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Emplacement history and evolution of the Deccan Volcanic Province, India

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(Received : 5/12/2018; Revised accepted : 1/05/2019)

<https://doi.org/10.18814/epiiugs/2020/020016>

A review of the existing knowledge on the Deccan Volcanic Province of India shows that it has a significant geographic bias towards the western parts, while the rest of the province is not as well constrained. Emerging data on its structure, geochronology and volcanology in the last decade suggests that many existing concepts and models of this large Continental Flood Basalt Province are open to revisions or replacement.

The explicit relation between the Deccan volcanism and the Reunion hotspot makes it a unique laboratory for studying magmatic evolution over active hotspots, its upward trajectory through a thick continental crust and the mode and mechanics of eruption and spread of large volumes of lava on continental settings. The temporal relation of the Deccan volcanism with the terminal Cretaceous biotic upheaval has direct bearings on understanding environmental crisis that result from such eruptive events. The impact of this basaltic substrate on the anthropogenic activity of more than 100 million people living on it needs no explanation. A multifaceted and interdisciplinary study with an aim of closing the gaps in its knowledge will facilitate a well-constrained understanding of the characters and robust models of this province in the years to come.

Introduction

The Deccan Volcanic Province (DVP) is one of the largest continental flood basalt provinces (CFBPs) of the world. It occupies a contiguous exposed area of around 500,000 km² (West, 1959; Vaidyanadhan and Ramakrishnan, 2008; Valdiya, 2016). Following the early reviews (e.g. Pascoe, 1956) on the knowledge of the DVP, large volumes of data has been published on these thick piles of tholeiitic basalts in the last four decades (e.g.: edited volumes -

Subbarao and Sukheswala, 1981; Subbarao, 1988; 1999; Deshmukh and Nair, 1996; Sheth and Vanderkluyzen, 2014; Mukherjee et al., 2017) with reference to its distribution, petrological and chemical characters and age. The evolutionary history of the DVP has direct linkages with global models of evolution of continental flood basalt (CFB) provinces and terminal Cretaceous faunal turnover mass extinctions. We summarize the existing knowledge on this province in the first part. This data is however lopsided in its geographic coverage to the western parts of the DVP, with sparse data for almost 75% of the province. A discussion on the volcanological features and architecture of the pile of basaltic flows that are essential for deciphering the emplacement history follows. Future multifaceted studies are essential to resolve prevailing ambiguities in the eruptive style, stratigraphy and evolutionary history of the DVP.

Deccan Volcanic Province

Aerial extent and volume

The continuous piles of the basaltic flows have thickness ranging from <50 m along the fringes of the province to more than 1650 m (at Kalsubai peak =1646 m above msl) along the Western Ghats Escarpment (WGE). Recent drilling in the Koyna-Warna seismic zone (Mishra et al., 2017) yielded a continuous 1251 m thick stack of subhorizontal basaltic flows resting on a Neoproterozoic basement (Bhaskar Rao et al., 2017). This yields an estimated lava volume of almost 2.8×10^5 km³ for the present exposures. Jay and Widdowson (2008) had projected a volume of 13×10^5 km³ for the Deccan volcanism. The environmental, tectonic and geomorphic impact of this volcanism can be imagined when one compares this volume with that of 1980 eruption of 1 km³ of lava from Mount St Helens in northeastern USA with a 'blast zone' of >500 km².

Detached outliers of basaltic flows are known in the surrounding areas in Gujarat, Rajasthan, Madhya Pradesh, Uttar Pradesh, Chhattisgarh, Andhra Pradesh and Karnataka states. They indicate a much larger aerial expanse of the DVP that may have been eroded away during the Tertiary and Quaternary times. Whether the basaltic flows exposed around Rajahmundry and the adjoining Krishna-Godavari basin represent long lava flows originating from a single edifice in the western DVP (Baksi, et al., 1994; Self et al., 2008b) or

represent an independent volcanic sequence altogether (Bastia et al., 2010; Sen and Sabale, 2011; Duraiswami et al., 2014; Manikyamba et al., 2015) is open to debate.

