Supplementary Data #3:

GEOCHRONOLOGICAL DATA

3.1 GEOCHRONOLOGY

The Deccan Trap basalts overlie or are interlayered by the sediments of Maastrichtian age along the Narmada valley, while the basalts are overlain by Tertiary sequences in Kutch. Fossils from such Trap-related sediments were used to propose that the Deccan volcanism occurred between Late Cretaceous and Early Tertiary times before the advent of geochronology. Early K-Ar and Ar-Ar ages suggested a wide span for the volcanism in the DVP. Kaneoka (1980) gave a span of over 20 m.y. (84-63 Ma), while Alexander (1981) suggested the range to vary from 102 to 30 Ma. Courtillot et al. (1986) argued for the Maastrichtian age for the lowermost basaltic flows on the basis of Maastrichtian shark found in the upper Lameta beds of Jabalpur. Jaeger et al. (1989) reviewed the fossils from the Infratrappean, Intertrappean and Supratrappean sediments and concluded that the Deccan Traps could have been emplaced in between 73 Ma and 69 Ma.

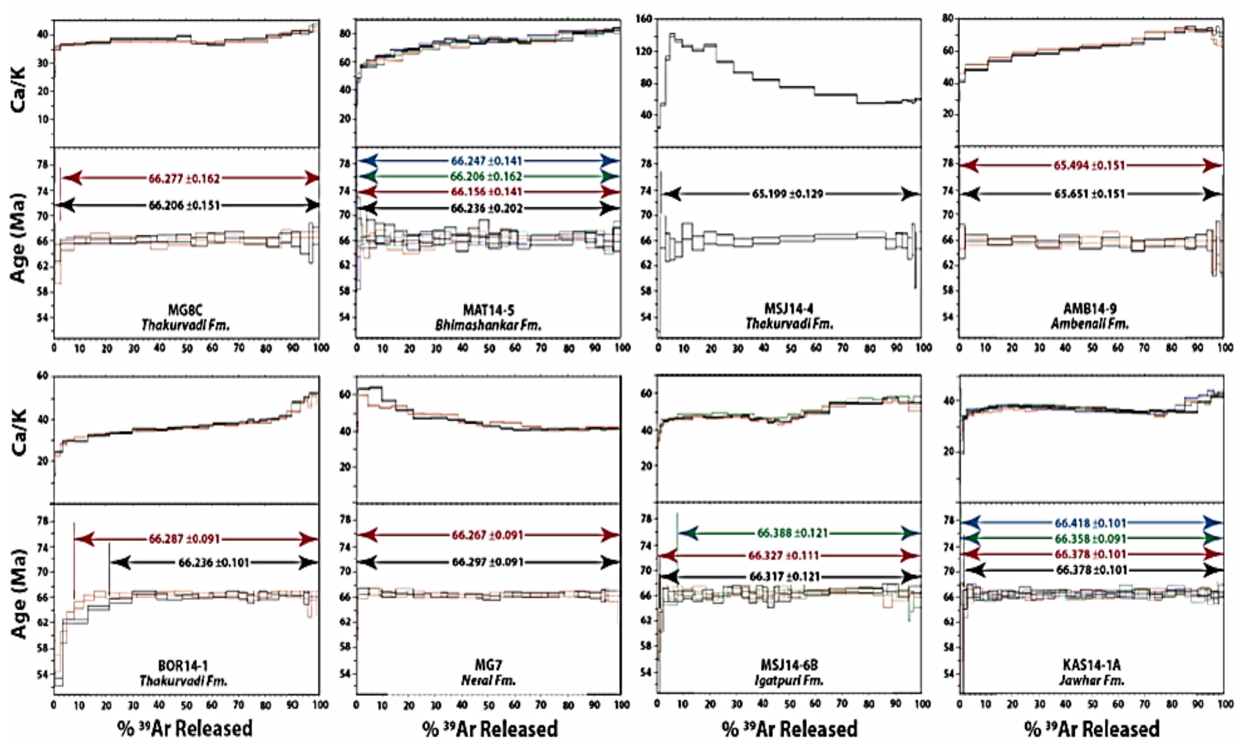
Courtillot et al. (1988), Duncan and Pyle (1988) and later Hofmann et al. (2000) used Ar-Ar radiometric to propose that the Deccan eruption spanned a short duration of <1 million years. An extended duration of about 5-7 million years for the Western Ghats sequence was advocated by Venkatesan et al.(1993). Widdowson, et al (2000) reported age of 62.8$\pm$0.2 Ma for dykes from Goa. Sheth et al. (2001) reported ages of 60 – 61 Ma for the Bombay trachytes from the coastal region of the DVP. Three separate pulses of eruptive activity spanning more than 5 million years in all were inferred by Pande (2002) on the basis of the then available geochronological data. Sheth and Pande (2014) gave ages of 62.6$\pm$0.6 Ma for rhyolites from Dongri, thereby providing additional evidence for a Palaeocene phase of late Deccan volcanism. The last phase of Deccan volcanism that occurred in the early Danian C29N, was responsible for the delayed biotic recovery of marine planktons on the basis of biostratigraphy of samples from 10 wells of Krishna- Godavari (K-G) Basin according to Keller et al. (2012).

