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Petrography, geomagnetism, and rare-earth element abundances of the Rajahmundry lavas, eastern India

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Abstract—Closely jointed, veined and locally sheared basalts some 15–20 m thick are exposed in quarries at Gauripatna and Kateru on the banks of the Godavari River, near Rajahmundry, Andhra Pradesh, India (17°N 21°E). The clinopyroxene in these basalts is variably replaced by saponite, which locally preserves the primary phenocryst shape. At Gauripatna, the amygdales have dolomite in the centre and saponite in the rim; opaque phases occur only as dendritic aggregates within saponite. At Kateru, dolomite is absent and large and hypidiomorphic magnetite mantles fresh clinopyroxene. Measured rare-earth element (REE) concentrations indicate the occurrence of light REE-enriched basalts, most probably derived from a single mantle source region by different degrees of partial melting. Comparison with published data indicates that the Rajahmundry basalts have REE abundances similar to lavas from the Deccan Traps, western India. Fairly intense brittle deformation of the Rajahmundry lavas, at both the scale of outcrop and hand specimen, is evident in the deeper parts of the quarries. A pilot study of the magnetic fabric shows a large apparent spread in azimuth. Palaeopole positions derived from such deformed lavas are likely to be unreliable, due to replacement of primary iron oxides. Copyright © 1996 Elsevier Science Ltd

Introduction

During the last two decades, the Oil and Natural Gas Commission and Oil India Ltd have drilled several boreholes along the western flank of the Bengal Basin, both onshore and offshore (inner shelf). This exploration programme has not yet been successful in locating an oilfield, but has revealed the presence of a largely concealed basaltic lava field, extending below the Bengal Basin from the Rajmahal Hills in the north to the continental shelf off the Mahanadi River in the south, a distance of nearly 500 km (Fig. 1). The basalts appear to be of Early Cretaceous age, ranging from *c.* 117 Ma in the Rajmahal area (Baksi 1986) to *c.* 100 Ma in the inner shelf sequence off the Mahanadi delta (U. Dasgupta personal communication 1993). Judging by the nature of the inter-trappean sediments, the volcanic eruptions appear to have occurred in both continental and marine environments. Whether these lavas continue below the offshore Tertiary sediments further south, near the coast of southern Orissa and northern Andhra Pradesh, is not known. Beyond a gap of about 415 km, lavas are again found near Rajahmundry, some 75 km inland from the present coast, but close to the Cretaceous shoreline (Fig. 1). The rocks are exposed intermittently on either side of the Godavari River from near Gauripatna (17°03′N, 81°34′E) on the Rajahmundry–Eluru Highway to near Kateru (17°02′N, 81°50′E). Since the 1950s, these rocks have been mapped and studied by a number of geologists (see Pascoe 1964, for references). Fossil assemblages in the inter-trappean sediments indicate that volcanic eruptions took place in a coastal environment towards the end of the Cretaceous.

The Rajahmundry lavas have recently been dated at *c.* 64 Ma ($^{40}Ar/^{39}Ar$; Baksi *et al.* 1992, 1994). Although there are outcrops of Deccan Traps lying only 340 km northwest of Rajahmundry, the estuarine fossils in the inter-trappean sediments in the latter area are indicative of a shallow marine eruptive environment—a feature that could possibly have prompted Pascoe (1964, p. 1381) to suggest that a correlation of the Rajahmundry lavas with the Deccan igneous province is doubtful. This paper presents petrographic, structural, rock magnetic and rare-earth element data from samples from the Rajhamundry volcanic field. The petrography of the lavas is discussed, and some of the problems inherent in geomagnetic studies of whole-rock samples are illustrated.