Deccan basaltic flows are known to occur below the Tertiary petroliferous sediments in the Cambay basin in parts of Rajasthan (depicted by star #1 in Fig.1) & Gujarat; besides off-shore basins in the Arabian Sea (Gombos et al., 1995; Calvès et al., 2011). They were down-faulted during the subsidence of these Tertiary petroliferous basins after the Deccan volcanic episode.

Late Cretaceous mafic dykes in the Gondwana basins in the Mahanadi valley (Auden, 1949), Bastar craton (Chalapathi Rao et al., 2014) and in the Dharwar craton near Bangalore (Kumar et al.,

2001) shown by numbered #2, #3, #4 stars respectively in Fig.1; indicate a contemporary thermal imprint in a much wider area. It is therefore possible to conclude that the Late Cretaceous volcanism is imprinted across in a radius of more than a 1000 km across the Indian Peninsular Shield and adjoining parts (Inset - Fig.1). The present contiguous outcrops of the DVP represent only a fraction of the area originally covered by the Deccan flood basalts.

Structural Framework & Tectonic Association

The DVP is linked of the passage of the Indian Plate over the Reunion hotspot during its northward journey that started in the Late

Figure 1. Map depicting the geographic subprovinces, major structural zones transecting it and the basement blocks of the Deccan Volcanic Province (DVP). The Western Ghats Escarpment (WGE) and adjoining hilly regions on the western edge of the Deccan Plateau are also referred to as the Sahyadri ranges. The Satpura subprovince is bounded in the north by the Narmada Son Lineament and in the east by the Pranhita Godavari Rift zone. Its boundary with the Deccan Plateau is diffuse. The Mandla Traps (Subprovince) includes all exposures in the Amarkantak Plateau. The western coastal exposures below the WGE are called the Konkan Coastal Belt (KCB). The different Precambrian blocks of Peninsular India are shown with varied ornamentation to bring out the diversity of sub-Trappean crust. Major regional lineaments (structural zones) that transect the DVP and have a Precambrian heritage (after Peshwa and Kale, 1997; Kale et al., 2017) are marked for reference. Detached exposures (marked by stars in the map and dots in the inset) of intrusive mafic dykes or subsurface basaltic flows of Late Cretaceous age are known from 1=Barmer basin, 2= Gondwana rifts east of the Mahakoshal Belt, 3=Bastar Craton, and 4= Southern Dharwar craton, besides the Bombay Offshore Complex. Inset depicts (a) the possible maximum extent of the DVP before erosional removal or under the cover of younger strata, (b) the major Cretaceous and younger volcanic provinces in the Indian Plate; and (c) the southward younging volcanic track that suggest a continuous link of the DVP with the Reunion hotspot and the Kerguelan hotspot with the Rajmahal Sylhet Traps (Ray et al., 2005).

Jurassic times (Morgan, 1981; Jai Krishna, 2017); and with its breakup from the mainland Gondwana block. This was followed by the separation from Madagascar in Turonian-Santonian times (~ 94 – 83 Ma) and then from the Seychelles microcontinent in Campanian – Early Maastrichtian times (Pande et al., 2017); after which the Indian Plate drifted northward till the eventual collision with the Asian mainland (Garzanti and Hu, 2015). Volcanics from the Himalayan region (dated around 72±2 Ma) and the Barmer basin (~ 68 - 69 Ma) mark the track of the Reunion hotspot within the Indian plate (see Inset: Fig. 1). The DVP manifests the outpouring of basaltic lavas on the Indian continental crust between 68 Ma and 62 Ma. The younger track of the Reunion hotspot is found along a linear path through the Kerala offshore dykes, Lakshadweep, Chagos and Carlsberg ridges (Inset: Fig. 1) in the Arabian Sea and Indian Ocean.

The horizontally exposed stacks of lava flows (yielding picturesque cliffs all along the edges of peneplained plateaux) are characters of the DVP that led to it being considered a structurally stable continental region (SCR) in traditional literature. Recent seismic events at Koyna (1967: M 6.3), Bhatsa (1983: M 4.2), Killari (1993: M 6.2), Jabalpur (1997: M 5.8), etc. within the Deccan Plateau disrupted this conventional notion of tectonic stability. Subsequent studies (Ramachandran and Kesavamani, 1998; GSI, 2000; Patro and Sarma, 2007) have established that the continental crust under the DVP is fragmented. The boundaries of the crustal blocks are regional zones of structural deformation of the Deccan Traps (Fig.1) which have a Precambrian heritage. They also show evidence of post-Trappean reactivation, manifested as Quaternary and Neogene tectonic events (Joshi et al., 2013; Kale et al., 2017); and are the foci of the recent seismicity.