The geochronological data and assessment of the fossil records from the Trap-related sediments (Baksi, 1994, 2014; Keller et al, 2008, 2009, 2011, 2012, 2016) in the last two decades is cohesive in confirming that the Deccan volcanism straddles the K-Pg Boundary, and had a role to play in the terminal Cretaceous mass extinction event (Self et al. 2008; Richards et al, 2015). Recent geochronological studies (Renne et al., 2015; Parisio et al., 2016; Sprain et al., 2019) have demonstrated that the duration the main pulse of eruptive activity in the Western Ghats sequence is a short one, spanning less than one million years. U-Pb zircon dates are reported by Schoene et al. (2015; 2019) who assumed that the youngest analysed zircon represents the eruptive age of Deccan basalts, although the origin (or source) of zircon in basalt is an open question. A broad correspondence of the Deccan Trap with the K-Pg Boundary is reaffirmed in the most recent precision dating techniques as well. The question of whether this was enough by itself or a combination of an extra-terrestrial impact and the volcanism together led to the terminal Cretaceous environmental crisis that caused the mass extinctions (Self et al., 2008; Richards et al., 2015; Renne et al., 2015; Schoene et al., 2015, 2019; Sprain et al., 2019) is beyond the scope of this work. What is certain is that all geochronological data indicate that a large volume of basalts was erupted just before the end of the Cretaceous.

3.2 RECALIBRATION

Parisio et al. (2016) recalculated Ar-Ar age data to assess the comparability and consequently reliability. We have expanded this using data from sources that provide background information enabling their comparability. All ages are recalculated against Fish Canyon Sanidine (FCs) age of 28.294 ± 0.036 Ma using the methodology given by Renne et al. (2010 & 2011). The published and supplementary data from Venkatesan et al. (1993, 1996), Baksi (1994), Hofmann et al. (2000), Courtillot et al. (2000), Pande et al. (2004), Schöbel et al. (2014), Renne et al. (2015), Shrivastava et al. (2015) have been used in this computation.

The representative age-spectra of recalculated values is depicted in SD#3 Fig.1 and 2. SD#3 Table 1 lists all such ages after recalculating against 523.1 Ma age of MMhb-1 monitor sample.



SD#3 Fig. 1: ^{40}Ar-^{39}Ar Plagioclase age-spectra of different Formations of Deccan after Renne, et al. (2015).

