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Discussion

Reply to '^{40}Ar/^{39}Ar dating of the Rajahmundry Traps, Eastern India and their relationship to the Deccan Traps: Discussion' by A.K. Baksi

Kim B. Knight [a,*], Paul R. Renne [a,b], Joel Baker [c], Tod Waight [d], Nicky White [e]

[a] Department of Earth and Planetary Science, University of California, Berkeley, CA 94720, USA
[b] Berkeley Geochronology Center, 2455 Ridge Road, Berkeley, CA 94709, USA
[c] School of Earth Sciences, Victoria University of Wellington, Wellington, New Zealand
[d] Geological Institute, Øster Voldgade 10, 1350 København K, Denmark
[e] Bullard Laboratories, Madingley Rise, Madingley Road, Cambridge CB3 0EZ, UK

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1. Introduction

We appreciate this opportunity for further discussion of flow and field relations within the Rajahmundry Traps, and their timing relative to Deccan Trap volcanism. Knight et al., 2003a relied on simplified stratigraphic designation and nomenclature for Rajahmundry Trap flows, labeling 'Upper' or 'Lower' flows relative to the presence of a primary sedimentary interlayer [1]. This designation and its implication of related lava packages may not be strictly valid, as suggested by Baski (this volume), and we present further insight below. Several points of the comment [2] are based on the assumption that a single flow is present for each of the Upper and Lower Rajahmundry Trap units. Both drill hole and field observation, however, suggest otherwise. Multiple flows (as many as 8) of Rajahmundry Trap lavas assigned to both Upper and Lower units are well documented [e.g., 3–5], often occurring sandwiched between multiple sedimentary horizons above and below the thick (and thus designated as the 'main') sedimentary interlayer. The assumption of a single flow may hold for the surface exposures of the Upper unit used in the study of [1], where flow boundaries (if present) were not possible to discern. Within Lower unit exposures, however, at least two distinct lava flows were observed and sampled in the field (Fig. 1), and have been reported by multiple authors from [6], to the present. Further geochemical evaluation (discussed here) supports the presence of at least three lava groups. The discussion [2] also presents a re-evaluation of our age data resulting in conclusions identical to those of [1]. We stand by our published acceptance and rejection criteria for our data, as well as our quoted errors. Additional graphics relating unpublished geochemical and chronological data [2] are interesting, but cannot be properly evaluated in the absence of the inclusion of the raw data.

2. Geochemical re-evaluation of Rajahmundry Trap samples

As noted [1], our geochemical analyses of lavas do not provide a good 'fit' with a traditional and simplified

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* Corresponding author.
E-mail address: kbk@uclink.berkeley.edu (K.B. Knight).

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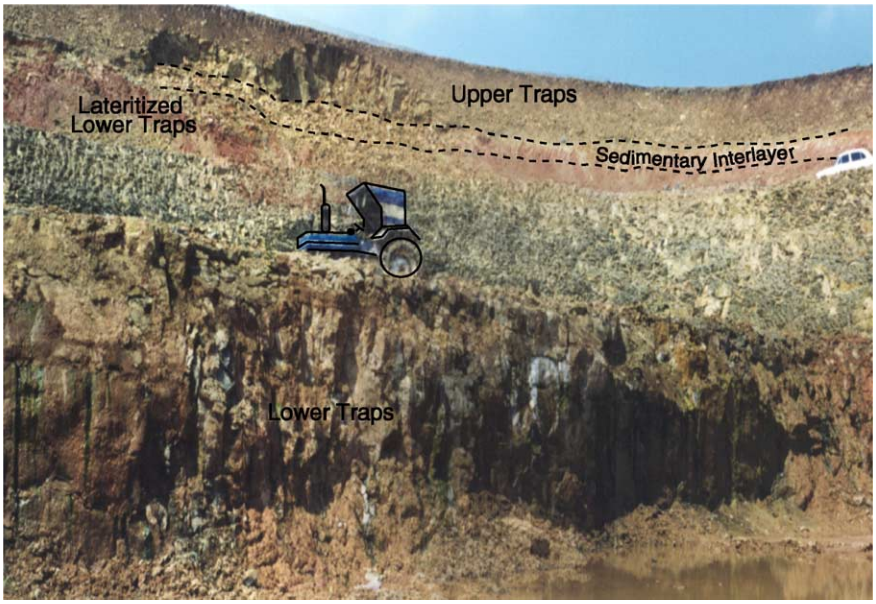

