Age and duration of the Deccan Traps, India: A review of radiometric and paleomagnetic constraints

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A review of the available radiometric and paleomagnetic data from the Deccan Flood Basalt Province (DFBP) suggests that the volcanism was episodic in nature and probably continued over an extended duration from 69 Ma to 63 Ma between 31R and 28N. It is likely that the most intense pulse of volcanism at 66.9 ± 0.2 Ma preceded the Cretaceous Tertiary Boundary (KTB, 65.2 ± 0.2 Ma) events by ~1.7 Ma. The magnetostratigraphic record in the Deccan lava pile is incomplete and it is therefore possible that the lava flows constituting the reverse polarity sequence were erupted in more than one reversed magnetic chron.

1. Introduction

The voluminous (~1.5 x 10⁶ km³) Deccan Traps of western and central India comprise a thick sequence of sub-aerially erupted basaltic flows that presently cover an area ~1.5 x 10⁶ km² which may originally have been much greater (figure 1). It has been hypothesised that the flood basalts marked the first eruption of lava related to the Reunion hotspot followed shortly afterwards by rifting apart of the Arabian Sea (Morgan 1981; Richards et al 1989). Moreover, it has been argued that the voluminous Deccan lavas erupted very rapidly in a rather short interval of less than 1 m.y. at the Cretaceous-Tertiary Boundary (KTB) leading to several biological and geological anomalies at the KTB (Courtillot et al 1986, 1988; Duncan and Pyle 1988). Both these proposals generated immense interest among the scientists to obtain the precise age and duration of the volcanism but dating of the Deccan traps have proved to be difficult. Attempts, however, have been made, using paleontological, radiometric and paleomagnetic dating methods (Baksi 1987, 1994; Jaeger et al 1989; Vandamme et al 1991; Venkatesan et al 1993; Venkatesan and Pande 1996; Hofmann et al 2000) but inferences about age and duration of Deccan Traps are based on plausibility arguments, the persuasiveness of which often depends more on the eloquence of their advocates than on the weight of the relevant data.

The Deccan Trap overlie and are often interlayered with sediments of Maastrichtian to late Maastrichtian age. The overlying sediments contain microfauna of P2 zone of the Paleocene (60–65 Ma). The biostratigraphy therefore limits the age of the Deccan to 73–60 Ma (Jaeger et al 1989). The magnetostratigraphy (figure 1) typically consists of a poorly exposed lower normal polarity zone, overlain by a middle reversed polarity zone that is capped by the upper normal polarity zone. If the magnetostratigraphy of the traps has continuously recorded the geomagnetic field, the eruption would have lasted for 3–4 m.y., the duration of the longest reversed polarity chron between 73 and 60 Ma (Courtillot et al 1986, 1987; Wensink 1987; Acton and Gordon 1989; Vandamme et al 1991). The radiometric ages have been obtained using K-Ar and Ar-Ar technique (Kaneoka 1980; Baksi 1987, 1994; Courtillot et al 1988; Duncan and Pyle 1988; Pande et al 1988; Vandamme et al 1991; Venkatesan et al 1993, 1996; Hoffman et al