SD#3 Table 1: Recalculated ages of the DVP used in this work based the MMhb-1 monitor sample. The listing is author-wise (with the original standard used) divided into the subprovinces of the DVP. [ND = Not defined by author; * = isochron ages]

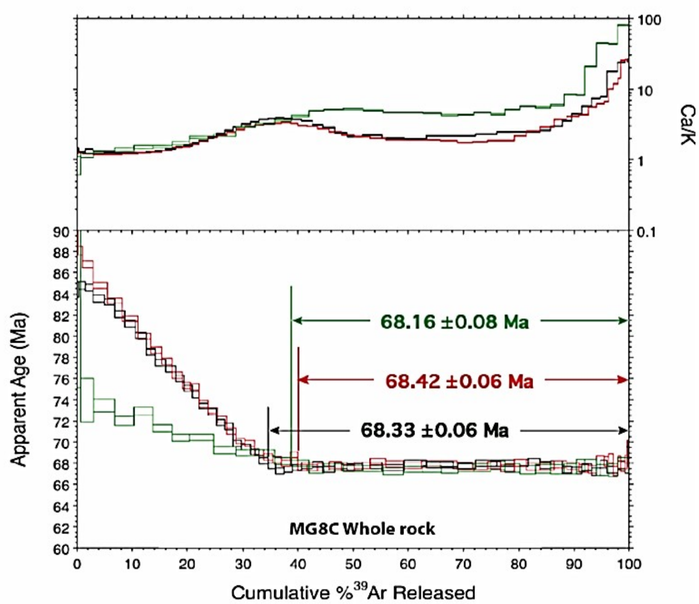
Sample Name	Formation / Chemical Type	Original Age in **Ma**	Error (2 σ)	**Recalculated Age** *w.r.t. FCs=28.294±0.03 Ma*
SAURASHTRA				
Venkatesan, et al., 1996 (MMhb-1 = 520.1±1.7 Ma)				
Z199 (WR)	ND	65.7	0.7	**66.7**
F Lower (WR)	ND	65.2	0.6	**66.2**
Courtillot, et al., 2000 (Hb3gr=1072 Ma)				
AJ4 (Plg)	ND	64.8	0.9	**65.5**
AJ3 (WR)	ND	66.8	0.5	**67.5**
AJ1 (Plg)	ND	66.3	0.7	**64.0**
AJ11 (Plg)	ND	67.0	0.6	**67.7**
AJ11 (WR)	ND	66.8	0.3	**67.5**
MALWA				
Schöble, et al., 2014 (FCs= 28.294±0.03 Ma)				
S 32 (Plg)	ND	67.12	0.44	**67.12**
S 32 (WR)	ND	67.73	0.22	**67.73**
MANDLA				
Shrivastava, et al., 2015 (FCT-3 biotite = 28.201 Ma)				
NL-F2/S2 (Plg)	ND	63.7	1.2	**63.9**
PLB-F12 (Plg)	ND	63.8	0.5	**64.0**
MK2 (Plg)	ND	63.2	1.2	**63.4**
SKF10 (Plg)	ND	64.1	0.7	**64.3**
MK6 (Plg)	ND	64.9	1.2	**65.1**
WESTERN DVP				
Baksi 1994 (FCT-3 biotite = 27.95 Ma)				
MAP-052MP (WR)	Mahabaleshwar	64.9	1	**66.3**
JEB-339Q (WR)	Neral	65.6	1	**67.0**
IGA-009Q (WR)	Jawahar	65.6	1.2	**67.0**