The NW-SE trending Son-Narmada Lineament (also sometimes referred to as the SONATA Zone: Deshmukh and Sehgal, 1988; Ravi Shanker, 1991) and N-S trending Konkan Coastal Belt (KCB) were known to host structurally deformed basaltic flows (Krishnaswamy, 1981). Although known since Auden (1949), the > 250 km long Ellichpur fault (also termed as the Tapi Lineament and clubbed within the SONATA zone) is a neglected fault in the DVP. This southern boundary of the Satpura horst (Sheth, 2018) marks the boundary between the Quaternary Tapi alluvium in the south and the Deccan Traps in the north and has folded basaltic flows dipping by more than 30° along it. The KCB, including the Panvel Flexure (Dessai and Bertrand, 1995) is aligned parallel to the structural grain and orientations in the petroliferous Bombay Offshore Complex that has been interpreted to be a result of the rifting of Madagascar and Seychelles from the Indian plate (Misra et al., 2014).

Geological and geophysical studies (Deshmukh and Sehgal, 1988; Peshwa and Kale, 1997; Raval and Veeraswamy, 2011) in subsequent years brought out the possibility of post-Trappean deformation along the Kurduwadi Lineament (KLZ), Pranhita- Godavari Rift zone (PGRZ) and the Koyna – Warna Seismic Zone (KWSZ). The KWSZ that has suffered sustained low-intensity seismicity for over 50 years (Gupta et al., 2017) is located along the Chiplun – Koyna Lineament. The deep crustal nature of these regional block boundaries has been validated by geophysical studies (e.g. Harinarayana et al., 2007; Rajaram et al., 2017). They have a Precambrian heritage, except perhaps the KCB. Such pre-existing weak zones would have provided crustal conduits for the upwelling magma during the Deccan volcanism (Auden, 1949; Peshwa et al., 1987; Hooper et al., 2010; Ju, et al., 2017).

The post-Trappean reactivations and seismicity along these block

boundaries reflect the combined effects of three significant stress-systems acting on the Indian continental block. Far-field stresses transmitted southwards from the compressive India-Asia collisional subduction (= Himalayan - Tibetan belt) on one side and the extensional spreading along the Indian Ocean Ridge (= Carlsberg and Chagos-Lakshadweep ridges) on the other side (Radha Krishna and Mahadevan, 2000; Misra et al., 2014) are the first two. The latter was initiated during India - Madagascar and then India - Seychelles rifting, leading to the formation of the Indian Ocean and the northward drift of the Indian Plate leading to the former collisional tectonic belt in the north. The vertically oriented stresses generated by flexuring of the crust during emplacement of this large igneous province, a remnant sub-lithospheric thermal anomaly (possibly triggered during the passage of the Indian Plate over the Reunion Hotspot) and subsequent denudationally driven isostatic uplift have contributed to differential uplift / subsidence of the crustal blocks within the DVP (Widdowson and Mitchell, 1999; Saunders et al., 2007; Richards et al., 2016).

Deccan Basement

According to the current eruptive model (e.g. Cox and Hawkesworth, 1985; Jay et al., 2009) Deccan lavas were emplaced on a peneplained basement, with early lava flows filling up whatever depressions were present and younger lavas overstepping them and spreading further. This model (Fig. 2a) complemented the chemical stratigraphy (see: #2.5, Table 1) that emerged in the late 1980's and was stretched in the last 30 years across the DVP.

Studies along the edges of the DVP (Fig. 2b) have shown that paleotopographic undulations of the magnitude of more than 200 m are encountered at several locations (Jain et al., 1995; Kale et al., 2014). The Trap-basement contact shows an elevation difference of almost 600 m within a linear distance of about 20 km across the WGE in deep drilling in the KWSZ (Gupta et al., 2017). Some of the chemostratigraphic formations of the Deccan Traps are of lesser thickness (see: Fig.1 in Schoene et al., 2015) than the amplitudes of the paleotopographic undulation of the basement. Therefore, correlations based on chemical typing across such undulations will be inherently doubtful. Taken together with the problems of the long distance correlation of flows (discussed below) and the aspect of the fragmented basement, the existing regional models of eruptive history based on long-distance chemical correlations are ambiguous.

