 108.6 ± 3.8 Ma. These data place the volcanic episode near the middle of the Cretaceous Normal (CN) Superchron (ca. 119–83 Ma; Harland et al. 1990). The lavas have, therefore, been a focus of investigations to evaluate the intensity of the magnetic field during this superchron (Sherwood et al. 1993).

More recent radiometric studies by Baksi et al. (1987) and...
Baksi (1995) have obtained a range of \(^{40}\text{Ar}/^{39}\text{Ar}\) age estimates from 111 to 119 Ma. Baksi (1995), reviewed the evidence, and proposed that the Traps were emplaced during a short period of time (~2 Ma) at ca. 117 Ma. Identification of a brief reversal within the lava succession would therefore enable emplacement of the traps to be constrained to the beginning of the CN Superchron. Accordingly, to evaluate the magnetic stratigraphy, we have sampled 158 cores at 27 sites through a succession at Bejam Pahar near the base of the sequence at Hettbandha in the north-western Rajmahal Hills. An outline geology of the sampled region is illustrated in Fig. 1(a) and the measured stratigraphic succession is shown in Fig. 1(b).

2 GEOLOGICAL OUTLINE AND FIELD SAMPLE COLLECTION

The Rajmahal Traps are the volcanic component of a lava-sediment succession which crops out over an area of about 10,250 km\(^2\) in West Bengal and Bihar, between latitudes 24.1°N and 25.4°N, and longitudes 87.0°E and 87.9°E (Fig. 1, inset). At two levels [including the study section; see Fig. 1(b)], the lavas are separated by inter-lava sediments; however, from the poorly preserved terrestrial faunas it is only possible to constrain eruption to the late Carboniferous-mid Cretaceous interval (Ghosh 1979). The traps comprise at least 600 m of tholeiitic lava flows of uniform composition. They are perceptibly horizontal and overlap with an erosional break and small angular discordance onto sediments of the Dubrajpur stage of Upper Triassic age and then onto metamorphic basement (Fig. 1a). Hobson (1929) identified a minimum of 10 independent lava flows, ranging in thickness from 20 to 75 m, whilst Pascoe (1959) considered that considerably more flows are present. At Bejam Pahar Hill, the location of this study, at least nine lava flows extend along a N–S outcrop for 7 km (Fig. 1a). The lava flows typically have coarse-grained interiors passing outwards into fine-grained vesicular and amygdaoidal margins.

Although the Traps are only constrained to an interval between the late Triassic (du Toit 1937) and the Cretaceous (Spath 1933) from faunal evidence, Shah & Jain (1965) suggested an age between early Jurassic and early Cretaceous from floral (spore and pollen) evidence. The \(^{40}\text{Ar}/^{39}\text{Ar}\) evidence noted above therefore provides the best constraint on the age of the volcanic episode, and places it within the Aptian stage (112–121 Ma) of the Cretaceous. The Traps comprise the highest (and only volcanic) formation of the Gondwana Super-group, which is divided into a Lower Gondwana sequence containing a Glossopteris flora (Lower Carboniferous-Lower Permian) and an Upper Gondwana sequence containing a Ptilophyllum flora (Upper Triassic-Cretaceous).

Between three and five oriented block samples were collected at intervals through the succession, as shown in Fig. 1(b). Sampling was concentrated on fresh, near-vertical outcrops, and a declination gradiometer (Doell & Cox 1962) was used to locate, and subsequently avoid, outcrop influenced by lightning strikes. Two or three cores 2.5 cm in diameter and 2.2 cm in length were drilled from each block in the laboratory.

Figure 1. (a) Simplified geological map of the north-western Rajmahal Hills, India, showing the location of the sampled section. (b) Measured stratigraphic section with location of palaeomagnetic sites and recognized flow boundaries; altitude is above O.D.
3 Palaemagnetic results

Rock magnetic results from the Rajmahal Traps are reported by Radhakrishnamurty, Likhite & Sahasrabudhe (1977, 1991) and Sherwood et al. (1993). The results were supplemented for this study by polished section investigation and thermomagnetic and X-ray analysis. Collective results confirm that titanomagnetite and ilmenite are the dominant opaque oxides in the basaltic lavas. Ilmenite occurs both as discrete grains and as intergrowths with magnetite. There are two contrasting textures. Samples from near the margins of the flows are characterized by skeletal magnetic forming rows of meltte cross in a typical quench texture. Thermal demagnetization and thermomagnetic (saturation magnetization, J_s, versus temperature) determinations highlight a Curie point of about 450°C, corresponding to ~17 per cent ulvospinel substitution (Nagata 1961); these grains and accompanying ilmenite grains appear homogeneous and correspond to low deuteric oxidation states.