SD#3 Table 1: Continued**.**

Sample Name	Formation / Chemical Type	Original Age in **Ma**	Error (2 σ)	**Recalculated Age** *w.r.t. FCs=28.294±0.03 Ma*
Venkatesan et al.,1993 (MMhb= 520.1±1.7 Ma)				
MB81-24 (WR)	Mahabaleshwar	62.4	0.8	**63.4**
AM83-7 (WR)	Mahabaleshwar	62.1	1	**63.1**
MB81-10 (WR)	Ambenali	64.1	1	**65.1**
MB81-4 (WR)	Ambenali	66.1	0.8	**67.1**
MB81-3/A (WR)	Poladpur	67	0.8	**68.0**
IG82-39 (WR)	Thakurwadi	66.8	0.6	**67.8**
IG82-34 (WR)	Thakurwadi	67.5	0.6	**68.5**
IG82-27 (WR)	Thakurwadi	66.5	0.8	**67.6**
IG82-4 (WR)	Jawahar	66.8	0.6	**67.9**
Hofmann, et al.,2000 (Hb3gr = 1072 Ma)				
MA2 (Plg)	Mahabaleshwar	63.0*	2.0	**63.7**
JW2 (Plg)	Jawahar	65.7*	1.0	**66.4**
JW4 (Plg)	Jawahar	65.0	1.5	**65.7**
JW5 (Plg)	Jawahar	66.2*	1.2	**66.9**
JW6 (Plg)	Jawahar	65.7	1.3	**66.4**
JW7 (Plg)	Jawahar	66.5*	1.4	**67.2**
Pande et al., 2004 (MMhb = 523.2 ±0.9 Ma)				
JEB127.1a (WR)	Bushe	66.5	0.9	**67.1**
JEB127.4b (WR)	Bushe	66.7	0.7	**67.3**

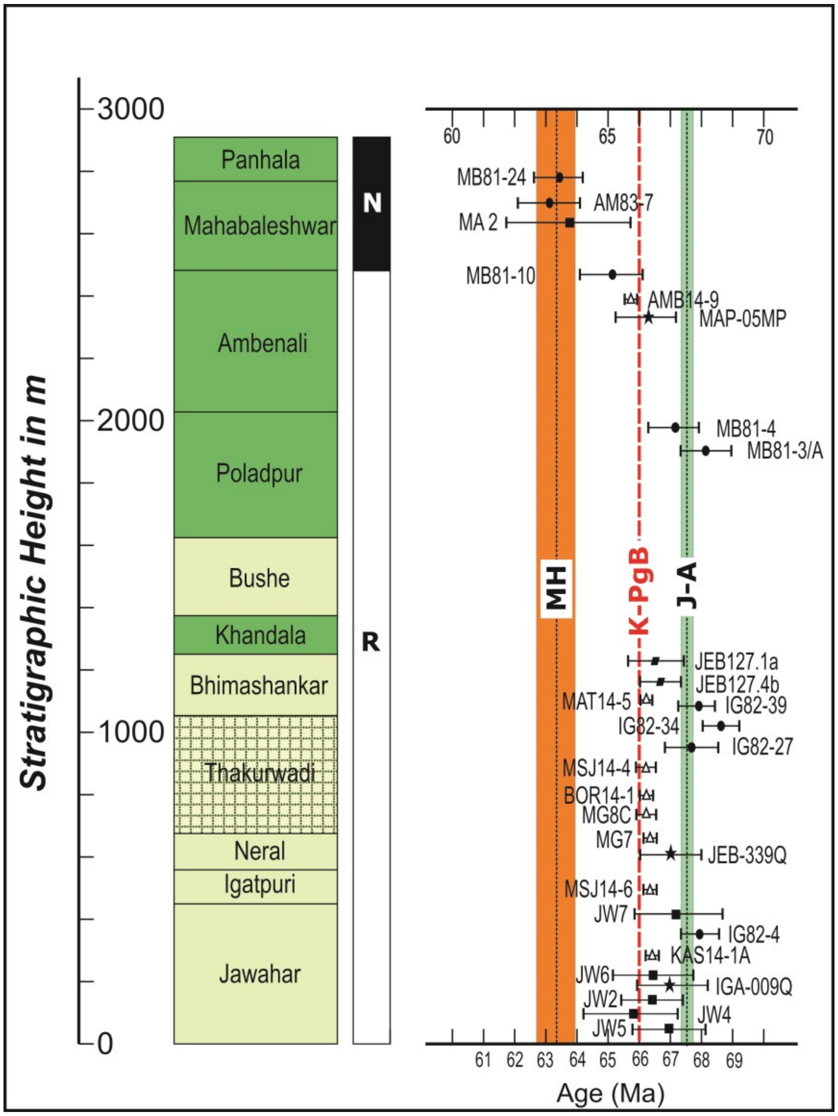
SD#3 Table 1: Continued.