Structural features and petrography

The countryside around Rajahmundry is nearly flat, and the lava flows are capped by laterite and lateritised sandstone. As a result, exposures of fresh lavas are not generally seen. It is only in the lower benches of the quarries that fresh rocks become available for study. Even the freshest rocks do not display primary flow structures. Secondary structures include (i) sphaeroidal weathering in the upper levels (5–10 m) of quarries, with flat and steeply dipping joint surfaces; (ii) strongly cleaved and sheared zones with impersistent veins of silica; (iii) zones of vertical to steeply dipping hexagonal joint systems, locally veined with silica; (iv) pockets of anastomosing veinlets with vugs of silica, up to 15 cm long and 8 cm wide; and (v) slickensided zones a few mm thick, consisting of chlorite-rich veins.

Below the weathered crust, the lavas are moderately porphyritic, with plagioclase (An_{40-60}) and colourless clinopyroxene phenocrysts. Plagioclase occurs both as fine to very fine laths, in intergranular arrangement with clinopyroxene, and in the form of glomeroporphyritic aggregates. Certain phenocrysts show normal or oscillatory zoning. Some zoned grains have partly resorbed nuclei, indicating disequilibrium in the magma chamber during plagioclase nucleation. The plagioclase grains are fresh, though frequently bent or broken. The clinopyroxene is also deformed and altered locally to chlorite, whose lamellae are bent (indicating that deformation is post-magmatic). Clinopyroxene is mantled by brown to greenish-brown saponite, carrying dendritic to star-shaped aggregates of opaques. Rarely preserved elliptical colour bands within saponite and inclusions of dolomite are seen in thin sections. These suggest that saponite and dolomite represent amygaloidal infillings. Commonly, the amygaloidal outline is smeared out. While the lavas at Gauripatna contain a low percentage of opaques, the Kateru samples show coarse-grained magnetite mantling all other minerals, including saponite.

The abundance of amygdales within the lavas is a serious limitation against dating whole-rock samples. However, single grain K–Ar or $^{40}Ar/^{39}Ar$ dating of fresh plagioclase phenocrysts could possibly yield acceptable concordia for determining the age of eruption.

Geomagnetic properties

Iron–titanium oxide minerals in the lavas are generally post-magmatic, as indicated by their texture. The degree of structural disturbance is also strong. It is suspected that the normal and reverse polarity of the flows, reported by Pal and Bhimasankaran (1971) and Subbarao and Pathak (1993), could signify post-eruptive regional magnetic fields. Therefore, the orientations may not provide a direct record of eruption and are not suitable for determination of palaeopoles (*cf.* Van der Voo 1990). To illustrate this point, oriented samples of basalt collected from the quarries at Gauripatna and Kateru were tested in a preliminary fashion for measuring the extent of variation within, and between, samples from the same location. Cores measuring 25.4 mm in diameter and 22 mm in height were drilled and extracted carefully from the oriented samples. The drilled cores were kept for a month before the measurements were performed, firstly on a Schonstedt spinner magnetometer at the National Geophysical Research Institute, Hyderabad, and then on a LAM 24 Astatic magnetometer at the Alibag Laboratory, Indian Institute of Geomagnetism. Measured values are listed in Table 1, where the two sets of results are seen to corroborate one another.

The samples were not magnetically cleaned, and significant differences in magnetic properties caused by alteration of the fine-grained opaque minerals cannot be ruled out (*cf.* Radhakrishnamurty and Subbarao 1990). The large departures in $D°$, $I°$ and J_n from one sample to another are, however, not due to errors in sampling or cutting and re-orienting, as demonstrated in Table 2 for two cores cut from the same sample.