Fig. 1. Rajahmundry Trap stratigraphy at the site of samples RA99.1A, RA99.1B, RA99.02, and RA99.05 with ~2 m high tractor for scale. This quarry site shows the presence of at least one lava flow above the ~1 m thick sedimentary layer (emphasized with a dashed line). Underlying the sediments is the lateritized surface of a second lava flow, in turn underlain by a third flow. The two flows underlying the sedimentary layer were designated as 'Lower flows' [1].

definition of Upper and Lower lava packages. It is suggested [2] that geochemical data may provide more definitive criteria for lava unit identification within the Rajahmundry Traps beyond pure field observation, possibly allowing identification of the 'burrowing' of Upper lava flows through the sedimentary interlayer. There is field evidence (Fig. 2) for localized intercalation between the lavas and sediments (although no observation of lava cross cutting the sedimentary interlayer has yet been published) and we re-examine our

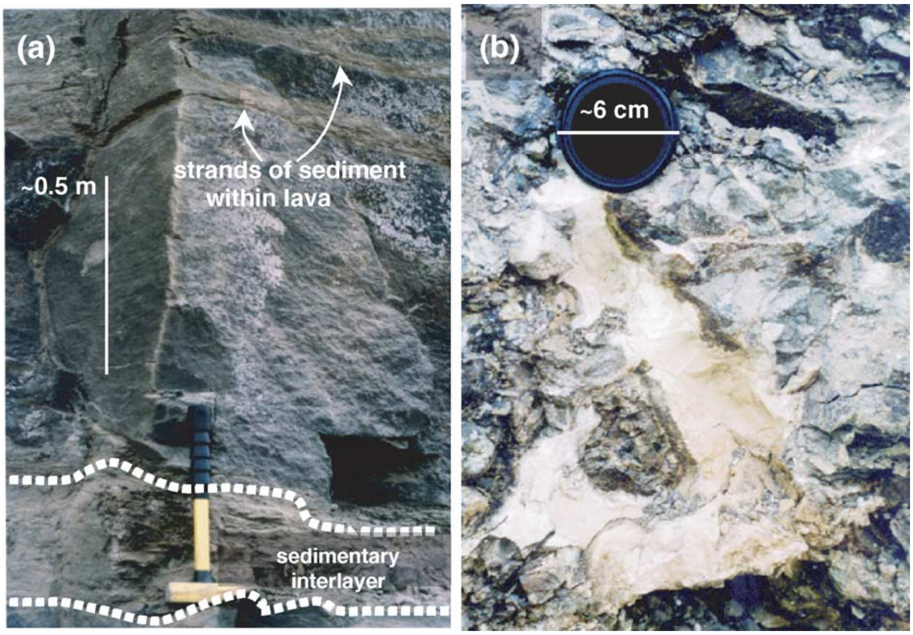

Fig. 2. a) Sandstone sediments incorporated into the Upper unit where RA99.14 was sampled. b) Limestone sediments incorporated into the Upper unit where sample RA99.11 was sampled. See [1] for site locations.

data in light of this. It is further suggested [2] that the presence of a several meters thick laterite horizon at the top of the Lower unit, which has been used to infer the passage of time [7], may instead be a baked contact zone caused by burrowing of Upper unit lavas. As a reverse to normal polarity transition is documented at this boundary [8,9] paleomagnetic study could potentially assist in determining this layer to be a baked (and therefore remagnetized) zone or merely a weathered horizon of Lower unit lavas. For now, however, such assertions remain inconclusive. It is suggested [2] that sample RA99.12 "was taken from a reversed polarity flow". We emphasize, however, that no paleomagnetic data exist for these [1] samples.

Closer examination of the sparse body of geochemical data available on the Rajahmundry Traps (Table 1) shows that previous geochemical work has differentiated Rajahmundry samples on the basis of sampling location relative to presence of the Godavari River (see map, [1]). This divides samples into the eastern outcrops near Rajahmundry (of which, only sample RA99.14 from [1] is derived) and western outcrops near Duddukuru with its prevalent sedimentary interlayer (where the majority of material for [1] was sampled). The western outcrops cover a reverse to normal transition, while the eastern outcrops (exposed at slightly higher elevation) have reportedly only normal polarity lavas [8,9]. The designation of eastern and western lavas has no petrogenetic significance beyond suggesting that the eastern outcrops expose only Upper unit lavas.

