The Rajahmundry Traps, Andhra Pradesh: Evaluation of their petrogenesis relative to the Deccan Traps

Ajoy K Baksi

Department of Geology and Geophysics, Louisiana State University, Baton Rouge, LA 70803, USA
(e-mail: abaksi@geol.lsu.edu)

Geochemical and geochronological data for rocks from the Rajahmundry Traps, are evaluated for possible correlation with the main Deccan province. Lava flows are found on both banks of the Godavari River and contain an intertrappean sedimentary layer. Based on $^{40}Ar/^{39}Ar$ age data, rocks on the east bank are post K-T boundary, show normal magnetic polarity, and belong to chron 29N. Their chemistry is identical to lavas in the Mahabaleshwar Formation in the Western Ghats, ~1000 km away. It was suggested earlier that the genetic link between these geographically widely separated rocks resulted from lava flowing down freshly incised river canyons at ~64 Ma. For the west bank rocks, recent paleomagnetic work indicates lava flows below and above the intertrappean (sedimentary) layer show reversed and normal magnetic polarity, respectively. The chemical composition of the west bank flow above the intertrappean layer is identical to rocks on the east bank. The west bank lava lying below the sedimentary layer, shows chemistry similar to Ambenali Formation lava flows in the western Deccan. $^{40}Ar/^{39}Ar$ dating and complete chemical characterization of this flow is required to elucidate its petrogenesis with respect to the main Deccan Province.

1. Introduction

The Rajahmundry Traps, ~400 km distant from the nearest surface exposure of the Deccan Traps, extend ~60 km on either side of the Godavari River, north of the city of Rajahmundry in Andhra Pradesh (figures 1 and 2). On the west bank, lavas outcrop for ~20 km, overlying sedimentary rocks, whereas on the east bank, they rest upon metamorphic rocks; in both areas they are overlain by the Cuddalore Sandstone (Pascoe 1964). The volcanic rocks display a thickness between 30 and 60 m, and dip gently (~5°) to the south. In each area, they are about 2 km wide, consisting of flows, with an intertrappean layer, a few meters thick (Pascoe 1964). The fossil content of **(a)** infratrappean limestone suggests the Traps cannot be older than Maastrichtian/ Danian, **(b)** inter-trappean sediments suggest that the upper flows are of Lowermost Tertiary age (Pascoe 1964). The Rajahmundry Traps appear to have been formed at a time close to the K-T boundary.

Initial correlation of the lava flows on both banks was based primarily on altitude, and in the light of the short distances involved and flatness of the flows, is not unreasonable (but see Vandamme and Courtillot 1992). Krishnan (1950, 1960) refers to a lower flow overlain by a fossiliferous bed, and two upper flows. The intertrappean sedimentary layer, consisting of limestone and marl, contain fauna of estuarine character (Pascoe 1964). It is clearly seen on the west bank and has been traced for ~10 km horizontally (see figure 2a). On this bank, lava flows can clearly be designated as lying above or below the intertrappean layer. On the east bank, the intertrappean layer can be traced for <1 km (figure 2b); and ~10 m above it in one place, another very thin sedimentary layer is seen, consisting of unfossiliferous yellow calcareous shale (Pascoe 1964). For the east bank, it not possible to delineate flows as lying above or below the inter-

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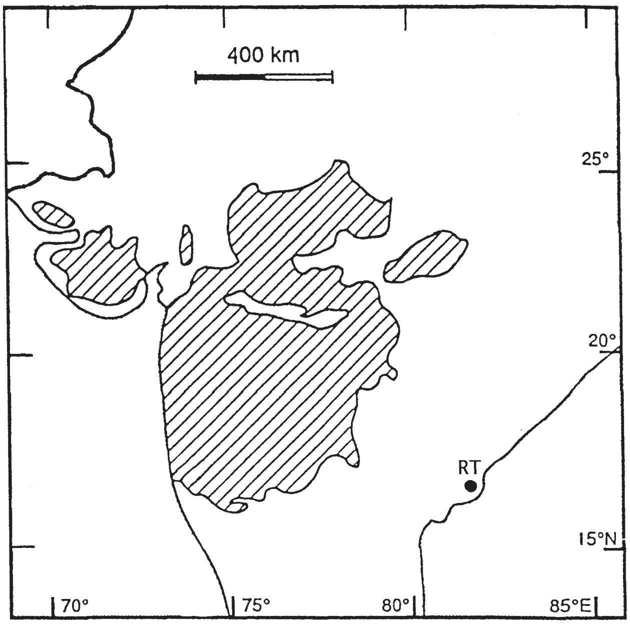

Figure 1. Map of Peninsular India (modified from Baksi *et al* 1994) showing the location of the Deccan Traps (hatched areas) and the Rajahmundry Traps (marked by the filled circle).

trappean layer. The latter may have been structurally placed therein. If it is regarded as being "*in situ*", stratigraphic conclusions may be in error. Thus, the laser $^{40}Ar/^{39}Ar$ work of Najman *et al* (2001) on the Balakot Formation of Pakistan, has lowered its age by ~15–20 m.y. "The marl units are structurally intercalcated .... and biostratigraphy cannot be used to date (this) succession" (Najman *et al* 2001, p. 194).

Further attempts at correlation of lava flows across the Godavari River were based on paleomagnetism and geochemistry. Geochemical studies on nine samples (labelled RT) suggested uniform composition for all lavas and possible derivation as intracanyon flows from an area near Kolhapur in the western Deccan (Baksi *et al* 1994). Details of this earlier work, critical to clarification of the number and type of lava flows on each side of the Godavari River are presented herein. N K Brahmam (written comm. 1985) reported all samples showed normal magnetic polarity and supplied sample location sites. Samples 2/2A and 1/1A, collected from the west bank; were thought to lie below and above the intertrappean layer, respectively. All these rocks were collected from boulders on the west bank of the river, "since no fresh exposures are available on that side of the river" (N K Brahmam, written comm., 1985). Five specimens (3, 3A, 4B, 5A and 9C) were collected from various outcrop locations on the east bank. Results of ongoing work on a suite of samples from the west bank lava, below the intertrappean sedimentary layer, will be reported.

