# 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.

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## 1. Introduction

The voluminous ($\sim 1.5 \times 10^6\,\text{km}^3$) Deccan Traps of western and central India comprise a thick sequence of sub-aerially erupted basaltic flows that presently cover an area $\sim 1.5 \times 10^6\,\text{km}^2$ 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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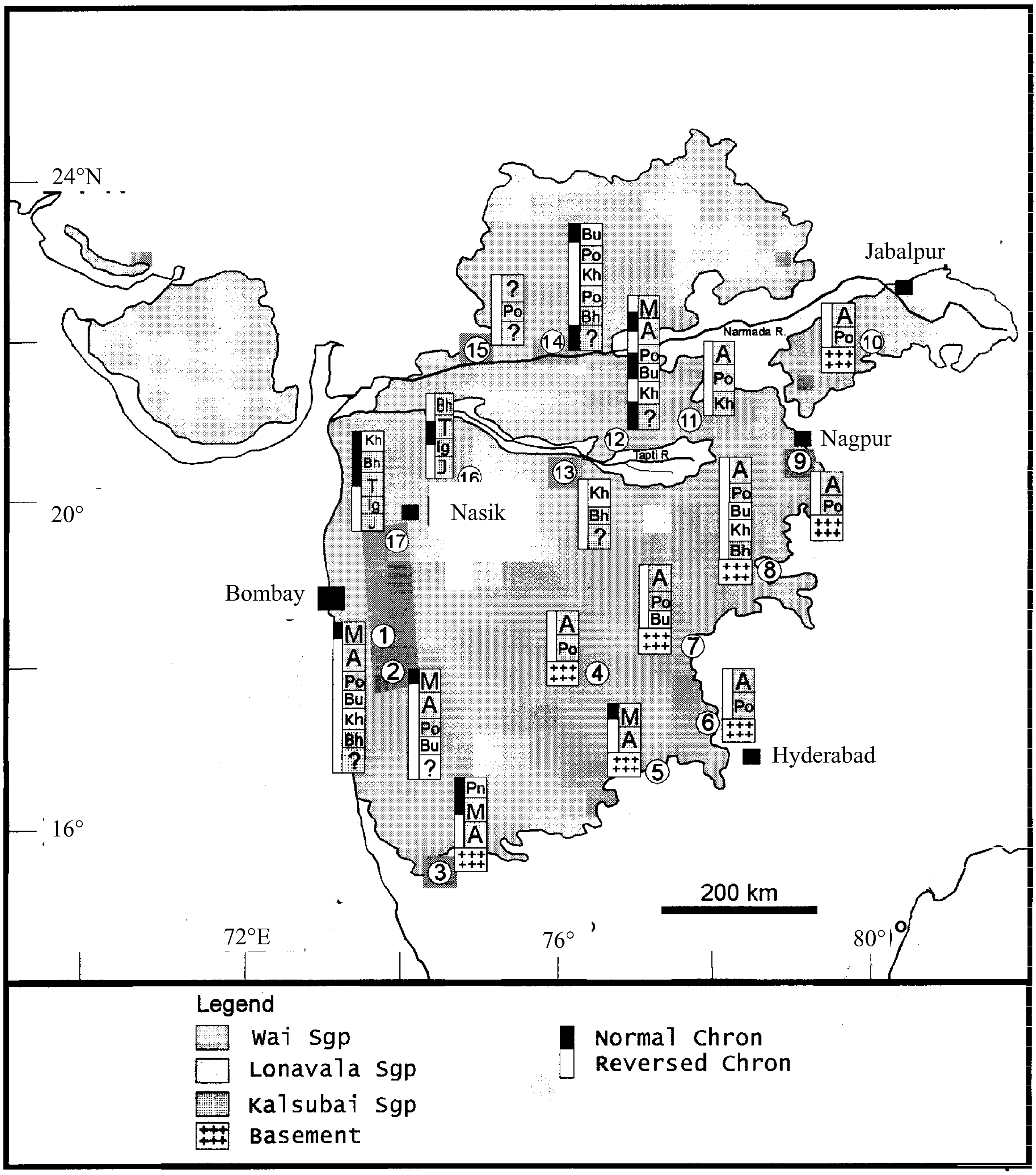