Sample Name	Formation / Chemical Type	Original Age in **Ma**	Error (2 σ)	**Recalculated Age** *w.r.t. FCs=28.294±0.03 Ma*
Renne et al., 2015 (FCs= 28.294±0.03 Ma)				
AMB14-9 (Plg)	Ambenali	65.6	0.3	**65.6**
MAT14-5(Plg)	Bushe	66.2	0.3	**66.2**
MSJ14-4 (Plg)	Thakurwadi	66.2	0.3	**66.2**
MG8C (Plg)	Thakurwadi	66.2	0.2	**66.2**
BOR14-1 (Plg)	Thakurwadi	66.3	0.2	**66.3**
MG7 (Plg)	Neral	66.3	0.2	**66.3**
MSJ14-6 (Plg)	Igatpuri	66.3	0.2	**66.3**
KAS14-1A(Plg)	Jawahar	66.4	0.2	**66.4**

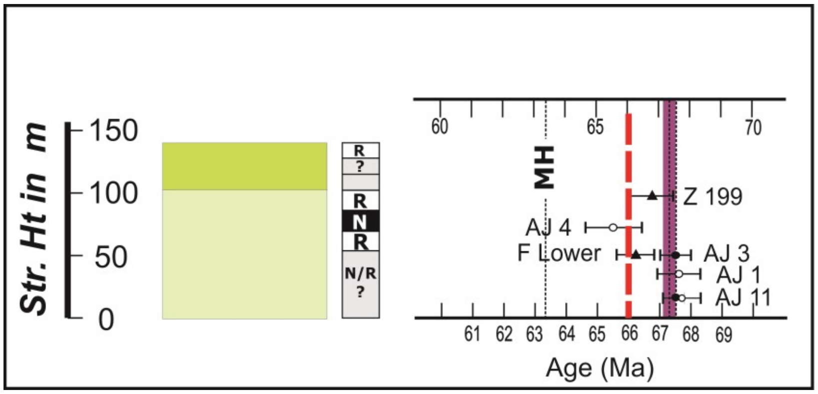


SD#3 Fig. 2: ^{40}Ar-^{39}Ar Whole rock ages of three aliquotes of one sample MG8C from Thakurvadi Formation whose plagioclase ages (after Renne et al, 2015) are depicted in SD#3 Fig.1.

The recomputed individual $^{40}Ar/^{39}Ar$ ages were plotted against the respective generalised stratigraphic columns of the subprovinces of the DVP (SD#3 Fig. 3) to examine their distribution. It is evident that (except for one sample – AMB83-7) all the samples from the western DVP sequence of Jawahar to Ambenali yield ages that precede the K-Pg boundary; and are indistinguishable within the limits of the error ranges. The implication being that all these flows (with a reverse polarity corresponding to the 29R chron) must have been erupted within a short time-span. We therefore conclude that, notwithstanding the chemostratigraphic subgroup boundaries, the sequence from the oldest Jawahar to the Ambenali Formation represent a continuous rapid outpouring of lavas without resolvable break. The Mahabaleshwar flows on the other hand yield a distinctly younger age than the K-Pg Boundary. Their normal polarity justifies their separation from the remaining underlying sequence in the western DVP into a separate volcanic episode. This subdivision based on geochronological data is different from the one indicated by the chemostratigraphic divisions and derivative models based on that (eg: Jay et al., 2009; Richards et al., 2015).