Samples from [1] were often located in quarries west of the Godavari River, exposing stratigraphically lower lying Rajahmundry Trap lavas than may have previously been sampled. A closer look at major element geochemistry (Table 1), supports the suggestion that [1] sampled previously uncharacterized Lower lavas. Major element chemistry generally indicates a strong difference between Lower and Upper Trap lava samples. The Lower lava flows, for example, have lower SiO_2, lower alkali content, higher CaO, lower TiO_2 and higher MgO (reported as weight% oxide) (Fig. 3). A comparison of published REE data (Fig. 4) support the occurrence of new (previously uncharacterized) lava groups in [1] and, based on this limited sampling, suggests the presence of three distinct groups within the Rajahmundry Traps.

3. Pb isotope data

Previously unpublished Pb isotope data for Rajahmundry Trap lavas from a set of 9 samples (Table 2;

Table 1
Summary of all published major element data for Rajahmundry Trap lavas

	Sample	Strat.	Loc.	SiO_2	Al_2O_3	TiO_2	FeO*	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5	H_2O
[11]	Raj. Trap			49.90	11.98	3.76	13.92	0.15	9.80	5.89	0.47	2.23	0.21	1.20
[6]	A		West	49.98	13.15	2.81	14.41		9.42	5.23	0.61	2.82		1.23
[6]	B		West	49.92	13.21	2.73	14.19		8.97	5.12	0.67	2.94		1.65
[6]	C		East	49.78	12.41	3.00	14.91		8.29	6.78	0.59	2.32		1.53
[6]	D		East	49.71	11.72	3.01	15.44		9.37	6.01	0.52	2.23		1.70
[10]	RT1	Below	West	49.7	13.1	2.69	15.4	0.22	9.9	6.1	0.31	2.42	0.27	1.4
[10]	RT1A	Above	West	50.9	13.2	2.74	13.9	0.24	10.0	5.7	0.42	2.61	0.27	0.4
[10]	RT2	?Above	West	51.0	13.0	2.74	14.2	0.24	10.0	5.5	0.42	2.55	0.27	0.6
[10]	RT2A	Above	West	50.7	13.0	2.79	14.6	0.25	10.0	5.4	0.40	2.54	0.29	0.6
[10]	RT3		East	49.7	13.6	2.81	14.7	0.24	9.9	6.1	0.30	2.45	0.28	1.7
[10]	RT3A		East	50.1	13.5	2.85	14.6	0.19	9.8	5.7	0.32	2.58	0.29	1.0
[10]	RT4B		East	50.2	13.6	2.89	14.3	0.19	9.9	5.8	0.27	2.58	0.29	1.1
[10]	RT5A		East	50.3	13.2	2.86	14.5	0.19	9.9	6.0	0.27	2.52	0.27	1.2
[10]	RT9C		East	50.4	13.1	2.75	14.4	0.24	10.2	5.9	0.35	2.40	0.26	0.9
[1]	RA99.1B	Below	West	48.50	14.15	2.64	13.46	0.19	11.30	6.26	0.12	2.28	0.23	
[1]	RA99.06		West	49.17	14.35	2.59	12.08	0.17	11.57	6.43	0.10	2.20	0.22	
[1]	RA99.12	Below	West	49.24	14.61	1.98	11.71	0.18	11.50	7.32	0.09	2.04	0.16	
[1]	RA99.02	[a]Below	West	50.95	13.43	2.76	13.82	0.24	10.30	5.45	0.41	2.50	0.27	
[1]	RA99.14	Above	East	50.33	13.02	2.85	13.98	0.25	10.36	5.81	0.36	2.37	0.27	
[1]	RA99.23	Above	West	50.10	12.93	2.80	14.78	0.24	10.08	5.67	0.39	2.36	0.26	

Older data [6,11] may or may not be relevant to data obtained by modern techniques. Stratigraphy is reported relative to the main sedimentary interlayer, where reported. Location is reported relative to the Godavari River, where reported. All relevant Rajahmundry trace element data are recently reported [1,10], and not reproduced, here. Additional data are reported (TiO_2, Zr/Nb, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ data from [9] and trace element data from [2]) but not yet published as numerical data, and so not discussed, here.

[a] Identified here as a burrowed Upper unit sample.

* All Fe shown as FeO*.