A second type of behaviour is recognized in samples from the interiors of the flows, in terms of stepped J_s-T and thermal decay profiles. These indicate two Curie points at about 200-300°C and 500-550°C, corresponding to contrasting grain properties in these interior sites. The lower unblocking magnetization is probably resident in the large, homogenous grains found only at these sites; higher unblocking magnetizations are linked to oxidation states 2-4 of Wilson & Watkins (1967), and low-Ti substitution could account for the high Curie point by progressive a.f. demagnetization and measured by an astatic magnetometer in the NGRI Laboratory at Hyderabad. Two sites (1.7 and 1.9) yielded no stable magnetizations; mean sites (1.7 and 1.9) yielded no stable magnetizations; mean directions for the remaining coherent site ChRMs after cleaning are summarized in Table 1.

Table 1. Site mean palaemagnetic results from the Rajmahal lavas, North West Rajmahal Hills (87.4°E, 25.0°N) after thermal and a.f. cleaning.

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<th>Site No</th>
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<th>D</th>
<th>I</th>
<th>k</th>
<th>α_{95}</th>
<th>R</th>
<th>Polarity</th>
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</table>

Group Mean, normally magnetized sites: 12 sites 300.2 -55.7 13 12.4 11.17
Group Mean, reversely magnetized sites: 7 sites 145.7 63.5 104 6.0 6.64
Overall Mean: 19 sites 308.5 -59.2 17 8.3 17.96
(Palaemagnetic Pole: 124.8°E, 9.3°N, dp/dm = 9.2/12.4')

D and I are the declination and inclination of the mean magnetization derived from the characteristic remanences in N cores at each site, yielding a resultant vector of length R; k is the Fisher precision estimate [=(N-1)R/(N-R)]; and α_{95} is the radius of the cone of 95 per cent confidence about the mean direction. dp and dm are the radii of the oval of confidence about the pole position derived from the mean direction in the colatitude direction and at right angles to it, respectively. Polarieties are N = Normal, R = Reversed and I = Intermediate (>40° from the mean).

Figure 2. Typical examples of intensity of magnetisation, J, normalized by the initial value, J_0, as a function of temperature. A dominantly low unblocking temperature spectrum characterizes samples from the margins of the flows; in contrast, samples from the interiors tend to have higher and more distributed blocking temperatures with stepped profiles. A small initial increase in J characterizes most of the samples with reversed polarity as a viscous component in the present field is removed.

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Site 1.1 identifies normal polarity in the lava at the base of the succession. Succeeding sites (1.2 to 1.5), in a fine-grained unit, yield divergent directions, but site 1.6 at the top was evidently baked by the immediately overlying 30 m thick blocky unit, which has uniform reversed polarity throughout (sites 1.8 to 1.13). The same polarity is recorded by the thin lava (1.14) within the intertrap sediments. However, by the time eruption of the traps resumed, the geomagnetic field polarity had reverted back to normal. This polarity is preserved in the succeeding flows, with the exception of the uppermost flow, where divergent, shallow, positive-directed magnetizations are recorded (Table 1) and suggest that possible inversion towards another reversed field was underway. Sample intensities of magnetization also drop at this point (Fig. 4), although a formal palaeointensity study would be required to support a link with the geomagnetic field behaviour here.

Group mean values of the normal and reversed field directions (see Fig. 5) are $D/I = 300.2^\circ/-55.7^\circ$ ($z_{95} = 12.4^\circ$) and $D/I = 145.7^\circ/63.5^\circ$ ($z_{95} = 6.0^\circ$). The confidence circles just overlap, but since it is likely that no more than seven short cooling intervals are represented in the succession here (five normal, two reversed; see Fig. 4), a reversal test is not meaningful. Whilst the considerable thicknesses of some of the lava units in this succession will have prolonged the interval of magmatic and deuteric processes responsible for fixing the magnetizations, it is therefore necessary to examine (i) whether secular
variation is averaged by the group mean calculation and (ii) whether the near-antiparallel field direction is representative of a field reversal.

Mean normal polarity directions derived from earlier (cleaned) studies show only minor differences from the results of the present study. The mean direction derived by Radhakrishnamurty (1970; $D/I = 323^\circ/-64^\circ$) is almost exactly antiparallel to the reversed direction obtained in this study. Whilst Radhakrishnamurty’s (1970) result has a slightly more northerly declination with respect to the studies of McDougall & McElhinny (1970; $D/I = 310^\circ/-67^\circ$) and Klootwijk (1971; $D/I = 315^\circ/-65^\circ$), and therefore might include a small present field component, such a contribution would be most prominently expressed in terms of a shallower inclination, which is not apparent. Thus, the reversed direction of this study is precisely antiparallel to normal field direction recorded in the Rajmahal Traps, although it may be recorded by no more than two volcanic events, as highlighted by the low dispersion of the site mean directions (Fig. 5).