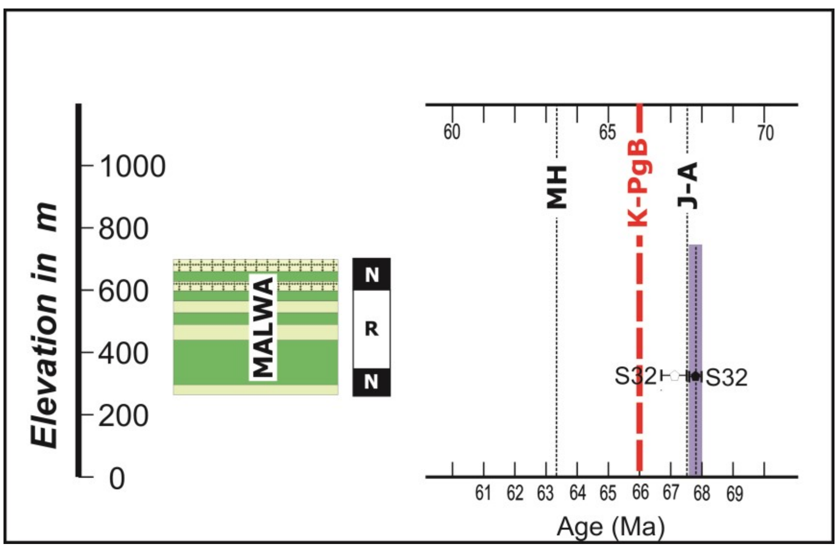


SD#3 Fig. 3a: Recomputed ages from Western DVP plotted against their stratigraphic position (using the chemostratigraphic divisions). The weighted means of the two clusters of whole-rock ages are named as J-A (after Jawahar-Ambenali sequence) that is plotted in light green (for the 2σ error in the weighted mean age); and MH (for Mahabaleshwar flows) which is plotted as in pale orange (for the 2σ error in the weighted mean age). The sample numbers are listed in SD#3 Table1. The paleomagnetic polarity is taken from Chenet et al. (2009) and Jay et al. (2009). The age of the Cretaceous – Paleogene Boundary (K-PgB) marked by thick dashed red line is based on Gradstein et al. (2012) and Renne et al. (2013).



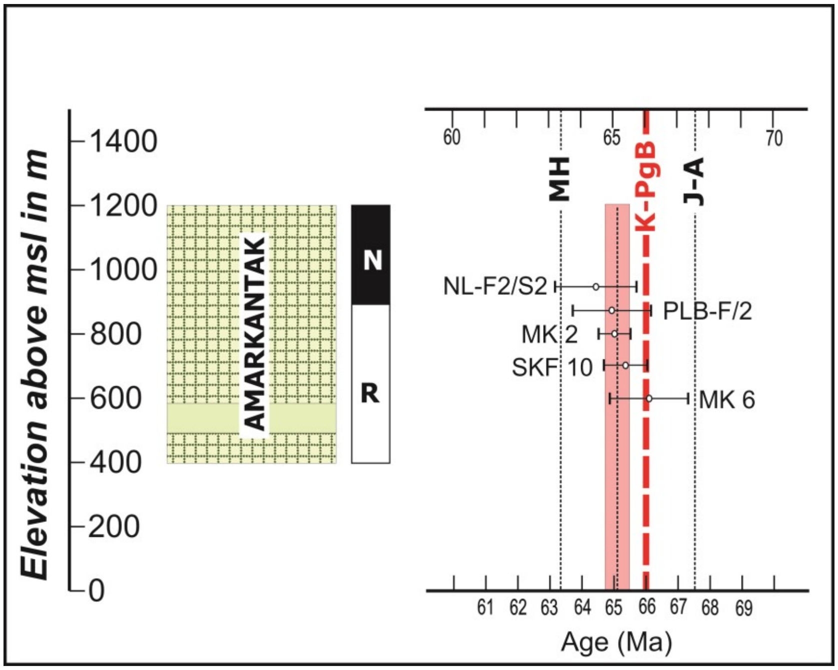
SD#3 Fig. 3b: Recomputed ages from Saurashtra subprovince plotted against their stratigraphic position of the sequence of lava flows and magnetic polarity recorded by Venkatesan et al. (1996) and Courtillot et al. (2000). The weighted mean age is depicted as a deep purple bar (for the 2σ error). The sample numbers are listed in SD#3 Table1. The age of the Cretaceous – Paleogene Boundary marked by thick dashed red line is based on Gradstein et al. (2012) and Renne et al. (2013).