Figure 1. Present day outcrops of Deccan volcanic province showing simplified chemo- and magneto-stratigraphic sections (not to scale; modified after Figure 11 in Widdowson *et al* 2000). **J, Ig, Bh, Kh, Bu, Po, A, M and Pn** are Jawhar, Igatpuri, Thakurvadi, Bhimashankar, Khandala, Bushe, Poladpur, Ambenali, Mahabaleshwar and Panhala Formations, respectively. Section localities: **(1)**, Pune-Purandhar; **(2)**, Mahabaleshwar; **(3)**, Belgaum; **(4)**, Khillari borehole; **(5)**, Gurumatkal; **(6)**, Bidar; **(7)**, Nazimabad; **(8)**, Adilabad; **(9)**, Nagpur; **(10)**, Jabalpur; **(11)**, Chikaldara; **(12)**, Buldana; **(13)**, Ellora-Outram; **(14)**, Mandaleswar-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 Sreenivasa 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 $^{187}$Re-$^{187}$Os chronometer (Allegre *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 $^{40}$Ar-$^{39}$Ar plateau 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 ± 0.3 Ma age of the Deccan Trap derived from $^{187}$Re-$^{187}$Os data is not unequivocal because of the uncertainty in the value of the decay constant $\lambda$ for $^{187}$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 $^{40}$Ar-$^{39}$Ar ages of Deccan Traps

The first $^{40}$Ar-$^{39}$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; Venkatesan *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, $^{40}$Ar-$^{39}$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 $^{40}$Ar-$^{39}$Ar data is also subject to the choice of a plateau or isochron age and whole rock or mineral dates. The $^{40}$Ar/$^{39}$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 $^{39}$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 ± 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 ± 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 ± 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 $^{40}$Ar-$^{39}$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 ± 0.3, 64.8 ± 0.6 and 62.3 ± 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 ± 0.2 Ma.

The $^{40}$Ar-$^{39}$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 52 $^{40}$Ar-$^{39}$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; Venkatesan and Ramesh 1993). I also plot the KTB at 65.2±0.2 Ma (recalculated to MMhb-1 age of 520.4 Ma). I am