The normal polarity direction of the present study is approximately 10° shallower than that defined by earlier studies. However, it is probably no more contaminated by present field components, because the declination is significantly more westerly and therefore removed from the present field direction. It is biased by the westerly declination and the increasingly negative inclination observed upwards through the first normal unit above the intertrap sediments (sites 1.15 to 1.19 in Table 1; Fig. 5). The mean calculation is biased by results from only three flows (sites 1.16 to 1.24), and is probably not a representative average of ancient secular variation. Because the Rajmahal succession seems to contain a rather small number of lava units (Hobson 1929; Pascoe 1959) only a grand mean of all results should be interpreted as a palaeomagnetic pole (Klootwijk 1971).

4 DISCUSSION

The Rajmahal Traps dip very gently towards the Bengal Trap subcrop to the east, and the section studied here from Hetbandha was probably emplaced at, or near to, the beginning of the volcanic episode. The palaeomagnetic study shows that a brief reversed event was recorded near commencement of trap emplacement (Fig. 4).

McDougall & McElhinny (1970) discussed palaeontological evidence for the age of the Rajmahal Traps, noting that the terrestrial floral evidence is weighted towards an age somewhat older than the late Lower Cretaceous. A younger age limit for the Traps is given by the age of the overlying Boipur Formation, which is correlative with the Rajmahal Traps in the Bengal Basin to the east and contains a flora of primitive dicotyledon pollens of Early Cretaceous to early Late Cretaceous age (Biswas 1963). The K–Ar age determinations of McDougall & McElhinny (1970) from four lava flows yielded ages ranging from 107 to 82 Ma; the authors argued the case for argon loss in their older age determinations and concluded that a minimum age of 103–108 Ma was implied by their results, thus placing the Rajmahal episode well within the CN Superchron. The more recent evidence of Baksi et al. (1987) and Baksi (1995) shifts the radiometric estimate of the emplacement age towards 117 Ma, and therefore close to the beginning of the CN Superchron.

$^{40}$Ar/$^{39}$Ar determinations from basalts between marine magnetic anomalies CM01 and CM1 give ages of 122–123 Ma (Mahoney et al. 1993; Pringle et al. 1993), suggesting a minimum age of 121.8 Ma for the M0 anomaly at the beginning of the CN Superchron (Pringle et al. 1993). The existence of a brief interval of reversed polarity ($<100$ ka) during this part of the superchron, designated as ‘ISEA’, has been recognized in Aiptian successions by VandenBerg, Klootwijk & Wonders (1978) and Tarduno (1990). Two of Baksi’s (1995) study sites are located within the Rajmahal Trap outcrop and towards its eastern margin; they include a maximum $^{40}$Ar/$^{39}$Ar determination of 118 ± 8 Ma. In the context of his general assessment that the data imply eruption of the traps over a short period at ca. 117 Ma, it seems probable that the short reversed event recorded by two lavas near the base of the succession represents the ISEA event. No reversed flows have been identified above this, and it seems probable that the entire eruptive episode was concentrated near the beginning of the CN Superchron.

Recent reconstructions of the north-eastern Indian Ocean have been based on the premise that the Rajmahal Traps were formed by the Kerguelen Hotspot that later formed the 90°E Ridge (Duncan & Richards 1991; Royer & Sandwell 1989). This assumption has been questioned by Curray & Munasinghe (1991), who proposed that the Rajmahal Traps, the 85°E Ridge, and the Afanasy Nikitin Seamount were formed as the trace of a hotspot on the Indian Plate. The hotspot subsequently formed the Crozet Islands on the Antarctic Plate. The assumed location of the hotspot at Crozet is compatible with published models of absolute plate motion (Duncan & Richards 1991). Furthermore, the palaeolatitude of the Rajmahal Traps [46.9°S, as derived from the regional sample of Klootwijk (1971)] is indistinguishable from the latitude of the Crozet Island Group [46.1°S–46.4°S]. The Crozet hotspot therefore appears to have fed the Rajmahal–Bengal–Sylhet Traps on the Indian Plate at ca. 117 Ma (Curray & Munasinghe 1991; Baksi 1995). Possible anticlockwise
rotation of the Indian Plate during emplacement is suggested by the mean declination of $D = 308^\circ$, derived from the base of the succession in this study, and the mean regional declination incorporating higher lavas of $D = 315^\circ$, derived by Klootwijk (1971).

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REFERENCES