Shear zones within the lavas also introduced major distortions. Two core samples were cut from another hand specimen, one along a 5-mm-thick shear zone filled with chlorite, and the other some distance away from this feature but cut parallel to the first core. The readings from the two cores are listed in Table 3. It is noteworthy that the values of inclination and intensity remain within

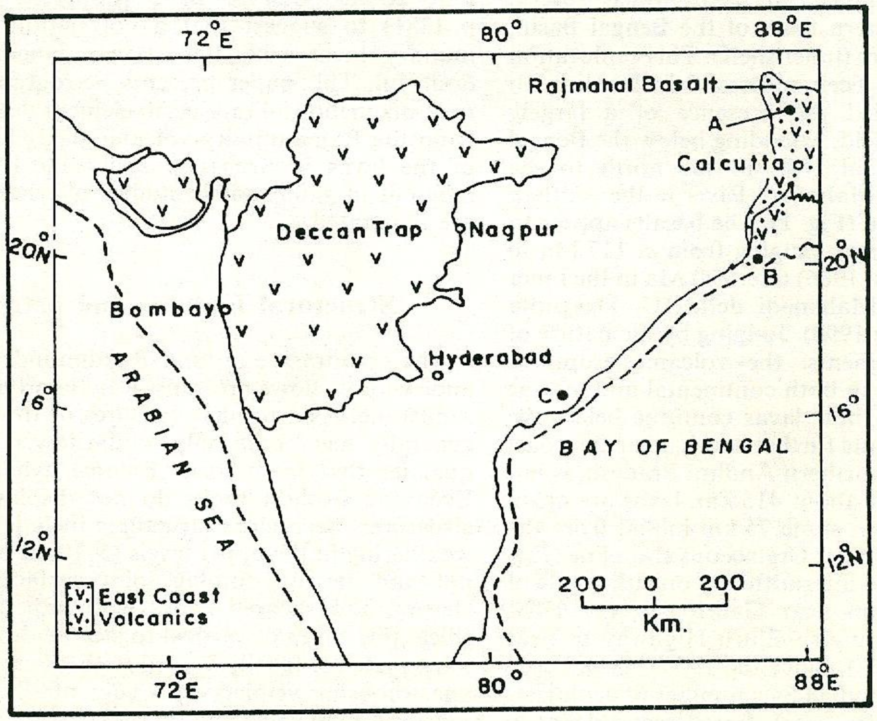

Fig. 1. Outline map of the Indian Peninsula, to show location of the Rajahmundry basalts. The edge of the continental shelf (approximated by the 150-m isobath) is indicated by a dashed line. Key: A, boreholes around Bolpur and Berhampur intersected volcanic rocks at 1000–3500 m below the sedimentary cover (*cf.* Roybarman 1983); B, boreholes off the Mahanadi delta intersected 25–850-m-thick volcanic rocks associated with tuffs and inter-trappean sediments, lying beneath Late Cretaceous to Holocen sediments (*cf.* Fuloria *et al.* 1992); C, Rajahmundry lavas.

Table 1. Magnetic vectors in lava samples from Rajahmundry

Sample No.	Locality	Latitude, longitude	Declination D°	Inclination I°	Intensity J_n (nT)
1	Gauripatna, quarry near temple (70 km post on road towards Eluru)	17°03′N 81°34′E	54.2	61.07	2.04
2	″	″	139.4	70.11	2.91
3	″	″	334.2	−63.01	2.01
4	″	″	286.1	71.20	10.10
5	″	″	42.1	78.98	1.41
6	Gauripatna, quarry near 68 km post	17°03′N 81°33′50″	126.9	85.31	4.21
9	″	″	306.4	−34.41	1.01
9a	Kateru quarry	17°02′N 81°50′E	323.2	−35.11	1.12
10	″	″	19.0	6.00	5.31

the bounds of precision in measurement, whereas the difference in delination is substantial. From this test, one can reasonably conclude that the large spread in declination, even among the few oriented samples studied, is a measure of the effect of brittle deformation on these lavas.

Rare-earth element concentrations

Rare-earth element (REE) abundances were measured on a set of representative lava samples collected from the lower benches of the Gauripatna quarries. Analyses were performed using an inductively coupled plasma atomic emission spectrometer at the Chemical Laboratory of the Geological Survey of India, Calcutta. The precision and accuracy of the results (not shown) are within the reproducibility limits of the two reference standards used (*viz*. GR and BCR-1)

Chondrite-normalised REE patterns (normalising values after Boynton 1984) reveal two basalt groups characterised by different degrees of light REE enrichment (Table 4 and Fig. 2).