2. Paleomagnetism

Bhimasankaram's (1965) rocks, collected from the east bank (see figure 2), exhibited normal magnetic polarity. Following subsequent work (Singh and Bhalla 1972) it was assumed that all lavas in the Rajahmundry Traps exhibited normal polarity. Recent work (Vandamme and Courtillot 1992; Subbarao and Pathak 1993) reveals the lower flow on the west bank showing reversed polarity, whereas the upper flow on the west bank and rocks on the east bank show normal polarity. The magnetic "break" occurs at an elevation of about 260 m (?) above sea level (Subbarao *et al* 1997). Samples 2/2A, thought to belong to the flow below the intertrappean layer on the west bank, show normal magnetic polarity; clearly they belong to the flow *above* the intertrappean layer. Banerjee *et al* (1996) reported normal magnetic polarity for rocks on the east bank and mixed polarities for rocks from the base of the lavas on the west bank. The normal polarity reported for the latter are spurious, and resulted from analysis of rocks without magnetic cleaning. The elevation of the lavas (240–300 *meters*) reported elsewhere (Vandamme and Courtillot 1992; Subbarao *et al* 1997) appears incorrect; the area around Rajahmundry, lying on the coastal plain, is at an elevation of 200–300 *feet* above sea level. (Venkayya 1949; Pal *et al* 1971).

3. Geochronology

3.1 *K-Ar dating – rocks from both banks*

All nine RT specimens were utilized since they showed no vesicles or amygdales. Dates were calculated utilizing the decay constants and isotopic abundances listed by Steiger and Jager (1977). Potassium analysis was carried out by flame photometry. The argon work was carried out at Queen's University, using a turret type of furnace (Baksi 1994) using 15–40 mesh whole-rock material. Spikes were calibrated versus LP-6 Bio 40–60# using the $^{40}Ar^{*}$ content determined by Baksi (1973). Table 1 presents the results; with a single exception, the rocks yield dates of 57–67 Ma. There is correlation between (higher) ^{36}Ar content of the rocks and (lowered) K-Ar dates, loss of $^{40}Ar^{*}$ by alteration (Baksi 1987, 1989). Samples 1, 3, 3A and 9C, less altered than the others, suggest a crystallization age of ~65 Ma.

3.2 *$^{40}Ar/^{39}Ar$ dating – rocks from the east bank*

Two relatively unaltered rocks, RT3A and 9C, showing somewhat higher K contents and K-Ar dates close to 65 Ma, were selected for stepheating