Absence of any thermal imprint on the strata (particularly the Proterozoic and infra-trappean impure calcareous sediments on which the Deccan lavas rest is intriguing. No baking effect or alterations have been recorded from such sub-trappean sediments (which are susceptible to recrystallization and/or thermal metamorphism at temperatures of less than 200°C). The exception is the development of wollastonite at the contact between the basaltic lava and Shahabad Limestones in the Bhima basin on the southeastern edge of the DVP (Kale and Peshwa, 1995). This aspect of the trap- basement contact and how the pre- trappean rocks (notably sediments) were insulated from the thermal imprints of the lavas that were erupted at temperatures ranging between 800°C and 1100°C; remains an unanswered question in the Deccan literature.

Constituents

Tholeiitic **basalts** constitute more than 95% of the exposed area and

Figure 2. (a) Overstepping of successive stratigraphic formations modelled for the eruptive history of the Deccan basalts along the Western Ghats by Cox and Hawkesworth (1985) and Widdowson and Cox (1996). The section line is N-S. Note they assume a gently northward sloping, peneplained basement on which the Deccan basalts were erupted. (b) Generalized cross section across a plateau edge in the DVP. The paleotopographic relief (exposed after erosion of the Deccan basalts) in the low-lying areas reveal hills rising up to more than 200 m above the base, completely devoid of basaltic flows. It is also relevant that intrusive bodies, dykes and dyke-swarms (related the Deccan volcanism) are exposed in such low-lying areas, but are absent on the tops of the plateaux. Note that the scale is only indicative and intended to bring out the vertical exaggeration. As a representative N-S section of the southern edge of the Malwa Plateau (North on right), the maximum elevations do not exceed 1000 m. As a representative E-W section (East on right) across the WGE-KCB, the width of the coastal plains is lesser than 100 km.

arguably an equal volumetric proportion of the DVP. The geometry and morphology of the flows in this province are discussed separately (see: #3.2). The overall consistency in the petrological composition of these basalt flows was recognized since the time of Washington (1922). Various data bases (Kale et al., 2019; GEOROC database of Max Planck Institute of Chemistry, Mainz, Germany: <http://georoc.mpch-mainz.gwdg.de>) of the chemical analyses of rocks from the DVP show that sub-alkaline tholeiitic basalts constitute more than 85% of the samples. Other variations include picritic, low-Ti / high-Ti tholeiites, alkaline basalts; besides minor rhyolitic flows (Krishnamurthy, 2008).

Plagioclase and augitic clinopyroxenes are the major components of these rocks with variable proportions of olivine. Olivine is partially or completely altered to iddingsite or may be serpentinised. Magnetite and minor proportions of ilmenite, apatite and glass (represented by palagonite and chlorophaeite) are the other primary minerals in these basaltic flows. Picritic basalts are richer in magnesian olivine and pyroxene than plagioclases. Vesicles of a variety of sizes and shapes (often containing zeolites, silica (crystalline quartz or cryptocrystalline varieties) and calcite are commonly present. The distribution (vertical

and horizontal) of vesicles is important in the study of these lava flows as it reflects the mode and volume of vapour loss / retention in the frozen lava.

The lava flows, including their chilled margins, display a porphyritic texture with phenocrysts / micro-phenocrysts in an aphyric to phyric groundmass. This suggests an eruption temperature that is lower than the liquidus temperature of basalts. Plagioclase is ubiquitous in the phenocryst phase, even in the high Mg / picritic basalts. Clinopyroxene is the other common phenocryst phase in the Deccan basalts. Picritic lavas often display euhedral to subhedral olivine phenocrysts with embayed xenocrystic character. The clinopyroxene phenocrysts in these horizons do not display the xenocrystic nature.