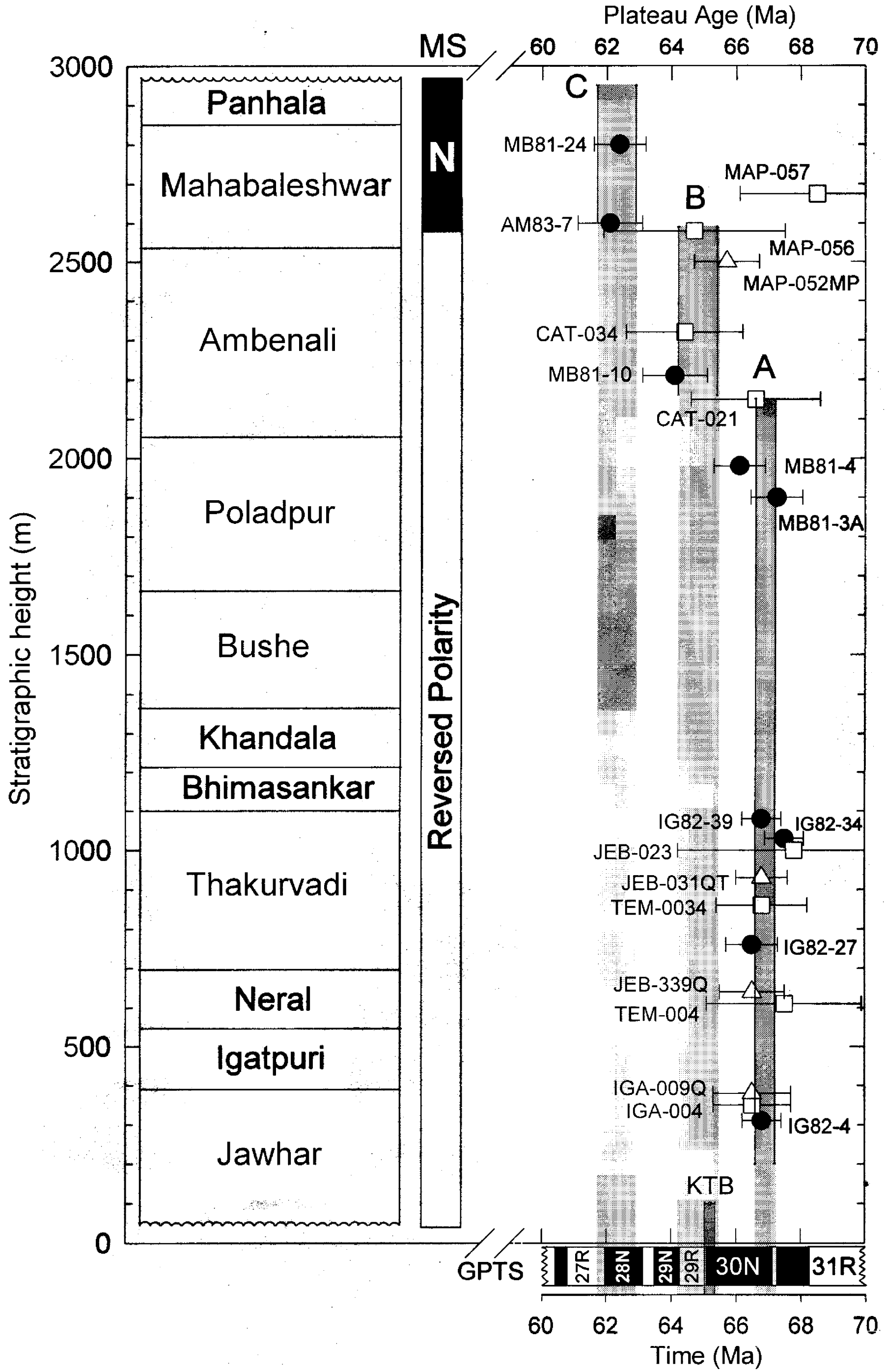

Figure 2. The $^{40}$Ar-$^{39}$Ar ages (normalised to MMhb-1 age of 520.4 ± 1.7 Ma) for the western ghat sequence plotted against composite lithostratigraphy and magnetostratigraphy. KTB marks the weighted mean ($\pm 2\sigma$) of the available estimate of the Cretaceous Tertiary Boundary. The shaded vertical rectangles show the $2\sigma$ limits of the mean values of the age clusters at A, B and C. The relative thicknesses of the formations for this composite section are from Widdowson *et al* (2000). Age data from ● Venkatesan *et al* (1993); □ Duncan and Pyle (1988) and Δ Baksi (1994). The geomagnetic polarity time scale (GPTS) at 70–60 Ma (Cande and Kent 1995) adjusted to place KTB within 29R chron is plotted at the bottom. Black = normal polarity, White = reversed polarity.