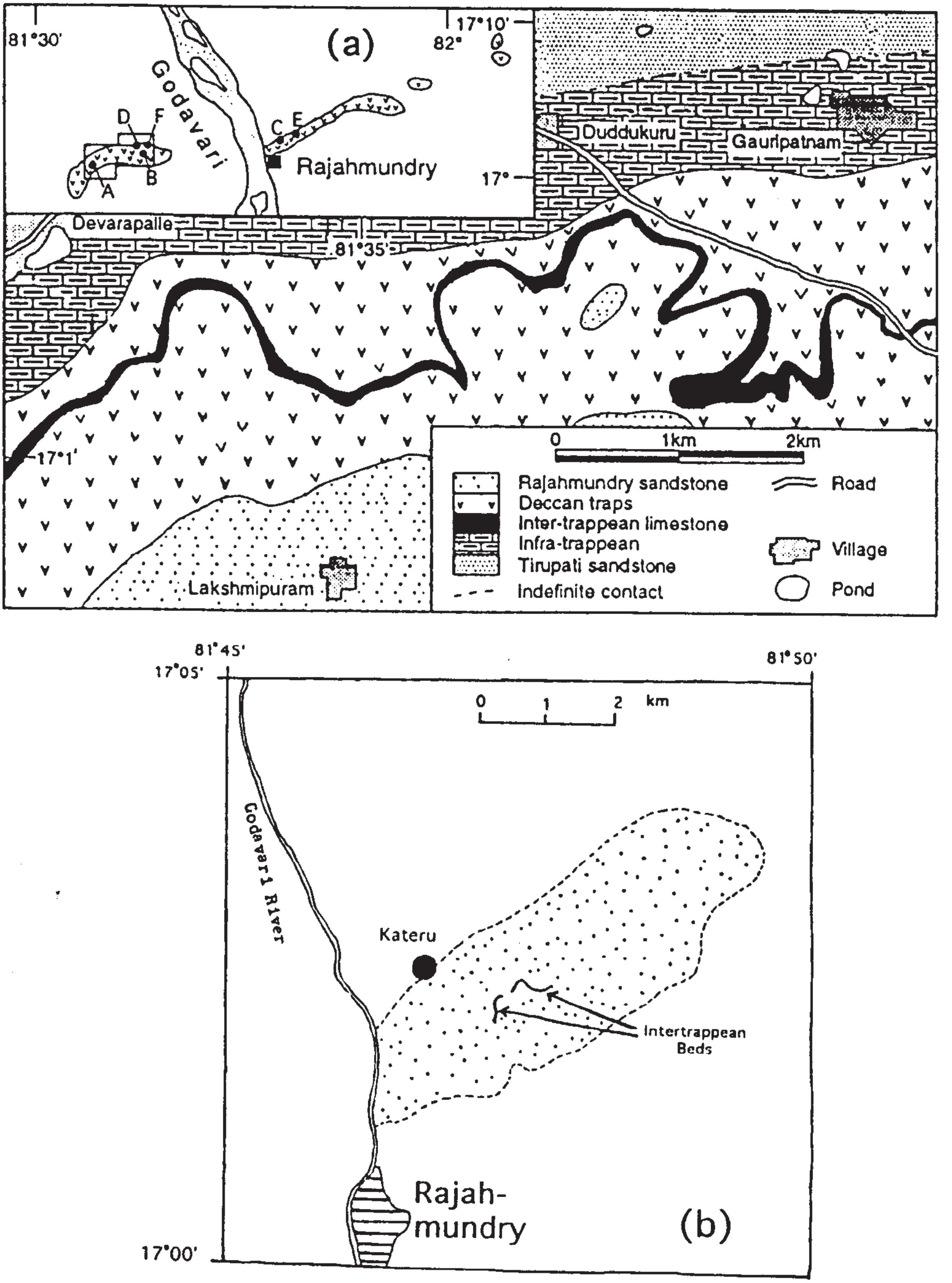

Figure 2. Geological map of the Rajahmundry Traps. **(a)** West bank outcrop (modified from Vandamme and Courtillot 1992); note widespread occurrence of intertrappean limestone layer. The upper left corner shows sample location areas; A, B and C – specimens 41, 42 and 43, respectively, of Vandamme and Courtillot (1992); D and E – Subbarao and Pathak (1993); F – G1 – 6 of Banerjee *et al* (1996). Rocks from B, D and F show reversed magnetic polarity, those from A, C and E show normal magnetic polarity. **(b)** East bank outcrop (modified from unpubl. map of R. Vaidyanathan). Trap exposure shown by dotted lines; note the very limited occurrence of intertrappean sedimentary beds (see text).

Table 1. *Analytical data for K-Ar dates on whole-rock basalts, Rajahmundry Traps, India.*

Sample number	K (%)	Mass fused (mg)	$^{40}Ar^*$ (%)	$^{40}Ar^* \times 10^7$ (cm^3 $STPg^{-1}$)	K-Ar data (Ma)	$^{36}Ar \times 10^{10}$ (cm^3 $STPg^{-1}$)
RT1	0.254	261	86.9	6.74	67.0	3.4
RT1A	0.337	241	75.2	6.87	51.7	7.7
RT2	0.346	222	84.3	8.39	61.4	5.3
RT2	0.331	250	79.6	7.48	57.2	6.5
		196	79.4	7.74	59.2	6.8
RT3	0.232	226	94.6	5.99	65.3	1.2
RT3A	0.264	224	89.6	6.90	66.0	2.7
		181	75.5	6.27	60.1	6.9
RT4B	0.219	224	93.9	5.31	61.3	1.2
RT5A	0.223	209	91.6	5.43	61.6	1.7
RT9C	0.277	184	83.6	6.55	59.9	4.4
		175	91.3	6.98	63.7	2.3

K determined by flame photometry. Argon contents determined using spikes calibrated versus LP-6 Bio 40-60# (Baksi 1973). Estimated 1σ errors in dates are ±2 m.y. Splits showing higher ^{36}Ar contents (lower $^{40}Ar^*$%) yield lower K-Ar dates, caused by loss of radiogenic argon from altered samples (Baksi 1987, 1989). Estimated crystallization age ∼65 Ma.

study. Two runs were carried out on each rock, the second involving a low temperature degassing step allowing the evolved gas to be pumped away. Ages are reported relative to those for standards listed by Baksi *et al* (1996). All errors in the figures are shown at the 1σ level, internal precision. To enable comparison of ages, crystallization (plateau and/or isochron) errors are quoted, including an additional term of $\sigma_J = 0.4\%$, compounded quadratically, allowing for estimated errors in the determination of the irradiation parameter (J).

Duplicate K-Ar analyses on both rocks showed variable ^{36}Ar contents, indicating they contain altered phases. The experiments utilizing an initial degassing step, give intermediate high temperature steps with higher amounts of $^{40}Ar^*$ than the undegassed splits (see table 2). This confirms that the initial degassing step is a useful adjunct in obtaining quality stepheating data on large amounts of whole-rock basalts (Baksi and Archibald 1997). Specimen 3A gave inverted U-shaped spectra (figure 3), indicative of whole-rocks that have lost $^{40}Ar^*$. Plateau sections yield an average age of 63.79 ± 0.31 Ma, and the same steps gave an isochron age of 64.2 ± 0 Ma, with an acceptable goodness of fit parameter (F) — see Baksi (1999). Specimen 9C, showed minor loss of $^{40}Ar^*$; the age spectrum shows descending staircase pattern, indicative of ^{39}Ar recoil redistribution (Turner and Cadogan 1974; Baksi 1990; Baksi 1994). Intermediate-high temperature steps yield a plateau age of 64.34±0.29 Ma, and the corresponding isochron, yields essentially the same age. Taken together, these (plateau) results suggest that the crystallization age of basalts on the east bank is 64.1 ± 0.2 Ma. This age is marginally younger than that of the K-T boundary — 64.7 ± 0.3 Ma (Baksi 1994; Widdowson *et al* 2000). The normal magnetic polarity of this lava and its radiometric age, indicates extrusion during chron 29N (see figure 4).

No radiometric data are available on the reversed magnetic polarity lava below the intertrappean layer on the west bank. Its very low K content (∼0.05%) will make recovery of accurate and precise data difficult. Its age remains critical to the determination of the length of the hiatus represented by the intertrappean sedimentary layer on the west bank.

4. Geochemistry

The RT samples were analyzed by XRF and ICPMS techniques. Results are presented in table 3; chondrite normalized REE and primitive mantle normalized trace element plots are shown in figures 5 and 6, respectively. The REE plot shows values that are identical within estimated measurement errors. The PMN plot shows all samples have very similar chemistry, with only elements most susceptible to movement by weathering processes (Rb through K), showing significant variation. The normal polarity rocks on both banks of the Godavari River, are chemically identical and appear to belong to the same flow. Vandamme and Courtillot (1992) reached a similar conclusion based on altitude data and magnetic behavior/directional observations.