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Figure 1. Present day outcrops of Deccan volcanic province showing simplified chemo- and magneto-stratigraphic sections (not to scale; modified after Figure 11 in Widdowson et al, 2000). J, Ig, Bh, Kh, Bu, Po, A, M and Pn are Jawhar, Igatpuri, Thakurdi, Bhimashankar, Khandala, Bushe, Poladpur, Ambenali, Mahabaleshwar and Panhala Formations, respectively. Section localities: (1), Pune-Purandhar; (2), Mahabaleshwar; (3), Belgaum; (4), Khillari borehole; (5), Gurumkal; (6), Bidar; (7), Nazimabad; (8), Adilabad; (9), Nagpur; (10), Jabalpur; (11), Chikaldara; (12), Buldana; (13), Ellora-Outram; (14), Mawalaswar-Pipaljopa; (15), Toranmal; (16), Chandwad; (17), Kalsubai peak. Compiled from Cox and Hawkesworth (1985), Beane et al (1986), Devey and Lightfoot (1986), Khadri et al (1988), Mitchell and Widdowson (1991), Subbarao et al (1994), Peng and Mahoney (1995), Peng et al (1998), Bilgrami (1999), Mahoney et al (2000). The polarity transitions (i.e., N, Normal; R, Reversed) are after Sreenivas Rao et al (1985), Vandamme and Courtillot (1992), and the references therein and the chemostratigraphy is after Widdowson et al (2000). The samples for which the $^{40}$Ar-$^{39}$Ar ages are plotted in figures 2 and 3 are from the regions shown as dark grey rectangles.
2000) and most recently by $^{187}\text{Re} - ^{187}\text{Os}$ chronometer (Allgre et al. 1999). The published K-Ar ages show a large spectrum resulting primarily from the sensitivity of the K-Ar system to post crystallisation alteration. However, it has been inferred from K-Ar ages that maximum outpouring of lava occurred between 68 and 57 Ma (Mahoney 1988; Vandamme et al. 1991). The $^{40}\text{Ar} - ^{39}\text{Ar}$ plate and isochron ages narrow down the range to 68–63 Ma though there are several ambiguities due to the different age of the monitor samples used by various laboratories. Similarly, the $65.6 \pm 0.3$ Ma age of the Deccan Trap derived from $^{187}\text{Re} - ^{187}\text{Os}$ data is not unequivocal because of the uncertainty in the value of the decay constant $\lambda$ for $^{187}\text{Re}$. In this paper, the available radiometric and paleomagnetic data have been reviewed to best constrain both the timing and duration of the Deccan volcanism.

2. Absolute age determinations

2.1 $^{40}\text{Ar} - ^{39}\text{Ar}$ ages of Deccan Traps

The first $^{40}\text{Ar} - ^{39}\text{Ar}$ data for the Deccan Trap (DT) were presented by Kaneoka (1980) but the ages spanned over 20 m.y. with large uncertainties. It was pointed out by Baksi (1987) that one of the three plateau ages published by Kaneoka (1980) was erroneous arguing that the injudicious choice of monitor sample (Bern 4M muscovite) artificially created a plateau. Therefore, in the present discussion, only two plateau ages determined by Kaneoka (1980) are considered. Over the last one and a half decades several papers have reported more precise Ar-Ar ages for both whole rock and mineral separates from the DT flows (e.g., Courtillot et al. 1988; Duncan and Pyle 1988; Pande et al. 1988; Duncan and Pringle 1991; Vandamme et al. 1991; Venketesan et al. 1993, 1996; Baksi 1994; Sen and Cohen 1994; Sheth et al. 1997; Hofmann et al. 2000) and the KTB (e.g., Izett et al. 1991; McWilliams et al. 1991; Hall et al. 1991; Swisher et al. 1992). The direct comparison of these data is not feasible because of the use of different monitors and uncertainties in the ages of the monitor sample(s) used for obtaining these ages. For example, $^{40}\text{Ar} - ^{39}\text{Ar}$ ages of the DT have been obtained against MMhb-1 standard, for which an age of 520.4, 519.5 and 513.9 Ma (equivalent of 162.9 Ma SB-3 biotite) have been used. The KTB ages have also been obtained with respect to ages of internal standards that have been calibrated against different ages of MMhb-1. These dates/ages need to be recalculated with respect to a particular age of the used monitor to compare them and critically examine their significance under the scenario of the suggested rapid eruption model. Additionally, the interpretation of $^{40}\text{Ar} - ^{39}\text{Ar}$ data is also subject to the choice of a plateau or isochron age and whole rock or mineral dates. The $^{40}\text{Ar} / ^{39}\text{Ar}$ technique can determine the level of alteration of samples more efficiently. Several criteria have been employed by various workers to select the ‘reliable samples’ (e.g., Iwata and Kaneoka 2000) and filter the available dates to obtain ‘good quality’ ages (e.g., Vandamme et al. 1991; Hofmann et al. 2000), however, the relative merits of whole rock and mineral ages (Duncan and Pyle 1988; Courtillot et al. 1988) as well as such criteria are debatable. A plateau is defined as that part of an age spectrum representing a significant amount of $^{39}\text{Ar}$ released from a sample and for which no difference in age can be detected between any two steps at $2\sigma$ level of confidence. As much as $2\%$ uncertainty in the age of MMhb-1 has been inferred by various workers (Renne et al. 1998 and references therein) and an age of $523.4 \pm 2.6$ Ma (Renne et al. 1998) is the latest recommended value for MMhb-1. For the present discussion, however, all the available Ar-Ar ages for DT and KTB were recalculated to a MMhb-1 age of $520.4 \pm 1.7$ Ma (Samson and Alexander 1987) for facilitating a comparison with the Cande-Kent geomagnetic polarity time scale (GPTS) for late Cretaceous and Cenozoic (Cande and Kent 1995) which was constructed using KTB age with respect to MMhb-1 age of $520.4 \pm 1.7$ Ma and only the whole rock plateau ages are considered.