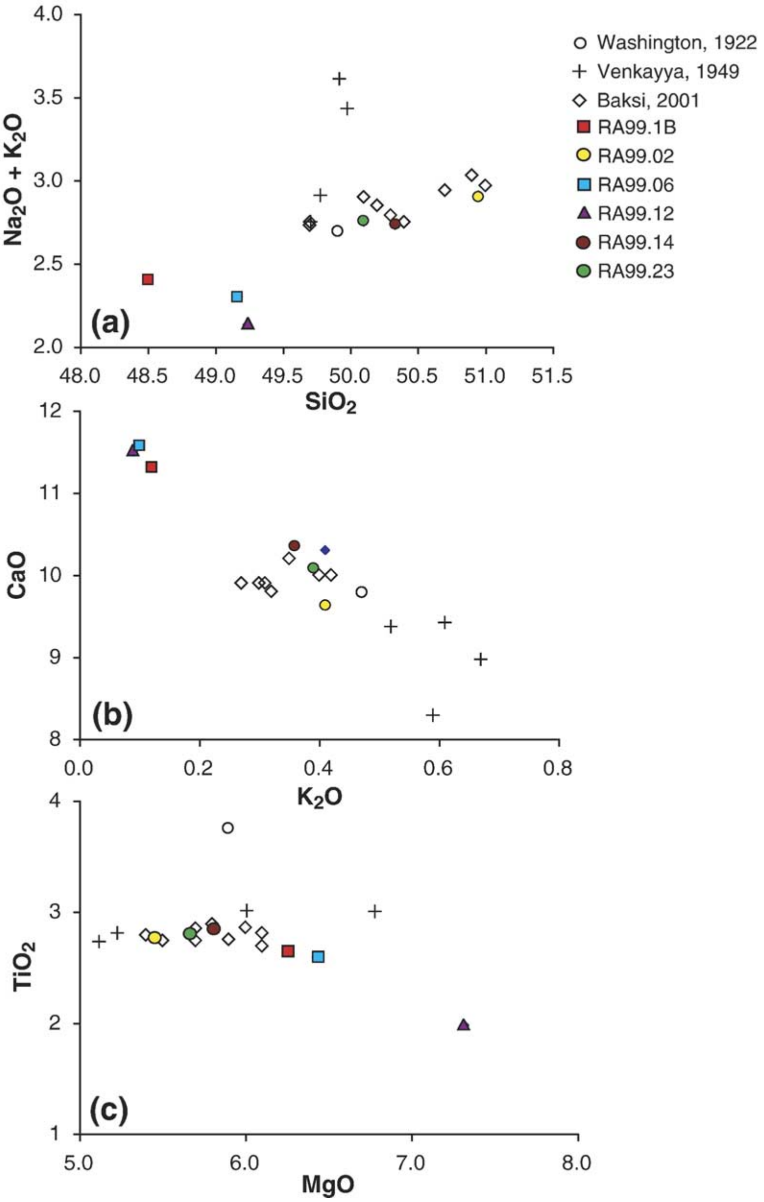

Fig. 3. a) Total alkali content vs. SiO_2 comparison of Rajahmundry Trap lavas. All fall within the compositional range of basalts. b) CaO vs. K_2O comparison of Rajahmundry Trap samples. c) TiO_2 vs. MgO comparison of Rajahmundry Trap samples. Major element analyses [1,6,10,11] demonstrate sampling of two primary Rajahmundry Trap groups along what may be interpreted as geochemical trends. Analytical errors for are smaller than symbol size [1,10] or unknown [6,11].

Fig. 5) are presented here to providing additional support to our observations based on major and trace element data. Isotopic ratios for the entire group are $^{206}Pb/^{204}Pb$ of 17.42–18.60, $^{207}Pb/^{204}Pb$ of 15.37–15.56 and $^{208}Pb/^{204}Pb$ of 38.14–39.95. Rajahmundry Trap data clearly fit the Pb isotope trend shown by north and northeastern Deccan Trap flows [16,17; Fig. 5 inset]. If the continental lithosphere is similar in character in both areas, these data may indicate subsurface transport of Rajahmundry Trap melt, with variable incorporation of crust. Alternately, if overland flow of lavas is implicated, these data may provide a partial means for identification of possible matches between eastern Deccan Trap flows. In order to identify magmatic source characteristics and distinguish between the two hypotheses, however, additional isotopic data are warranted.