Attempts at correlation of these rocks with the main Deccan province was facilitated by the wealth of data available in the literature (Cox and Hawkesworth 1985; Beane *et al* 1986; Devey and Lightfoot 1986; Mahoney 1988; Lightfoot and Hawkesworth 1988; Lightfoot *et al* 1990; Mitchell and Widdowson 1991; Peng *et al* 1998; Mahoney *et al* 2000). The search focused on TiO_2

Table 2. *Analytical data for $^{40}Ar/^{39}Ar$ stepheating runs on whole-rock basalts, Rajahmundry Traps, India.*

Temperature (°C)	Cumulative $^{39}Ar_K$ (%)	$^{40}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{37}Ar/^{39}Ar$	$^{40}Ar^*$ (%)	Age $\pm 1\sigma$ (Ma)
RT3A, run 1 – 1.65 g, J = 0.003639, total gas age = 61.8 ± 0.6 Ma						
500	13.6	19.16	0.03907	4.07	41.3	51.22 ± 1.15
590	30.2	14.33	0.01660	5.53	68.6	63.51 ± 0.53^{P}
680	55.8	13.26	0.01311	7.33	74.9	64.20 ± 0.40^{P}
760	67.0	13.76	0.01582	9.29	71.0	63.29 ± 0.51^{P}
840	81.8	14.37	0.01826	10.85	68.1	63.38 ± 0.70^{P}
920	93.3	16.33	0.02511	12.07	60.0	63.63 ± 0.45^{P}
1150	100.0	18.49	0.03802	27.19	50.2	60.87 ± 1.19
RT3A, run 2 – 1.32 g (degassed at 450° C for 20 m), J = 0.003711, "total gas" age = 63.1 ± 0.8 Ma						
530	9.7	14.98	0.02215	4.18	58.3	57.58 ± 1.30
610	29.2	12.62	0.01101	5.55	77.5	64.38 ± 0.58^{P}
690	52.8	11.83	0.00895	7.43	82.3	64.19 ± 0.58^{P}
780	71.2	11.87	0.01004	9.44	80.9	63.41 ± 0.58^{P}
890	87.5	13.22	0.01475	11.14	73.4	64.06 ± 0.77^{P}
1150	100.0	16.95	0.03338	28.15	54.2	61.47 ± 1.30
RT9C, run 1 – 1.57 g, J = 0.003597, total gas age = 64.4 ± 0.5 Ma						
480	5.9	19.02	0.03515	4.59	47.1	57.33 ± 1.50
560	14.6	14.66	0.01416	5.30	74.1	69.27 ± 0.81
650	32.6	12.31	0.00741	7.00	86.4	67.95 ± 0.30
700	51.8	11.24	0.00617	9.12	89.8	64.57 ± 0.30^{P}
750	65.3	11.41	0.00695	9.15	88.0	64.20 ± 0.33^{P}
800	83.6	12.35	0.01043	9.56	80.8	63.86 ± 0.52^{P}
1120	100.0	15.20	0.02598	24.35	61.4	60.43 ± 0.41
RT9C, run 2 – 1.42 g (degassed at 450° C for 20 m), J = 0.003503, "total gas" age = 64.6 ± 0.5 Ma						
520	6.4	11.63	0.00890	4.60	80.3	58.08 ± 2.00
580	13.5	12.77	0.00634	5.27	88.4	70.04 ± 0.91
640	25.8	11.79	0.00424	6.80	93.7	68.64 ± 0.30
710	47.2	10.91	0.00433	8.87	94.4	64.13 ± 0.26^{P}
770	72.3	11.02	0.00444	8.95	94.2	64.62 ± 0.30^{P}
830	90.8	10.97	0.00441	9.08	94.3	64.43 ± 0.37^{P}
1170	100.0	16.00	0.02810	26.90	60.7	61.26 ± 0.49

Isotopic ratios corrected for decay since fast neutron irradiation. Rocks analyzed with a conventional setup at Queen's University (see Baksi 1994). Monitor samples: FCT-3 Bio, age = 27.95 Ma (Baksi *et al* 1996). Internal precision errors listed ($\sigma J = 0$). ^{P}Steps used for plateau and isochron calculations (see figure 3 and Baksi 1999).

contents of ~2.8%, then looked to immobile trace elements. A lava flow (BAS235) in the Kolhapur Unit of the Mahabaleshwar Formation, some ~1,000 km distant (figure 7), provided a match. REE and PMN plots (figures 5 and 6 – see also table 3) illustrate this. Despite the different analytical techniques utilized for analysis of BAS235 and the RT rocks, the match in major/trace/ rare earth elements is excellent. As a further check on possible correlation, Sr isotopic values were compared. Given their uniform trace element chemistry, the RT samples showed a large range of values, 0.7048–0.7062. A plot of these values versus whole-rock $\delta^{18}O$ (figure 8), shows a clear correlation, reflecting alteration of the rocks by interaction with sea water at low temperature, a process that is known to alter both oxygen and strontium isotopic values. The more altered rocks show higher values of LOI (see table 3) and contain more clay minerals as seen in thin section examination. Muehlenbachs and Clayton (1972) suggested 10% alteration of sea floor basalts, could raise the $\delta^{18}O$ value by 5‰, by the formation of clay minerals. Interaction with seawater, whose Sr isotopic composition was ~0.7077 at 64 Ma (Burke *et al* 1982), raised the isotopic composition of the altered rocks. Extrapolation of the Sr - O isotopic plot, to a $\delta^{18}O$ value of ~6.0‰, suggests that the unaltered Sr isotopic composition of the upper lava was ~0.7040; this is close to the value of 0.7043 for lava BAS235 in the Western Ghats (Lightfoot *et al* 1990).