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-

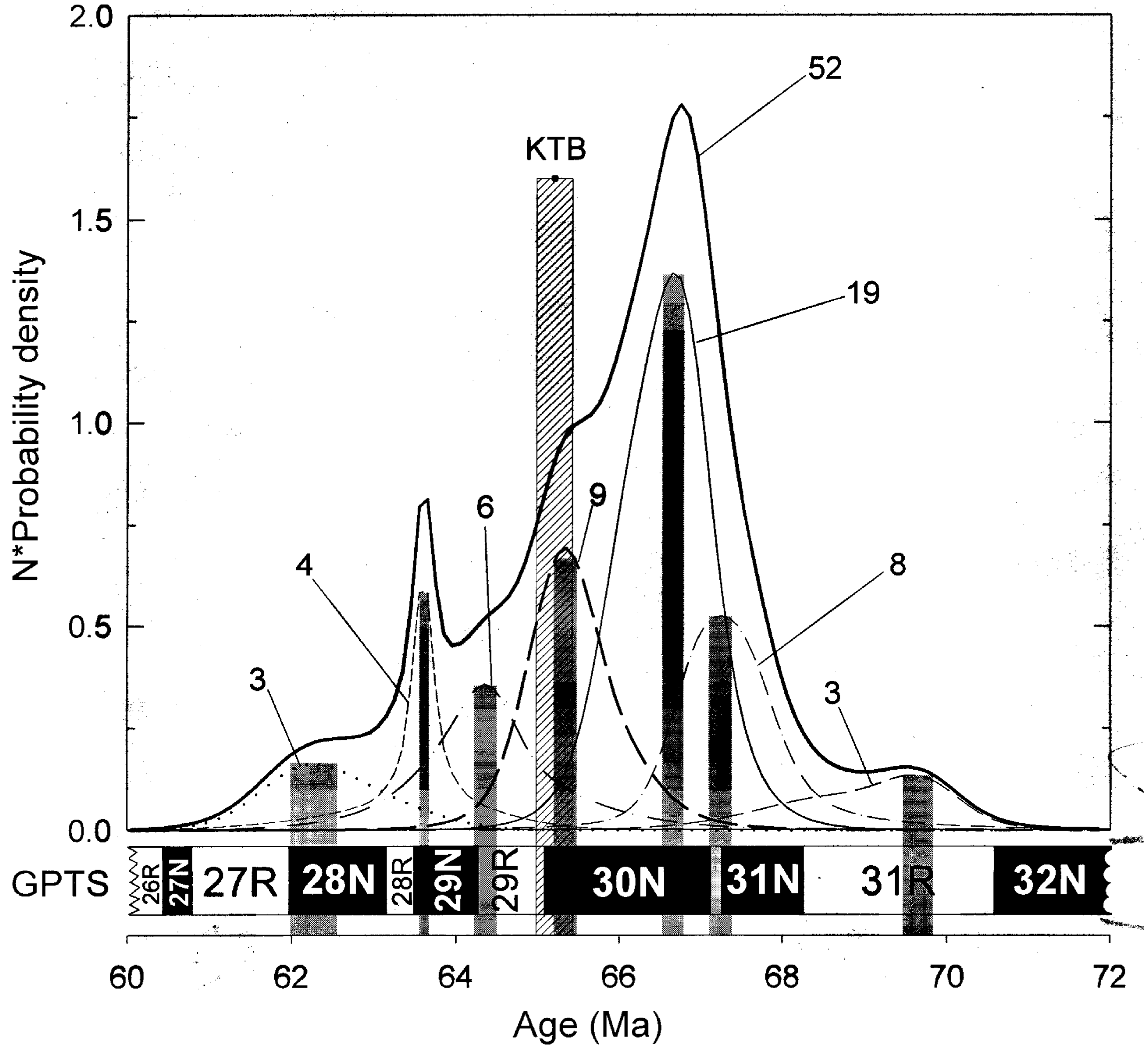

Figure 3. Histogram of all available $^{40}Ar/^{39}Ar$ ages (recalculated to an age of 520.4 ± 1.7 Ma for MMhb-1). Each datum is given unit weight and represented by a Gaussian distribution with standard deviation ($1\sigma$) equal to the uncertainty in the age (Vandamme *et al* 1991; Venkatesan and 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, 66.5–66.8, 67.1–67.4, 69.5–69.8 Ma. Significantly enough the three cluster of ages 61.7–62.9, 64.2–65.4 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 $^{40}$Ar-$^{39}$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 $^{187}$Re has some uncertainties. The authors prefer to determine an age of $65.6 \pm 0.3$ Ma from the $^{187}$Re-$^{187}$Os isochron using a value of $\lambda = 1.663 \times 10^{-11}\ y^{-1}$ 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 $^{187}$Re-$^{187}$Os isochron age ($65.6 \pm 0.3$ Ma) is at $1\sigma$ level whereas the paper says it is $2\sigma$. Further, the isochron has an MSWD of 42, calculated using the Isoplot/Ex.2.49 package (Ludwig 2001), indicating excess scatter. This undoubtedly implies that the initial $^{187}$Os/$^{188}$Os is more variable than acknowledged and the error is therefore underestimated by at least a factor of SQRT(MSWD) = 6.5. The isochron age at $2\sigma$ level, therefore, is really $65.6 \pm 3.9$ Ma! This age is not more precise than the $^{40}$Ar-$^{39}$Ar ages discussed in the preceding section. In fact, within the $2\sigma$ uncertainty the $^{187}$Re-$^{187}$Os age shows the same spread for Deccan volcanism as the $^{40}$Ar-$^{39}$Ar data.

## 3. Magnetostratigraphy

The magnetostratigraphy of lava flow sequences at several localities in the Deccan province has been depicted with the chemical stratigraphy in figure 1. The chemostratigraphy is after Widdowson *et al* (2000), and the polarity transitions (i.e. N, R) are after Sreenivasa Rao *et al* (1985), Vandamme and Courtillot (1992) and the references therein. It is, however, important to bear in mind that whether a particular chemostratigraphic 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; Vandamme *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 Khandala 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 NRNRNR (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 $^{40}$Ar-$^{39}$Ar ages (68.5 – 62.1 Ma) from the western ghats section of the Deccan, apparently at variance with the paleomagnetic 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 $^{40}$Ar-$^{39}$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 chrons. 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 $2\sigma$ 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 chrons 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 paleomagnetic data are not available. In the absence of detailed data, except for the samples from the western ghats 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 chrons 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 paleomagnetic 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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