Rajahmundry Trap Pb isotope data unequivocally support the presence of at least three lava groups [14]. Generally, two of these groups (with the most

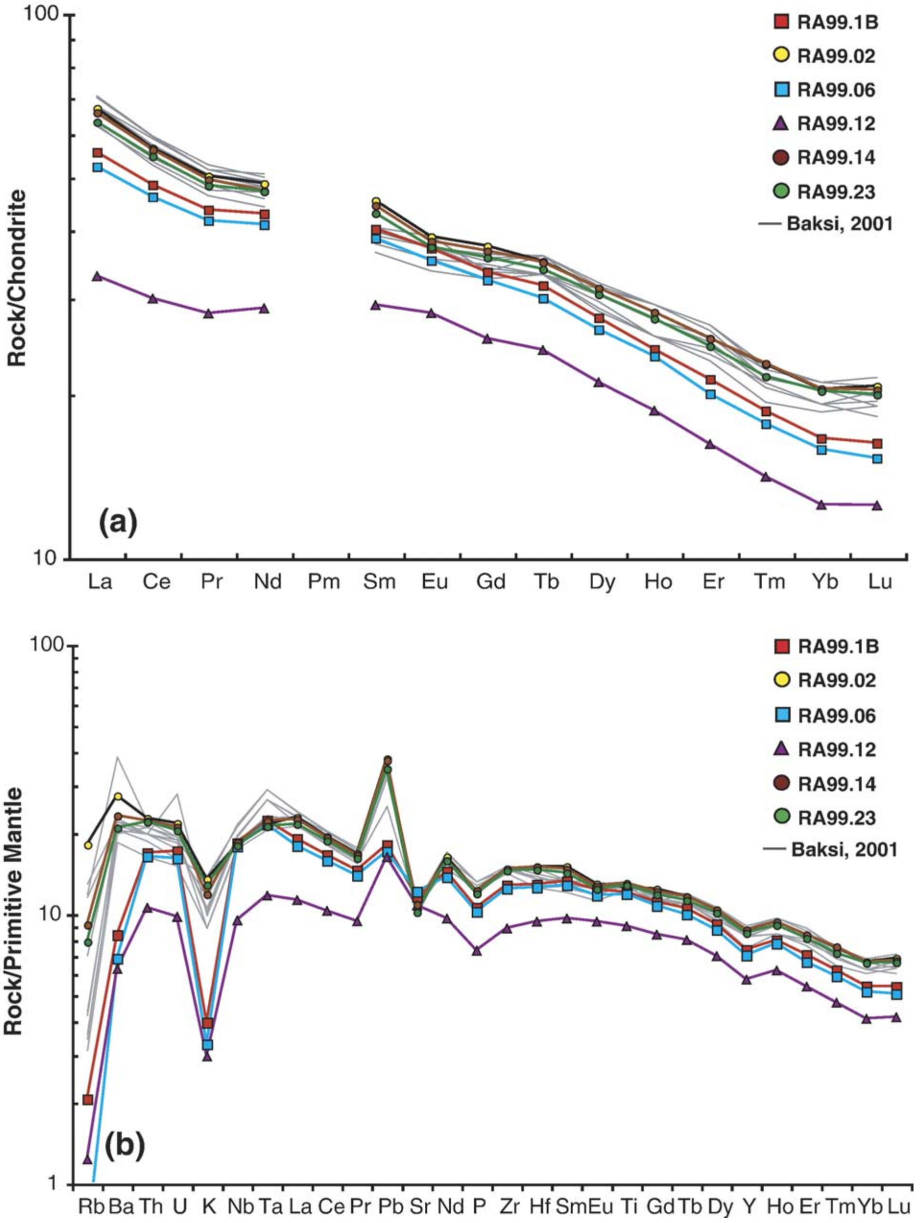

Fig. 4. a) Chondrite-normalized [12] rare earth element patterns and b) primitive mantle normalized [13] trace element diagrams comparing published Rajahmundry Trap trace element data [1,10].

radiogenic and intermediate Pb isotope ratios) agree with the stratigraphic definition of the Lower Trap lava flows (i.e. samples were located below the main sedimentary interlayer). The group with the least radiogenic Pb isotope ratios agrees with our stratigraphic designation of the Upper Trap lava flows.