The postulated genetic relationship between the normal polarity lavas in the Rajahmundry area and the Kolhapur Unit some 1,000 km distant is best addressed by the mechanism of intracanyon flows (Baksi *et al* 1994). For the Columbia River Province USA, it has been demonstrated that coastal basalts in Oregon and Washington were derived from lavas erupted ~500 km upriver (Beeson *et al* 1979). In the western Deccan, the upper

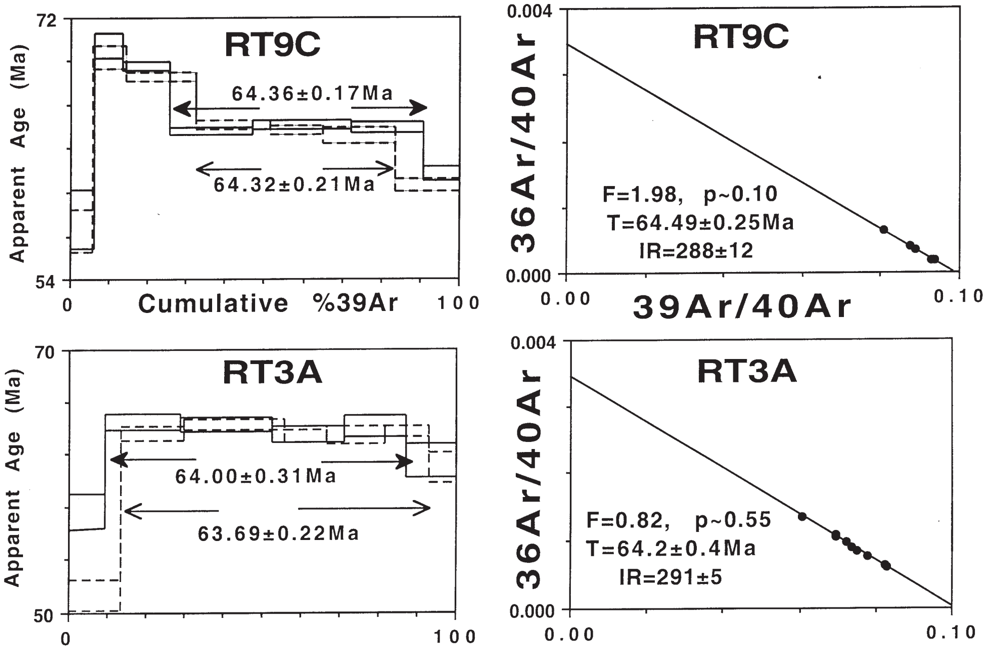

Figure 3. Age spectra and isochron plots for $^{40}Ar/^{39}Ar$ stepheating studies on two Rajahmundry Trap whole-rock basalt samples, from the east bank of the Godavari River. Duplicate analyses shown on age spectra. Isochron plots (following York 1969) utilize plateau steps from two runs; F= goodness of fit parameter, p = probability of obtaining given F value, T = age, and IR= $(^{40}Ar/^{36}Ar)_i$. All errors shown and listed at the 1σ level. These rocks are marginally younger than the K-T boundary (see figure 4 and text).

sections of the Mahabaleshwar Formation contain numerous red boles and weathering horizons (Cox and Hawkesworth 1985; Lightfoot *et al* 1990), suggestive of waning volcanism. Highly fluid magmas erupted in the Kolhapur area, flowed into freshly incised river canyons, and flowed down to the east coast of India (Baksi *et al* 1994). The area around the Kolhapur Unit lies near a tributary of the *Krishna* River today, whereas the Rajahmundry Traps lie on the banks of the *Godavari* River (see figure 7). The disposition of rivers and tributaries at ∼64 Ma remains unknown and river piracy in the Deccan province over the past ∼5 m.y. has been noted (Kale and Rajaguru 1988).

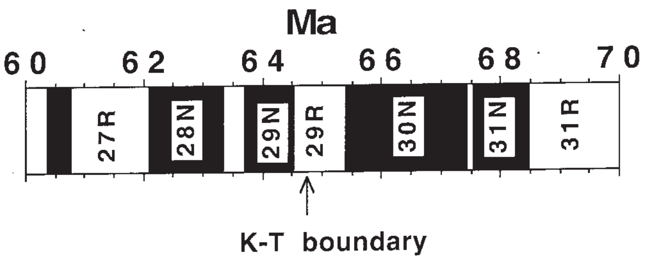

Figure 4. Geomagnetic polarity time scale (chrons numbered) for 70–60 Ma, with the K-T boundary placed at 64.7 Ma. (modified from Cande and Kent 1992 and Baksi 1994). Black = normal polarity, white = reversed polarity. The east bank Rajahmundry Traps rocks, age = 64.1±0.2 Ma, belong to chron 29N.

The current elevation of the Rajahmundry Traps has bearing on possible flexural uplift of the area following continental collision (cf. Lyon-Caen and Molnar 1983). Sea level was ∼200 m higher than today at ∼64 Ma (Harland *et al* 1990); a current elevation of ∼100 m for the Rajahmundry Traps, indicates the area was under shallow marine conditions at the time of deposition of the intra-canyon flow derived from the Kolhapur area. This is in agreement with the estuarine character of the fauna in the intertrappean sedimentary layer. Flexural uplift in this area following collision of the Indian and Eurasian plates, was minimal, i.e. <100 m.

4.1 *Lava(s) on the western bank, below the intertrappean layer*

Banerjee *et al* (1996) presented REE data (only) for material collected from a basal level near Gauripatnam (figure 2a). Sample G3, with extremely low REE contents (figure 9, inset), cannot be a (type 1) basalt; it shows lower total REE than MORB and may be cumulate dominated. The pattern is similar to that for modeled source rocks for various types of basalts, showing chondrite normalized La and Lu values of ∼9 and 3, respectively (Frey *et al* 1978, figures 5, 8 and 10). Quartzose sedimentary rocks and sediments show REE patterns similar to G3 (figure 8, inset). Banerjee *et al's* (1996) type 2 rocks (G1, 2, 4 – 6), show REE patterns more normal for basalts. Individual patterns intersect (figure 9), suggesting the rocks may not

Table 3. *Geochemical data for whole-rock basalts, Rajahmundry and Deccan Traps, India.*