Some of the flows (occurring at multiple stratigraphic levels) display large concentrations and sizes of plagioclase phenocrysts, leading to their designation as mega-porphyritic or giant phenocryst basalts - GPBs (Karmarkar et al., 1971; Hooper et al., 1988; Higgins and Chandrasekharam, 2007). They have been used to mark the 'top of Formations' in both chemostratigraphy (Sheth, 2016) and lithostratigraphy (Godbole et al., 1996; GSI, 2001) of the Deccan

Traps. The plagioclase phenocrysts in Thalghat GPB (at the top of Jawhar formation) compositionally uniform character with few of the phenocrysts exhibiting normal zoning. The relatively albitic rims of such phenocrysts have an overlap with the groundmass plagioclase compositions of the same rock (Subbarao et al., 1988). In contrast, the Kashele GPB that caps the Igatpuri sequence mostly has zoned phenocrysts that show multiple zones. Thus, although the GPBs are texturally similar and have compositionally evolved character irrespective of their stratigraphic position, they do not have similar crystallization histories. The presence of such megacrystic flow fields is marked with the acronym of GPB (= giant phenocryst basalts) in the stratigraphic table (Table 1 below) and as “M_” in the various stratigraphic logs given below (Figs. 4,7,8).

Intrusive dykes, sills and other bodies have been mapped in various parts of the DVP (Blanford, 1869; Crookshank, 1936; Auden, 1949). The importance of the dykes as potential feeders for the lava flows has been discussed by various authors (Blanford, 1867; Auden, 1949; Peshwa et al., 1987; Deshmukh and Sehgal, 1988). The dyke-fed fissure eruption model has however suffered from the absence of any

known unambiguous exposure where the feeder relationship is visible (see: Sheth, 2000; Vanderkluisen et al., 2011; Sheth and Cañón-Tapia, 2015). Fig. 3 depicts the location and major orientations of the dykes from the DVP.

The Narmada valley dykes are dominantly oriented in the ENE-WSW direction, with few E-W and NW-SE dykes (Deshmukh and Sehgal, 1988; Ju et al., 2017). Some of these dykes are exposed cutting through the sub-trappean Cretaceous and Proterozoic rocks (Peshwa et al., 1987). The Satpura dykes which intrude the Deccan Traps and the Gondwana sediments, display the same preferred orientation. The other dyke swarms only cut across only the Deccan basaltic flows. The Dhule swarm (Ray, et al., 2007; Sheth et al., 2018) has a preferred E-W orientation; and few dykes oriented oblique to this trend. The Sangmaner dykes (Bondre et al., 2006) show a bidirectional distribution in the NNE-SSW and WNW-ESE direction.

The Coastal swarm has a dominant N-S to NNE-SSW trend of dykes and has been considered to be an artifact of the development of the Panvel flexure (Deshmukh and Sehgal, 1988; Dessai and Bertrand, 1995; Peshwa and Kale, 1997) which is perhaps linked to the India - Seychelles rifting and evolution of the western continental

Figure 3. Locations and dominant trends of dyke swarms in the DVP. The distribution of the flow-types across the province is based on the GSI (2001) District Resources Map (DRM) series data with limited field validations across the province (Kale, et al., 2019). Details of the sheet and lobate types are given in section 3.2.

margin of the Indian plate (Misra et al., 2014; Misra and Mukherjee, 2017).

Besides the doleritic (basaltic) dyke swarms, gabbroic, ultra-alkaline, lamprophyres and associated intrusive bodies are known from the DVP (see: volumes edited by Subbarao and Sukheswala, 1981; Subbarao, 1988, 1999; Deshmukh and Nair, 1996; reviews in Vaidyanadhan and Ramakrishnan, 2008; Valdiya, 2016). Their relations with the Deccan volcanism have been interpreted in a variety of models (e.g. Bose, 1980; Chatterjee and Bhattacharji, 2001; Dessai and Viegas, 2010; Karmalkar et al., 2005, 2014; Chandra et al., 2018) involving hybridization, liquid immiscibility, fractionation and metasomatic melting of primary subcontinental lithospheric mantle derived magmas. It is interesting that the alkali rocks exposed in Kutch and Saurashtra (from the northwestern part of the province are generally accepted to be related to the early magmatism in the DVP (Karmalkar et al., 2016), while such non-doleritic intrusives along the Narmada valley and KCB are generally attributed to the late magmatic events (Fosu et al., 2018).