The question of initiation and duration of the Deccan volcanism can be better resolved by considering the data only on the stratigraphically well constrained western ghats section of the province. In figure 2, we plot the available normalised whole rock $^{40}\text{Ar} - ^{39}\text{Ar}$ data against the composite stratigraphy and magnetostratigraphy. It can be easily seen that all samples except MAP-057 are consistent with stratigraphic order. Also, the samples display ages ranging from $67$ Ma to $62$ Ma, which can be grouped into three clusters A, B, and C at $66.9 \pm 0.3$, $64.8 \pm 0.6$ and $62.3 \pm 0.6$ Ma respectively. The thickest section of lava flows from the base of this stratigraphic column yields a very narrow range of ages at $66.9 \pm 0.2$ Ma.

The $^{40}\text{Ar} - ^{39}\text{Ar}$ whole rock plateau ages for the entire DT show a wide range from $68.7$ to $62.1$ Ma. Figure 3 shows a histogram of the available $^{40}\text{Ar} - ^{39}\text{Ar}$ plateau ages. Each datum is given unit weight and is represented by a gaussian distribution with standard deviation equal to the uncertainty in the age ($2\sigma$) and $N$ is the number of samples (Vandamme et al. 1991; Venketesan and Ramesh 1993). I also plot the KTB at $65.2 \pm 0.2$ Ma (recalculated to MMhb-1 age of $520.4$ Ma). I am
aware that any interpretation of such a treatment of data is subject to sampling bias, for example, if the same lava flow has been sampled and dated several times it may lead to an artificial peak in the histogram. Such a possibility is minimum since 

I have considered ages reported for samples from distinct locales (shown as dark grey boxes in figure 1) viz., the stratigraphically controlled western ghat section (Duncan and Pyle 1988; Venkatesan et al 1993; Baksi 1994), the east-west Nagpur-
Figure 3. Histogram of all available $^{40}$Ar/$^{39}$Ar ages (recalculated to an age of 520.4 ± 1.7 Ma for MMhb-1). Each datum is given unit weight and represented by a Gaussian distribution with standard deviation (1σ) equal to the uncertainty in the age (Vandamme et al. 1991; Venkatesan and Ramesh 1993). N is the number of samples. The number corresponding to each curve indicates the number of samples in that group. The hatched rectangle marks the limits of Cretaceous Tertiary Boundary (KTB). The geomagnetic polarity time scale (GPTS) at 70–60 Ma (Cande and Kent 1995), adjusted as in figure 2, is plotted at the bottom. Black = normal polarity, White = reversed polarity. The Ar-Ar ages are from Kaneoka 1980; Courtillot et al. 1988; Duncan and Pyle 1988; Pande et al. 1988; Duncan and Pringle 1991; Venkatesan et al. 1993, 1996; Baksi 1994; Sen and Cohen 1994; Sheth et al. 1997 and Pande et al. (in preparation).