The most radiogenic Pb isotope ratios (Fig. 5, ^{206}Pb/^{204}Pb ~18.58, ^{207}Pb/^{204}Pb ~15.56, ^{208}Pb/^{204}Pb ~38.93) are represented by three samples. RA99.1A and RA99.1B are located within the lowest flow of Fig. 1 and show a strong isotopic affinity with Lower lava flows, supported by major element (Fig. 3) and trace element (Fig. 4) chemistry for sample RA99.1B. Thus, we contest the assertion [2] that RA99.1B can be termed a ‘burrowed’ Upper lava flow. Curiously, sample RA99.06 has a contrary affinity to the Lower Traps (also clearly seen in Fig. 1 of [2]). Initial work (Halkett, pers. comm.) suggested that this sample was collected below the sedimentary boundary. Later work [7], however, locates this sample above the sedimentary horizon (where it was placed in [1]). Although the location of all other samples from this study has been reconfirmed,

Table 2
Pb isotope data from Rajahmundry Trap samples [14]

Sample ID	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	Relative stratigraphy
RA99.05	17.423	15.376	38.160	Upper
RA99.06	18.560	15.557	38.921	*Unknown*
RA99.11	17.753	15.459	38.468	Lower
RA99.12	17.763	15.462	38.483	Lower
RA99.14	17.428	15.373	38.146	Upper
RA99.1A	18.577	15.557	38.920	Lower
RA99.1B	18.604	15.558	38.953	Lower
RA99.19	17.434	15.375	38.166	Borehole sample
RA99.18	17.451	15.388	38.208	Borehole sample

Sample position relative to the primary sedimentary interlayer is noted. See text for discussion of sample RA99.06.

Pb isotope data were obtained on Pb separated from hand-picked (*ca*. 1–2 mm) rock chips that were subjected to acid leaching in hot (130 °C) 6M HCl for one hour prior to digestion. Approximately 100–200 mg of leached rock chips were digested in concentrated HF-HNO_3 acids. Pb was separated using standard anion exchange techniques and analytical blanks were insignificant (≤ 100 pg). Pb isotopic measurements were made with a double focusing multiple-collector inductively coupled plasma mass spectrometer at the Danish Lithosphere Centre in 2001. Instrumental mass bias was corrected with reference to the mass bias observed in Tl admixed to the sample Pb, using the exponential mass fractionation law and $^{205}Tl/^{203}Tl = 2.3889$. Replicate analyses of SRM981 during the analytical session yielded mean Pb isotope ratios of: $^{206}Pb/^{204}Pb = 16.938 \pm 0.003$; $^{207}Pb/^{204}Pb = 15.492 \pm 0.004$; $^{208}Pb/^{204}Pb = 36.702 \pm 0.011$ ($n = 13$; 2 sd). However, the long-term external reproducibility reported by Baker et al. [15] ($\pm 0.04\%$ per atomic mass unit) for this analytical methodology is a more realistic assessment of the reproducibility of *this* dataset, and is much smaller than the overall isotopic variations observed between the sample groupings. Pb isotopic data are presented as measured values and have not been age-corrected to 65 Ma.

the field location of sample RA99.06 relative to the sedimentary interlayer was not photo-documented. Both elemental and isotopic geochemistry suggests that RA99.06 is an Upper Rajahmundry lava, but with no accompanying photos to provide clarification at this time, we can only suggest that it may be mislocated in [1] and, while it should be considered in the context of general Rajahmundry lava characteristics, it cannot be considered when contrasting Upper and Lower lava characteristics.

The intermediate Pb isotopic group (Fig. 5, $^{206}Pb/^{204}Pb$ ~17.76, $^{207}Pb/^{204}Pb$ ~15.46, $^{208}Pb/^{204}Pb$ ~38.48) is represented by two samples (RA99.11 and RA99.12). Selected trace element data (Fig. 4) for RA99.12 support the occurrence of this third group, while major element data (Fig. 3) as well as Pb-isotope data suggest an affinity to the Lower Rajahmundry lavas. We suggest the occurrence of these two distinct Pb-isotope groups as supporting geochemical evidence for at least two lava flows in the Lower Traps. Both RA99.11 and RA99.12 were sampled from well beneath the sedimentary interlayer, but their stratigraphic position with respect to other Lower Trap lava samples cannot be precisely determined. Elemental geochemistry data (TiO_2 and Zr/Nb) for RA999.12 are strikingly similar to previous data reported from the lowest flows of western Rajahmundry [9].

Samples RA99.05 (not dated) and RA99.14 occur above the sedimentary interlayer, and clearly define an Upper lava group with the least radiogenic Pb isotope ratios (Fig. 5, $^{206}Pb/^{204}Pb$ ~17.43, $^{207}Pb/^{204}Pb$ ~15.38, $^{208}Pb/^{204}Pb$ ~38.16) supported by trace element data (Fig. 4). Without Pb isotope data, we cannot know if sample RA99.02 also falls within this group. Initially identified as a Lower Rajahmundry sample [1] due to its location within a relatively less altered portion of the lateritic zone underlying the main sediment layer (Fig. 1), elemental geochemistry and isotopic data along with the sample location suggest that RA99.02 may indeed be a ‘burrowed’ Upper lava. Two additional samples taken from lava flows recovered in drill holes (RA99.18 and RA99.19; Table 2) also fall into the isotopic range of Upper Rajahmundry lavas, but their stratigraphic position with respect to the main sedimentary interlayer cannot be precisely determined.