Xenoliths have been recorded from intrusive dykes along the KCB south of Mumbai (Dessai et al., 2004); alkaline plugs and lavas in Kutch (Karmalkar et al., 2008), and intrusive dykes around Kanherwadi, Chalisgaon and Nandurbar in the central DVP (Ray et al., 2008), in addition to the dykes in the Mandleshwar – Khalghat section of the Narmada valley. They include a spectrum of upper crustal rocks (such as gneisses, granite mylonites, quartzites), pyroxenites and felsic granulites derived from the lower continental crust, as well as spinel peridotites, lherzolites and other ultramafic rocks derived from the upper mantle.

They provide an excellent window to the lithospheric section transected by the ascending magma during the Deccan volcanic episode. They also suggest that the crustal contamination of the magma would reflect the diversity of the sub-Trappean cratonic segments below its different subprovinces as depicted in Fig. 1. Compositional differences in crustal contamination therefore need to account for this diversity when applying chemical parameters and cannot be generalized province-wide.

Petrochemical characters and Chemostratigraphy

As enumerated above, the DVP is dominated by tholeiitic basalts with significantly smaller proportions of picritic, low-Ti / high-Ti tholeiites, alkaline basalts; and minor rhyolitic flows. Their compositional consistency posed inherent problems in classifying them into a systematic sequence. In 1980s, significant variation in the minor and trace element abundances, their ratios as well as $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were noticed during detailed chemical profiling of a few hundred field sections in the western DVP. These chemical variations/proxies led to the recognition of 12 chemostratigraphic units comprising over 25 chemical types, later termed as formations (Najafi et al., 1981; Cox and Hawkesworth, 1985; Beane et al., 1986; Bodas et al., 1988 & Subbarao and Hooper, 1988). This represents the first classification of the Deccan lavas into stratigraphic units, based on reproducible data from the lava flows rather than notional extrapolations based on fossil data from the trap-related sediments exposed only on the fringes of the province.

GPBs were used to identify the formation boundaries in the lower parts of the stratigraphic column, because they were easy and reliable

field markers traceable over long distances. In addition, they showed distinct geochemical signatures of chemically evolved units and marked the end of cycles of magmatic evolution. In the middle and upper parts, the formations were identified by their overall chemical uniqueness (e.g. Bushe and Ambenali).

This chemostratigraphic framework for western Deccan lava pile (Table 1) was used by later workers (Melluso et al., 2004; Jay et al., 2008; Chenet et al., 2009; Shrivastava et al., 2014; etc.) to chemically characterize lava successions in other parts of the DVP and suggest correlations of the chemical formations. To establish such correlations, $^{87}\text{Sr}/^{86}\text{Sr}$, Zr/Nb ratios, Mg^* , $\text{TiO}_2\%$, etc. were used in combination with a spectrum of bivariate and multivariate functions including discriminant function analysis (Mahoney et al., 2000; Bondre et al., 2004; Vanderkluysen et al., 2011 and Sheth, 2016). Several models of long-distance correlations (Self et al., 2008b), computation of eruptive volumes and their temporal variations (Jay and Widdowson, 2008; Richards et al., 2015; Sprain, et al., 2019) and linkages with the Terminal Cretaceous Mass-extinctions (Font et al., 2016; Scheone et al., 2019) relied on the validity of such chemostratigraphic correlations across the province.

In contrast, Deshmukh et al. (1996) identified the chemical analogs of Poladpur, Ambenali and Mahabaleshwar formations of the western Deccan in central and eastern parts of the Deccan Volcanic Province but argued against extending the stratigraphic terminology to these areas. Sengupta and Ray (2011) recognized discrete chemical groupings of basaltic flows based on the differentiation and crustal contaminations in the sequence of flows in the Mandla lobe. Shrivastava et al. (2014) compared them with western Deccan types. This study yielded some bizarre results with the Bushe flows resting above the Poladpur or between Poladpur and Ambenali types (*op cit*: Fig. 6) in contrast to the western succession of Bushe – Poladpur – Ambenali formations. Studies by Sheth et al (2018) recognize a similar problem for the Nandurbar region, rendering such correlations ambiguous. Kale et al. (2019) provide a detailed critique on the efficacy of the chemostratigraphic correlations across the DVP. Significant overlap in the ‘fields’ of various formations, statistical bias of overwhelmingly large number of samples in the Western DVP, absence of due considerations of variations in the crustal contaminations resulting from diversity of the sub-Trappean crust and inability to trace chemical formations across long distances (except in the Western DVP) are the key issues which need to be addressed, before such correlations are accepted.