Location	RT1 W	RT1A W	RT2 W	RT2A W	RT3 E	RT3A E	RT4B E	RT5A E	RT9C E	BAS235 KU	BHVO-1 Standard	BIR-1 Standard
Major elements (%)												
SiO_2	49.7	50.9	51.0	50.7	49.7	50.1	50.2	50.3	50.4	49.3	50.2	48.2
Al_2O_3	13.1	13.2	13.0	13.0	13.6	13.5	13.6	13.2	13.1	13.2	13.8	15.5
TiO_2	2.69	2.74	2.74	2.79	2.81	2.85	2.89	2.86	2.75	2.88	2.76	0.97
FeO*	15.4	13.9	14.2	14.6	14.7	14.6	14.3	14.5	14.4	14.4	11.1	10.3
MnO	0.22	0.24	0.24	0.25	0.24	0.19	0.19	0.19	0.24	0.26	0.17	0.17
CaO	9.9	10.0	10.0	10.0	9.9	9.8	9.9	9.9	10.2	10.3	11.5	13.3
MgO	6.1	5.7	5.5	5.4	6.1	5.7	5.8	6.0	5.9	6.2	7.32	9.75
K_2O	0.31	0.42	0.42	0.40	0.30	0.32	0.27	0.27	0.35	0.41	0.53	0.03
Na_2O	2.42	2.61	2.55	2.54	2.45	2.58	2.58	2.52	2.40	2.75	2.35	1.76
P_2O_5	0.27	0.27	0.27	0.29	0.28	0.29	0.29	0.27	0.26	0.34	0.28	0.02
(LOI)	1.4	0.4	0.6	0.6	1.7	1.0	1.1	1.2	0.9	nd	nd	nd
Minor, trace and rare earth elements												
Ni	55	45	50	45	55	50	55	55	50	75	105	165
Cr	70	75	60	60	65	65	75	75	65	100	255	380
Sc	45	45	45	40	45	45	45	50	40	nd	27	44
V	420	430	415	425	435	440	460	450	430	390	310	315
Sr	225	210	220	210	240	240	235	225	230	225	385	108
Zr	160	165	170	170	165	165	170	160	165	170	165	22
Zn	125	135	120	135	135	130	150	135	120	115	95	70
Cu	130	250	305	230	265	55	50	100	75	215	135	125
Ga	20	23	25	25	23	23	25	25	27	nd	19	16
La	14.8	15.5	16.6	16.7	15.0	16.0	16.0	14.7	15.9	14.5	16.0	0.8
Ce	32.3	34.4	36.4	36.5	33.3	35.2	36.1	32.8	34.8	35.9	37.4	1.9
Pr	4.3	4.7	4.8	4.9	4.5	4.7	4.8	4.4	4.6	nd	5.3	0.4
Nd	20.2	22.5	22.5	22.9	20.9	22.0	23.2	21.5	21.9	24.2	24.7	2.2
Sm	5.4	5.9	6.0	6.0	5.6	5.9	6.0	5.7	5.8	6.5	5.5	1.1
Eu	1.9	2.1	2.1	2.1	2.0	2.1	2.2	2.0	2.1	2.2	2.0	0.5
Gd	6.5	6.8	7.2	7.1	6.5	7.0	6.7	6.9	6.7	7.5	5.9	1.9
Tb	1.2	1.2	1.3	1.3	1.2	1.3	1.3	1.2	1.2	1.2	0.86	0.4
Dy	7.1	7.7	7.9	7.8	7.0	7.5	7.5	7.3	7.5	nd	5.2	2.9
Ho	1.4	1.6	1.6	1.6	1.4	1.5	1.5	1.4	1.5	1.3	0.95	0.6
Er	3.9	4.2	4.3	4.3	3.7	4.0	4.1	3.8	4.1	nd	2.5	1.8
Tm	0.51	0.53	0.56	0.55	0.48	0.52	0.53	0.52	0.55	0.5	0.35	0.3
Yb	3.1	3.3	3.4	3.4	3.0	3.1	3.3	3.1	3.4	3.3	2.0	1.7
Lu	0.50	0.49	0.53	0.53	0.47	0.48	0.47	0.45	0.51	0.55	0.30	0.3
Ba	155	145	270	155	145	150	140	130	160	115	180	7
Th	1.7	1.6	1.9	1.8	1.7	1.7	1.8	1.4	1.7	1.7	1.3	0.01
Nb	13.6	13.3	15.2	15.5	13.9	14.1	12.8	12.6	14.0	15	20.3	0.5
Y	38.0	39.8	41.6	40.7	34.4	37.8	37.9	37.8	38.1	40	28.2	16.2
Hf	3.9	4.2	4.6	4.4	4.3	4.2	4.2	3.9	4.3	4.6	4.3	0.5
Ta	0.90	0.96	1.2	1.2	1.1	1.1	0.94	0.85	1.1	1.1	1.2	0.03
U	0.40	0.34	0.41	0.40	0.59	0.39	0.41	0.32	0.37	nd	0.44	0.00
Pb	2.3	2.4	2.6	2.5	2.3	2.5	2.4	1.8	2.6	nd	3.4	2.8
Rb	2.7	7.4	7.6	8.3	2.2	2.8	2.3	2.0	4.5	10	nd	0.3
Cs	0.03	0.08	0.10	0.11	0.03	0.03	0.03	0.02	0.06	nd	nd	0.01
$^{87}Sr/^{86}Sr$	0.70592	0.70482	0.70499	0.70486	0.70617	nd	nd	0.70607	nd	0.70428	nd	nd
$\delta^{18}O$(%.)	6.9	6.3	6.7	6.5	7.2	7.1	7.1	7.3	6.9	nd	nd	nd

Samples RT1-9C = Rajahmundry Traps. Location: E/W refer to east/west of the Godavari River (see text). Sample BAS235 is from the Kolhapur Unit, western Deccan Traps; data by XRF and neutron activation analyses from Lightfoot *et al* (1990) and C J Hawkesworth (written comm. 2001). Others – analyses at Washington State University by XRF and ICP-MS. BHVO-1 and BIR-1 are geochemical standards (see Govindaraju 1989). Major elements normalized to 100.0%, LOI = loss of weight on firing at 1000°C for 20 m., nd = not determined. Sr isotopic compositions determined at Louisiana State University (NBS987 = 0.70126), corrected to an age of 65 Ma. Oxygen isotopic values determined at USGS, Menlo Park (J R O'Neil, written comm. 1985).