To summarize this geochemical evaluation using major, trace element and Pb isotope characteristics, we interpret samples RA99.1A, RA99.1B, RA99.06, RA99.11, and RA99.12 to be Lower Rajahmundry lavas, likely representing at least two lava flows. We place RA99.05 and RA99.14 and RA99.23 as Upper Rajahmundry lavas, possibly representing multiple sampling of a single flow unit. We tentatively agree with the assertion of [2], choosing RA99.02 to be chemically affiliated with Upper Rajahmundry lavas, but would consider additional Pb isotopic work to provide the most conclusive evidence. These stratigraphic and geochemical (as well as inferred paleomagnetic) relationships should continue to be tested. Present data, however, suggest that geochemistry at all levels (major element, trace element, or isotopic data) may allow unambiguous identification of Upper and Lower Trap lava groups, and may prove a useful tool for correlation of discontinuous Rajahmundry lavas (such as drill hole sample lavas).

4. The ‘best’ age for the Upper and Lower Rajahmundry Traps

In [1], we chose to use the traditional designations for Upper and Lower lava flows, erring on the side of caution in assigning the lava flows to a single (and thus,

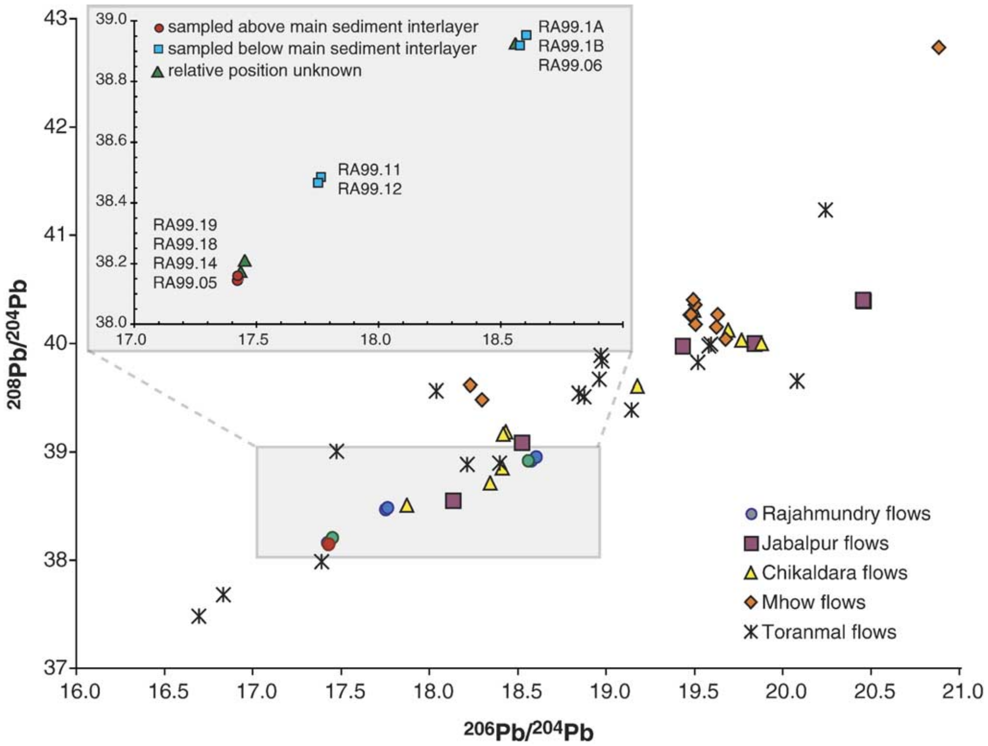

Fig. 5. $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ data from northern and northeastern Deccan Trap lava formations [16,17] and preliminary $^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$ data (Table 2, [14]) from Rajahmundry Trap samples [1]. Inset shows Rajahmundry lavas, only, and highlights the occurrence of three distinctive lava groups, with symbols indicating stratigraphic context. See Table 2 for analytical detail and error discussion. Pb isotope data are not age corrected.