The geochronological data from the Saurashtra sequence is derived from the Anjar section in Kutch. The weighted mean age of 67.3+0.2 Ma is distinctly Maastrichtian, but is rendered ambiguous by their R-N-R polarity sequence.



SD#3 Fig. 3c: Recomputed ages from Malwa subprovince plotted against their stratigraphic position of the sequence of lava flows recorded by Venkata Rao et al. (1996) and GSI (2001). Note that the stratigraphic column is plotted against the elevations in m above msl rather than stratigraphic heights. The weighted mean age is depicted as a light purple bar (for the 2σ error). The sample numbers are listed in SD#3 Table1. The age of the Cretaceous – Paleogene Boundary (K-PgB) marked by thick dashed red line is based on Gradstein et al. (2012) and Renne et al. (2013).

Geochronological data from the Malwa subprovince is limited. It is however certain that the lavas predate the K-Pg Boundary. However, the N-R-N magnetic polarity recorded in this subprovince remains to be suitably tagged.



SD#3 Fig. 3d: Recomputed ages from Mandla subprovince plotted against their stratigraphic position of the sequence of lava flows recorded by GSI (2001). Note that the stratigraphic column is plotted against the elevations in m above msl rather than stratigraphic heights. The weighted mean age is depicted as a pink bar (for the 2σ error). The sample numbers are listed in SD#3 Table1. The age of the Cretaceous – Paleogene Boundary (K-PgB) marked by thick dashed red line is based on Gradstein et al. (2012) and Renne et al. (2013).

All geochronological data of the Mandla subprovince shows that these flows are Danian in age, and post-date the K-Pg Boundary. These ages are much younger than the ages of the Poladpur and Ambenali Formations from the Western DVP with whom a correlation is proposed based on geochemical characters (Shrivastava et al, 2015). It is not easy to reconcile this age difference in the volcanological perspective. The R-N magnetic polarity recorded in this sequence of lavas may not necessarily correspond with the 29R-29N chrons postulated for the sequence in the Western DVP. Pathak et al. (2017) have also expressed similar doubts.

3.3 CONCLULDING REMARKS

This compilation of the geochronological data demonstrates that there is a need of a more methodical and wide-spread effort to date various flows from different subprovinces of the DVP. The data is geographically lop-sided and therefore may not be valid (as assumed earlier) to be applicable for the entire province. Detailed implications of this analysis are discussed in the main paper.

This data is explicit in showing that the Deccan volcanism occurred on either side of the K-Pg Boundary. A vast majority of the flows present in the Western DVP, some of those in Saurashtra and Malwa preceded the K-Pg Boundary and therefore their contribution to the terminal Cretaceous environmental crisis is unquestionable. What is equally evident is that the upper flows in the Western DVP and perhaps the entire Mandla sequence are Danian in age; younger than the K-Pg Boundary. The magnetic polarity recorded in the four subprovinces although partly ambiguous; does not support a temporal correlation between flows. Some of the flows from diverse subprovinces may belong to different magnetic chrons (and consequently have differing ages) even if they show common (normal or reverse) polarity.

In context of models that propose long-distance correlations of flows; the monocentric eruptive history and its punctuations, the available geochronological (and paleomagnetic data) in our opinion is ambiguous. The geochronological and geomagnetic data in fact does not support correlations across subprovinces. Further inputs from future studies are essential for resolving the ambiguity.

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