Bombay traverse (Vandamme et al. 1991) and several other parts of the Deccan province (Courtillot et al. 1988; Duncan and Pringle 1991; Sen and Cohen 1994; Venkatesan et al. 1996; Sheth et al. 1997). The distribution reveals several peaks at 62.0–62.5, 63.5–63.6, 64.2–64.5, 65.0–65.4, 66.5–66.6, 67.1–67.4, 69.5–69.8 Ma. Significantly enough the three cluster of ages 61.7–62.9, 64.2–64.5 and 66.3–67.2 Ma from the western ghats stratigraphic section, shown in figure 2, are also reflected in figure 3 as peaks. It is thus evident that the Deccan volcanism continued episodically over a protracted period from 68.7 to 62.1 Ma with several periods of repose and that the peaks in the distribution correspond to pulses of volcanism. More importantly, if the formation thickness is assumed proportional to the relative volume of a particular chemostratigraphic unit, it appears that the most intense pulse of Deccan occurred at 66.9 ± 0.2 Ma clearly predating the KTB (figure 2). These observations need to be confirmed with newer and more accurate data since we have no information regarding eruption volumes per unit time, and formation thickness alone need not necessarily equate to relative volume of a particular chemostratigraphic unit.

2.2 $^{187}$Re-$^{187}$Os systematics

The determination of an accurate age using the $^{187}$Re-$^{187}$Os is as critically dependent on the value
of decay constant $\lambda$ as the $^{40}\text{Ar} - ^{39}\text{Ar}$ system is on the uncertainty in the age of the monitor sample. As mentioned by Allegre et al (1999) at present the decay constant of $^{187}\text{Re}$ has some uncertainties. The authors prefer to determine an age of 65.6 ± 0.3 Ma from the $^{187}\text{Re} - ^{187}\text{Os}$ isochron using a value of $\lambda = 1.663 \times 10^{-11}$ yr$^{-1}$ which supports their hypothesis that the KTB is coincident with DT. The meteorite-derived decay constant is less accurately determined than these authors state, particularly because it can be no more accurate than the Pb/Pb isochron it was derived from, which has at least 0.2% error just from the uranium decay constant uncertainties. Also, the reported uncertainty in the $^{187}\text{Re} - ^{187}\text{Os}$ isochron age (65.6 ± 0.3 Ma) is at 1σ level whereas the paper says it is 2σ. Further, the isochron has an MSWD of 42, calculated using the Isoploto/Ex.2.49 package (Ludwig 2001), indicating excess scatter. This undoubtedly implies that the initial $^{187}\text{Os}/^{188}\text{Os}$ is more variable than acknowledged and the error is therefore underestimated by at least a factor of $\text{SQRT(42)} = 6.5$. The isochron age at 2σ level, therefore, is really 65.6 ± 3.9 Ma! This age is not more precise than the $^{40}\text{Ar} - ^{39}\text{Ar}$ ages discussed in the preceding section. In fact, within the 2σ uncertainty the $^{187}\text{Re} - ^{187}\text{Os}$ age shows the same spread for Deccan volcanism as the $^{40}\text{Ar} - ^{39}\text{Ar}$ data.

3. Magnetostratigraphy

The magnetostratigraphy of lava flows sequences at several localities in the Deccan province has been depicted with the chemical stratigraphy in figure 1. The chemostatigraphy is after Widdowson et al (2000), and the polarity transitions (i.e. N, R) are after Sreenivasa Rao et al (1985), Vandumme and Courtillot (1992) and the references therein. It is, however, important to bear in mind that whether a particular chemostatigraphic unit is normal (N) or reverse (R) can only be established with certainty if palaeomagnetic data are available on the materials from that particular locality, which may not be the case for some of the sections.

It is generally believed that the Deccan trap volcanism may have covered no more than three polarity intervals - thin normal sequence, a thick intermediate reversed sequence and an upper normal sequence - and a large fraction (on the order of 80%) of the activity to have taken place during the middle reversed chron (Duncan and Pyle 1988; Courtillot et al 1988; Vandumme et al 1991; Baksi 1994; Hofmann et al 2000). It is, however, obvious that the simplistic interpretation of the magnetostratigraphic data is fraught with problems. For instance, in sequence 1 (figure 1) of western ghats the lava flows at the elevations of Bhimashankar and Khandaala formations show reverse polarity whereas in sequence 17 the lava flows at these levels are normally polarised. The magnetostratigraphy in the southern part of Narmada valley shows NNRRNR (figure 1 sequence 12) though it is suggested that this sequence may have been caused by tectonic repetition or complex remagnetisation. A critical analysis of the available database of palaeomagnetic results suggests that the simple NRN sequence cannot be applied everywhere in the Deccan.