same-aged) flow for each of the Upper and Lower units. This has a direct bearing on the use [2] of an MSWD criterion applied to our age data. This statistical method is not valid for Lower unit flows, where we can conclusively support the presence of at least two distinct lava flows, but may be applicable to the Upper unit. If we choose to follow the approach of [2], however, making the clarifications above that geochemical evidence can clearly pinpoint three distinct lavas, we can tease out the best age for Lower and Upper eruptive units. It should be noted that the age of RA99.02 is 65.8 ± 0.5 Ma (shown correctly in Fig. 5 of [1]) was mistyped in Table 3. We appreciate [2] for bringing this to our attention. The basis of the exclusion [2] of sample RA99.06 by use of ^{36}Ar as a proxy for alteration is arbitrary and unjustified. We do not include RA99.06 in the following mean age calculations contrasting Upper and Lower lavas, however, as we cannot confidently reconfirm its sampling stratigraphy (as discussed, above). In addition, we continue to exclude previous whole rock data, due to the unidentifiable impact of recoil and alteration problems.

From three Upper lava ages, we exclude sample RA99.02 (as discussed in [1]). The best age determination for the Upper Trap lavas is then most appropriately given as the weighted average age from the two remaining samples, 64.5 ± 0.3 Ma. From the Lower lava samples, we presented four dated samples from

Table 3
Ages designating the start and end of GPTS chrons based on the time scale of [18]

Start (Ma)	End (Ma)	Chron
61.480	58.452	C26r
61.838	61.480	C27n
63.069	61.838	C27r
64.211	63.069	C28n
64.555	64.211	C28r
65.329	64.555	C29n
66.167	65.329	C29r
68.212	66.167	C30n
68.338	68.212	C30r
69.346	68.338	C31n
71.695	69.346	C31r

Ages are normalized to the Fish Canyon sanidine monitor age of 28.02 Ma [19] and adjusted to a revised Cretaceous Tertiary boundary tiepoint of 65.58 Ma [20].
Note that the CK95 timescale [18] places the boundary *within* C29r (0.3 from the younger end of C29r).

which we exclude RA99.1A and RA99.1B (as discussed [1]). The remaining two samples, on the basis of Pb isotopic data, may represent the same lava. Sample RA99.12 has two robust replicate analyses with MSWD's ~1, however, while sample RA99.11 has an MSWD of 0.1 suggesting that errors from individual steps have been overestimated. We would suggest that the best age for the Lower unit, given these limited data, is the weighted average age for these two samples, 64.4 ± 0.5 Ma. This remains in excellent agreement with our original (more conservative) conclusions, which placed eruption of the Rajahmundry Trap lavas in a very brief period of time ca. 64.5 Ma, potentially coincident with late stage Deccan Trap volcanism. We continue to stress, however, that caution should be exercised and further mineral separate chronology should be applied for more robust conclusions.

5. The Rajahmundry Traps and the geomagnetic polarity time scale

With respect to the geomagnetic polarity time scale (GPTS), it is unclear whether or not [2] has readjusted the CK95 timescale [18], which is presented relevant to a ^{40}Ar/^{39}Ar monitor mineral standard age of 27.84 Ma for Fish Canyon sanidine, to the monitor age relevant to these data [1], which used Fish Canyon sandine at 28.02 Ma [19]. In addition, adjustment must be made in light of his replacement of the CK95 timescale 'tiepoint' (which originally used 65.00 for the Cretaceous–Tertiary boundary age within C29r chron) with the now revised to 65.58 Ma (see [20]). To clarify this, we provide the CK95 timescale revised to reflect the monitor standard age of these data (Fish Canyon sanidine, 28.02 Ma), and with the absolute 'tie point' of the Cretaceous–Tertiary boundary reflecting the revised age of 65.58 Ma (Table 3). This leaves the possibility open that the Rajahmundry Traps cross the C28 reverse to normal transition relative to the C29 reverse to normal polarity transition observed in the bulk of the Deccan Traps [8]. Given the remaining uncertainties surrounding the GPTS at this juncture, however, the true magnetostratigraphic correlation of the Rajahmundry Traps remains indeterminate.

6. Conclusions

Clarification of field relationships, further paleomagnetic study and, specifically, additional isotopic work remain necessary to conclusively distinguish between an overland flow model or subsurface melt transport model for emplacement of the Rajahmundry Traps relative to the Deccan Traps with certainty. Regardless, we find the comments of [2] in good general agreement with our initial conclusions, and we continue to encourage publication of new studies to further clarify the origin and context of these lavas.

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