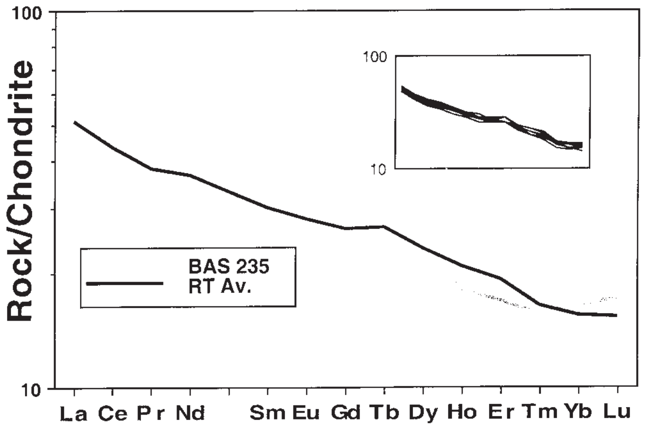

Figure 5. Chondrite normalized rare earth element values for normal magnetic polarity Rajahmundry Trap (RT) samples on both banks of the Godavari River, and lava BAS235, Mahabaleshwar Formation, Western Ghats. RT Av = average of nine samples RT1 - 9C; inset shows patterns for the individual samples. Values for RT determined by ICPMS (table 3) and BAS235 by NAA (Lightfoot *et al* 1990). The patterns are identical within measurement errors, suggesting a genetic link between flows separated by ~1,000 km (see text).

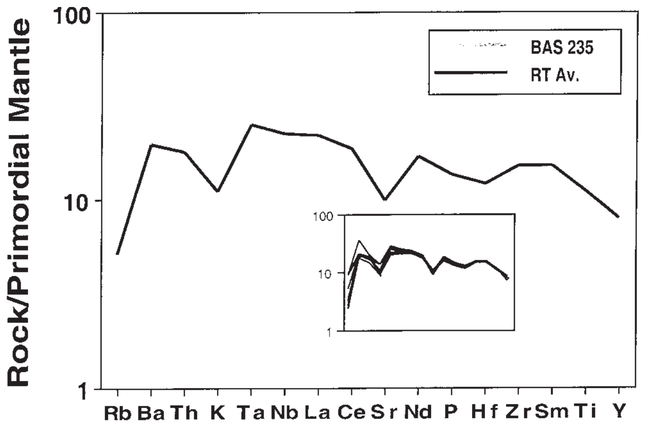

Figure 6. Primitive mantle (Wood *et al* 1981) normalized plot for elements on normal magnetic polarity Rajahmundry Traps rocks on both banks of the Godavari River, and flow BAS235 in the Mahabaleshwar Formation, Western Ghats. RT Av = average of nine samples RT1 - 9C, determined by XRF and ICPMS (table 3). Inset shows plots for individual samples, which are identical except for elements (Rb through K) susceptible to alteration. Results for BAS235 derived by XRF and NAA (Lightfoot *et al* 1990). For immobile elements, the patterns are identical with measurement errors, suggesting a genetic link between flows separated by ~1,000 km (see text).

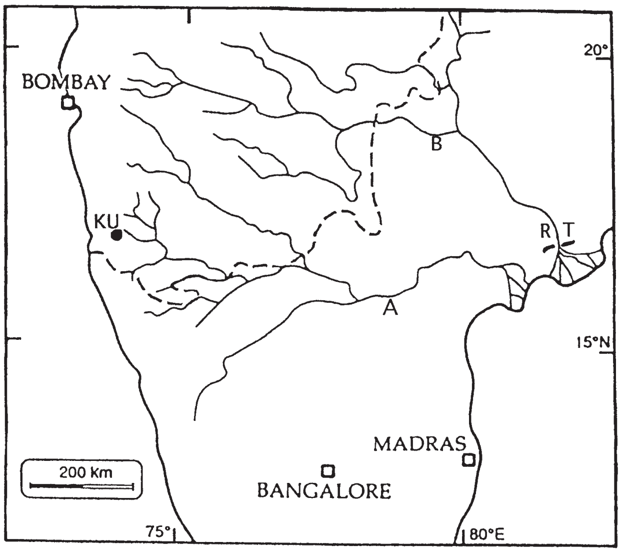

Figure 7. Drainage patterns in Peninsular India (modified from Baksi *et al* 1994). The Krishna and Godavari River systems are labeled A and B, respectively. Dotted lines denote the outer limits of the Deccan Traps. RT and KU mark the locations of the Rajahmundry Traps and the "equivalent" rocks in the Kolhapur Unit, respectively. The normal magnetic polarity lavas Rajahmundry Traps, and the KU are hypothesized to be linked through lavas descending through freshly incised river canyons at ~64 Ma (see text).