The wide range of $^{40}\text{Ar} - ^{39}\text{Ar}$ ages (68.5 – 62.1 Ma) from the western ghats section of the Deccan, apparently at variance with the palaeomagnetic observations, has been attributed to the difference in monitor ages and laboratory procedures, and alterations such as argon excess and recoil rather than real time/age differences (Baksi 1994; Allegre et al 1999; Hofmann et al 2000). This contradiction stems from the fact that hypotheses proposing a causal relationship between DT and KTB place all the reversed polarity lava flows in 29R chron, thereby arguing for a short duration of Deccan volcanism. Implicit in such a proposal is that the flow sequence exhibits an uninterrupted volcanic outpouring and, therefore, the ambient Earth’s magnetic field is continuously recorded in it. Such a simplistic interpretation of magnetic stratigraphic data may be unrealistic, especially in a volcanic sequence where the rate of eruption of flows can be highly variable and episodic with short spurts of activity separated by long intervals of quiescence. There is a finite possibility that the reversed polarity flows may belong to two or more reversed polarity chrons there being no record of eruption during the intervening short normal chron. The Deccan flows displaying reversed polarity cannot be assigned to a particular reversed polarity chron 31R or 29R with certainty and there is considerable subjectivity and personal bias in interpreting the magnetostratigraphic data (e.g., Courtillot et al 1987; Wensink 1987; Acton and Gordon 1989). Such interpretations/inferences often leave one utterly confused.

4. Discussion

As mentioned in the previous section the wide range of $^{40}\text{Ar} - ^{39}\text{Ar}$ ages for the Deccan is apparently at variance with the palaeomagnetic data, which suggest that only two magnetic chrons (bottom reverse and top normal) are represented in the major areas of the Deccan Traps. This inconsistency arises because it has been assumed that the magnetostratigraphic record in Deccan is complete. In order to evaluate whether this assumption
is valid we need to consider the age and palaeomagnetic data together. Of the three clusters (A, B, C) of ages for western ghat composite sequence (figure 2), the lava flows of A and B were laid down in reverse polarity and those of C in normal polarity. The two different age clusters (A and B) for the reverse polarity flows indicate that they represent two distinct eruptive events and may belong to two different reverse chronns. Similarly, seven peaks in the probability histogram (figure 3) strongly suggest several distinct phases of eruptions. At the bottom of figures 2 and 3, is plotted the geomagnetic polarity timescale (GPTS) of Cande and Kent (1995) at 70–60 Ma, so adjusted that the KTB within 2σ error falls in 29R. It can be seen that the flows belonging to clusters A, B and C (figure 2) were erupted in 30R, 29R and 28N, respectively. Also the seven peaks in the histogram (figure 3) correspond to different magnetic chronns between 31R and 27R. An unexpected feature of this correlation, that however needs further investigation, is the 66.5–66.8 Ma peak defined by 19 samples that falls in 30N. In this context it is pertinent to note that for most of the samples that have been plotted the palaeomagnetic data are not available. In the absence of detailed data, except for the samples from the western ghat section, a critical evaluation of this histogram can at best be indicative. One obvious feature of this distribution (figure 3) is that lava flows have erupted during 31R, 30R and 29R, therefore, an attempt to correlate the entire pile of reversed polarity flows to a single reverse polarity chron is far from reality. In conjunction with figure 2 it can be inferred that most of the western ghat reversed lava flows, representing cluster A fall in chron 30R with a smaller volume of cluster B within 29R post dates the KTB. The belief that the Deccan lava sequence spans only three magnetic chronns is not correct, rather the volcanism continued over a long period (69–62 Ma) with several episodes of eruptions punctuated by periods of quiescence.