(1) *Type* 1 *basalts* (e.g. sample 3)—marked by low total REE abundances when compared to Type 2 basalts. The chondrite-normalised REE pattern is marked by an initial rise from La to Ce, and then a steady fall down to Lu. A Eu anomaly is not observed. The $(La/Ce)_N$ and $(La/Yb)_N$ ratios of the Type 1 basalts are lower than in Type 2 basalts (where subscript n denotes normalisation to chondrite). However, the close similarity in $(La/Sm)_N$ and $(Sm/Nd)_N$ ratios between the two types suggests a genetic linkage.

(2) *Type* 2 *basalts* (samples 1, 2 and 4–6)—the large variation in $(La/Yb)_N$ in this suite (4.9–10.0) suggests fractional crystallisation of the magma prior to eruption. Negative Eu anomalies in samples 1, 5 and 6 are indicative of plagioclase fractionation. The total REE content of the Type 2 Rajahmundry basalts is comparable to those of the light REE-enriched basalts from the Rajmahal Hills (Storey *et al*. 1989, Fig. 10), but lower than that of the Deccan basalts (e.g. Alexander and Gibson 1977; Paul *et al*. 1984). The chondrite-normalised REE patterns are quite similar to those of some Deccan lavas (Fig. 2), but distinct from those of normal mid-ocean ridge basalts and ocean island basalts (e.g. McKenzie and O'Nions 1991).

Rajahmundry Type 1 basalts lie at the same stratigraphic level as the Type 2 lavas. Samples 2 and 3 were collected from locations only 30 m apart. Similarly, samples 4 and 5 (showing contrasting Eu anomalies) were collected from localities only 100 m apart, within the same quarry as samples 2 and 3. The occurrence of distinct chondrite-normalised REE patterns naturally raises the question of whether the Rajahmundry lavas were derived by partial melting of more than one mantle source. Local variability in REE abundances within a light REE-enriched suite of lavas could result either from different degrees of partial melting of homogenous mantle, or else may reflect source heterogeneity. In the absence of Sr–Nd–Pb isotopic data, it is difficult to make any conclusive choice, but the close proximity of the two lava types, at the same stratigraphic level, suggests that different degrees of partial melting of the same mantle source is the most likely explanation.

Summary and conclusions

Although recent $^{40}Ar/^{39}Ar$ work indicates that the Rajahmundry lavas and Deccan Traps are almost identical in age, very few studies have been made of the petrology, chemistry and geomagnetism of the former rocks. The present data suggest that the Rajahmundry rocks are relatively unaltered transitional basalts with REE abundances similar to certain lavas from the Deccan province. However, further work is required to elucidate stratigraphic relationships between the Rajahmundry and Deccan basalts, notably the position of the Rajahmundry lavas relative to geochemical units, or 'magma types', identified by other workers in the western part of the Deccan.

Table 2. Variation in magnetic vectors for two cores from Rajahmundry

Core No.	Declination D°	Inclination I°	Intensity J_n (nT)
I	54.2	61.07	2.04
II	51.9	57.21	2.12

Table 3. Variation in magnetic vectors for sheared and unsheared core samples from Rajahmundry

Core No.	Declination D°	Inclination I°	Intensity J_n (nT)
A (sheared)	323.20	−35.11	1.12
II (unsheared)	306.41	−34.41	1.01

Table 4. Rare-earth element abundances (ppm) in selected Rajahmundry lavas, Gauripatna*