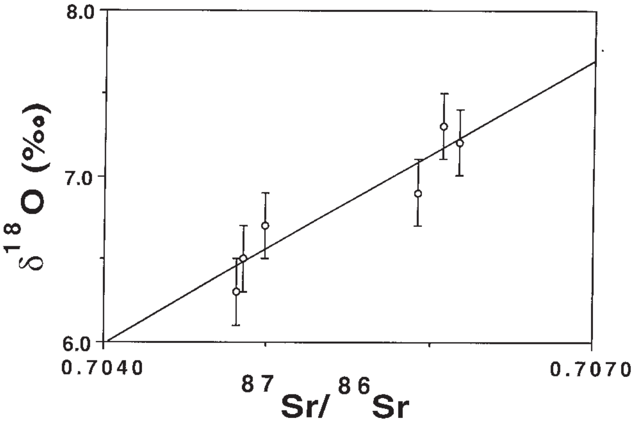

Figure 8. Sr-O isotopic plot for normal magnetic polarity Rajahmundry Traps whole-rock basalts (RT). Sr isotopic composition corrected to 64 Ma; errors in oxygen isotopic values shown at the estimated 1σ level. The straight line (correlation coefficient = 0.87), suggests alteration of isotopic values by interaction with seawater. Extrapolation to unaltered mantle derived $\delta^{18}O$ value (~6.0‰), yields $^{87}Sr/^{86}Sr$ ~ 0.7040 (see text).

be genetically related. The RT rocks display no Eu anomaly, whereas three samples from Banerjee *et al* (1996) show a negative Eu anomaly and one (G4) a slight positive anomaly (figure 9). Assuming ±10% error in determination of REE, ~ 60% fractionation of plagioclase from a basaltic liquid yields a discernible Eu anomaly (cf. Hanson 1980). Analytical errors in REE determination and/or misidentification of rocks by Banerjee *et al* (1996) remain possible. Major/trace element and geochronological results on these rocks, as well as field work, are required to verify their petrological nature and genesis.

Rocks from the reversed magnetic polarity lava on the west bank, show very different composition from the RT specimens. They display lower TiO_2,

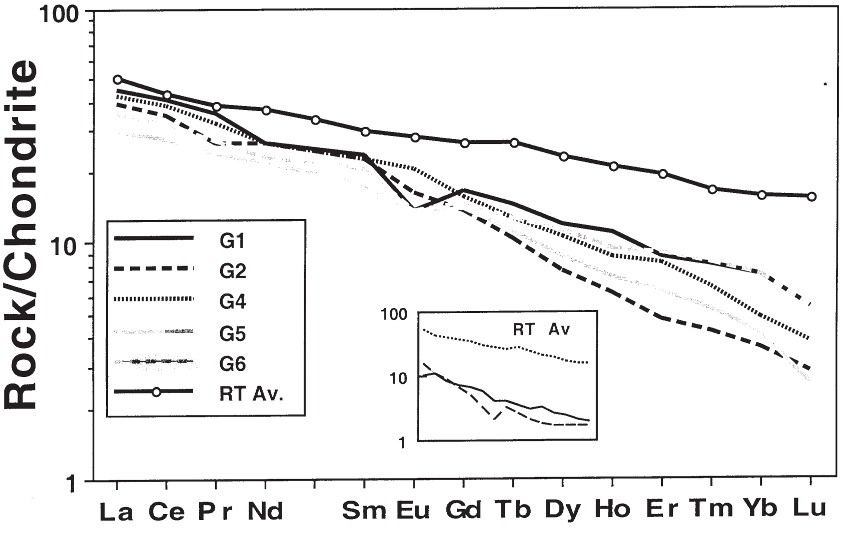

Figure 9. Chondrite normalized rare earth element plots for west bank Rajahmundry Trap "basalts", lying, below the intertrappean sedimentary layer. G1 - 6 – Banerjee *et al* (1996); RT Av. – average of nine samples (RT1 - 9C) for normal magnetic polarity rocks. **Inset:** solid and dotted lines denote G3 and average of Libyan desert sand and Permian orthoquartzites from Australia (Taylor and McClennan 1985), respectively. G3 cannot be a basalt; positive identification of the Banerjee *et al* (1996) rocks and evaluation of their petrogenesis, requires major/trace element and geochronological data (see text).

Ba and K contents, and higher Mg numbers (Subbarao *et al* 1997). Further work is in progress to obtain more complete chemical characterization of this flow.

5. Discussion

Based on the ΔNb values (= log (Nb/Y)+1.74 − 1.92 × log (Zr/Y) - Fitton *et al* 1997), a deep mantle derived component is seen in the Rajahmundry Traps. Positive values of this parameter reflect a "plume" component (Baksi 2001). The utility of this technique is demonstrated by Hawaiian rocks showing a hotspot linkage; the basalt standard (BHVO-1 – see table 3) shows ΔNb = +0.12, and lava flows in Maui spanning the Brunhes - Matuyama geomagnetic reversal (Baksi *et al* 1992) show values of 0.14 − 0.26 (A K Baksi unpubl. data). The Icelandic basalt standard, BIR-1, shows a clear plume component (ΔNb = +0.37), based on the high precision analyses (Nb, Y, Zr = 0.54, 13.5 and 13.1 ppm, respectively) of Niu *et al* (1999). For the RT rocks (table 3), the average ΔNb value is +0.08 and that of BAS235 (Kolhapur Unit) is +0.11.

The case for relating the Rajahmundry Trap flows on the east bank and that above the intertrappean layer on the west bank to lavas some ∼1,000 km distant appears valid. Paleomagnetic work (Vandamme and Courtillot 1992; Subbarao and Pathak 1993) shows that west bank lavas above and below the intertrappean sedimentary layer are not coeval; there is no necessity of appealing to the burrowing action of sheet flows through unconsolidated sediment (see Baksi *et al* 1994). However, this may explain the nature of the sedimentary layers (structural emplacement) on the east bank. Subbarao *et al* (1997) noted that the intertrappean layer on the west bank marks a break both in the geochemistry and magnetic polarity of lavas. Preliminary results show that the lower reversed lava on the west bank shows chemistry similar to Ambenali Formation lavas of the western Deccan (cf. Subbarao *et al* 1997). On biostratigraphic grounds, this lava on the western bank may be pre K-T boundary in age. $^{40}Ar/^{39}Ar$ dating is required to place it within 29R or an older (reversed) chron (see figure 4). Complete chemical characterization and dating work will help unravel a possible genetic link between the reversed polarity flow in the Rajahmundry Traps and the main Deccan province. Alternately, it may indicate magmatism at ∼65 Ma in the Andhra Pradesh coastal area.

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