5. Conclusion

Critical evaluation of the available absolute age data and palaeomagnetic constraints reveals that Deccan volcanism spanned a much larger duration from 69 Ma to 62 Ma between 31R and 28N than hitherto believed. This is consistent with the growing circumstantial evidence for an extended duration (~8 m.y.) of Deccan magmatism as indicated by the dates of alkaline rocks (~68.5 Ma) from northern Deccan (Basu et al 1993), trachytes and basalts (~60.5 Ma) from Bombay (Sheth et al 2001a,b; Lightfoot et al 1987), an intermediate dyke (~62 Ma) from west coast (Kaneoka et al 1996), and doleritic dykes (~62 Ma) from Goa (Widdowson et al 2000). The magnetostratigraphic record in the Deccan lava pile is incomplete because the lavas were extruded in several episodes punctuated by extended periods of quiescence. The intense pulse of volcanism perhaps occurred in 30R chron, predating the Cretaceous-Tertiary Boundary, with considerably high but not impossible extrusion rates.

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References

Acton G D and Gordon R G 1989 Limits on the age of the Deccan Traps of India from palaeomagnetic and plate reconstruction data and their uncertainties; J. Geophys. Res. 94 17713–17720
Baksi A K 1987 Critical evaluation of the age of the Deccan Traps, India: Implication for flood-basalt volcanism and faunal extinction; Geology 15 147–150
Basu A K, Renne P R, Dasgupta D K, Teichmann F and Poreda R J 1993 Early and Late Alkaline igneous pulses and a high 3He plume origin for the Deccan Flood Basalts; Science 261 902–905
Bilgrami S Z 1999 A geologic map of the eastern part of the Deccan Traps (Bidar-Nagpur); In: The Deccan Volcanic Province, Geol. Soc. Ind. Mem. (ed) K V Subbarao 43(1) 219–232
Cande S C and Kent D V 1995 Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic; J. Geophys. Res. 100 6093–6095
Cox K G and Hawkesworth C J 1985 Geochemical stratigraphy of the Deccan Traps at Mahabaleshwar, Western Ghats, India, with implications for open system magmatic processes; *J. Petrol.* **26** 355–377

Devey C W and Lightfoot P C 1986 Volcanology and tectonic control of stratigraphy and structure in the western Deccan Traps; *Bull. Volcanol.* **49** 195–207

Duncan R A and Pringle M S 1991 K/T boundary events were synchronous with rapid eruption of the Deccan flood basalts. *EUC 301*


Hofmann C, Féraud G and Courtillot V 2000 40Ar/39Ar dating of mineral separates and whole rocks from the Western Ghats lava pile: further constraints on duration and age of the Deccan traps; *Earth Planet. Sci. Lett.* **180** 13–27


Iwata N and Kaneoka I 2000 On the relationships between the 40Ar/39Ar dating results and the conditions of basaltic lavas; *Geochim. J.* **34** 271–281


Sheth H C, Duncan R A, Chandrasekharam D and Mahoney J J 1997 Deccan Trap dioritic gabbros from the western Satpura-Tapi region; *Curr. Sci.* **75** 755–757


Vandamme D, Courtillot V, Besse J and Montigny R 1991 Paleomagnetism and age determinations of the Deccan Traps (India): Results of a Nagpur-Bombay traverse and review of earlier work; *Rev. Geophys.* **29** 159–190

Venkatesan T R and Pande K 1996 A review of 40Ar/39Ar ages from the Western Ghats, Deccan Trap Province, India; Implications for K/T events; *Gondwana Geol. Mag.* **2** 321–328

Venkatesan T R and Ramesh R 1993 Consideration of analytical uncertainties while plotting histograms; *Geol. Soc. India* **41** 313–317

Venkatesan T R, Pande K and Ghevariya Z G 1996 40Ar/39Ar ages of Anjar Traps, western Deccan province (India) and its relation to the Cretaceous Tertiary Boundary events; *Curr. Sci.* **70** 990–996

Wensink H 1987 Comments on “Deccan flood basalts at
the Cretaceous/Tertiary boundary?” by V Courtillot,
J Besse, D Vandamme, R Montigny, J-J Jaeger and
H Cappetta; Earth and Planet. Sci. Lett. 85 326–328

A post K-T Boundary (Early Palaeocene) Age for
Deccan-type Feeder Dykes, Goa, India; J. Petrol. 41
1177–1194

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