	1	2	3	4	5	6
La	14.0	12.0	3.0	13.0	9.2	11.0
Ce	33.0	28.0	9.0	31.0	22.0	26.0
Pr	4.3	3.2	1.0	3.9	2.9	3.3
Nd	16.0	16.0	4.3	16.0	13.0	14.0
Sm	4.60	4.00	1.10	4.40	3.40	4.00
Eu	1.00	1.20	0.29	1.50	1.00	1.00
Gd	4.30	3.50	1.00	4.00	3.60	3.80
Tb	0.67	0.48	0.16	0.59	0.52	0.59
Dy	3.80	2.40	0.96	3.40	2.80	3.60
Ho	0.79	0.44	0.22	0.62	0.51	0.67
Er	1.80	0.98	0.53	1.70	1.30	1.90
Yb	1.53	0.75	0.44	1.00	0.85	1.50
Lu	0.17	0.09	0.06	0.12	0.08	0.17
$(La/Ce)_N$	1.1	1.1	0.9	1.1	1.1	1.1
$(La/Sm)_N$	1.9	1.9	1.7	1.9	1.7	1.7
$(La/Yb)_N$	6.2	10.8	4.6	8.7	7.2	4.9
$(Sm/Nd)_N$	0.9	0.8	0.8	0.9	0.8	0.9

*Determinations were made by ICP-AES at the Chemical Laboratory, Geological Survey of India, Calcutta. Details of precision and accuracy, together with data for international reference standards, are available from the authors upon request.

In conclusion, it is noted that the occurrence of the Rajahmundry basalts some 340 km to the southeast of the main Deccan lava pile requires explanation. It is possible that the distance between the two lava suites may be a function of eastward channeling of the lavas along canyons, as envisaged by Baksi *et al.* (1994). Alternatively, the Rajahmundry basalts could merely represent outliers of a once more-extensive Deccan lava field, preserved from erosion by downfaulting and the development of a thick laterite cover.

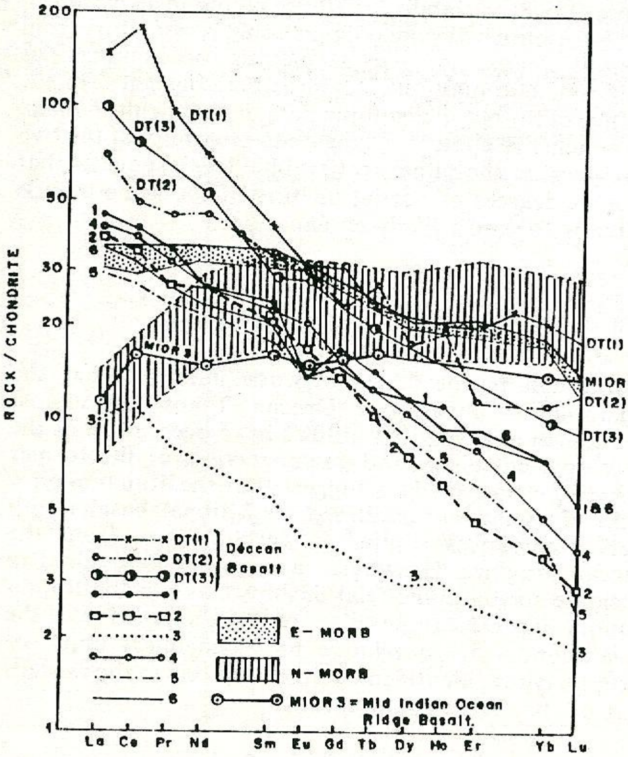

Fig. 2. Chondrite-normalised rare-earth element patterns in Rajahmundry basalts (1–6), compared to selected samples from the Deccan Traps (DT1–3: Frey *et al.* 1968; Balashov and Nesterenko 1966; Alexander 1979), Indian mid-ocean ridge basalt (MORB: average of 14 samples collected near to the Indian Triple Junction; Price *et al.* 1986), and enriched (E-type) and normal (N-type) MORB from the East Pacific Rise between 10 and 12°N (Thompson *et al.* 1989).

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