Most continental flood basalts (CFBs) with zero to negative ϵ_{Nd} & $^{87}\text{Sr}/^{86}\text{Sr} > 0.704$ differ from normal mid-oceanic ridge basalts (MORBs) which have positive ϵ_{Nd} values & $^{87}\text{Sr}/^{86}\text{Sr} < 0.7035$. This along with other chemical parameters indicates that the CFB magmas are derived from enriched mantle sources. Adiabatic decompression melting of the asthenospheric anhydrous mantle (garnet- / spinel-) peridotites at the head of a rising mantle plume are the primary sources of melts for the CFBs (Peng et al., 1994; Krishnamurthy, 2008; Lai et al, 2012). Cox and Hawkesworth (1985) proposed that the primary melt resided in a sub-crustal magma chamber. This magma underwent cycles of progressive fractionation, followed by release (tapping by the volcanic vents) and periodic picritic replenishment. The cycles manifest as the recurrence of picritic to plagioclase phyric lava in the stratigraphic sequence in the Western Ghats. Subsequent studies on the petrogenesis of the Deccan magma upheld this, although some authors (Sheth, 2016) have inferred the possibility of more than one sub-crustal magma chambers. Variable degrees of crustal

contamination have been recorded in different parts of the DVP, underlining the heterogeneous nature of the sub-Trappean basement.

The common heritage of the basaltic flows and doleritic dykes across the DVP appears to be undeniable. The progressively fractionated subcrustal magma suffered diverse degrees of crustal contamination and cycles of differentiation and replenishment during its ascent to the surface. This is reflected in the chemical diversity of the dominantly tholeiitic basaltic lava flows. The petrogenetic relations between the basaltic magma and the non-basaltic rocks that occur as surface flows (rhyolites, andesitic tuffs, etc.) or intrusives (lamprophyres, andesitic and alkaline basaltic dykes; carbonatites), and related igneous complexes (e.g. Girnar, Ambadongar, etc) that form integral components of the DVP remains a conundrum. However, under this overarching generalization, finer details, such as the nature of the primary and secondary differentiation suffered by the magma, the compositional impact of its crustal trajectory through more than 20-25 km of continental crust and the signatures of the diverse crustal segments below different parts of the DVP remain unexplored.

Paleontological records

Trap-related sediments are the source of paleontological data from the DVP. Earlier studies of the fossils from such sediments was responsible for the erstwhile westward younging classification of the lava sequences into Lower (on the east), Middle and Upper Traps (in the west). Infratrappean Bagh Group, Lameta Formation (exposed in the Narmada valley) and other sequences (from Saurashtra, Mandla and Central subprovinces) host a rich flora and fauna of Late Cretaceous age (Sastri and Lahiri, 1981; Sahni and Bajpai, 1988; Mahobey and Udhoji, 1996; Kapur and Khosla, 2018). Some of these infratrappean sequences at Pisdura (Maharashtra), Anjar, Balasinor and Patcham Island (Gujarat) are renowned for hosting some of the largest dinosaurian nesting sites in the world (Srikarni et al., 2017) confirming their Maastrichtian age. It is not unlikely that some of these 'infra-trappean' sediments were coeval with some of the lavas exposed in adjoining areas.

These intertrappeans often contain volcanoclastic (tuffaceous) components, while some of them are entirely composed of silicified tuffs, confirming that their deposition was closely linked with volcanism. The intertrappeans at Mandla were deposited on erosional depressions in the underlying flows, indicating that there was a gap between successive flows. This interval must have been large enough for the underlying flow to have cooled down, weathered and eventually covered by the sediments (that may have some components derived from the volcanic rocks themselves).

Some of the intertrappeans, including the ones near Anjar and Rajahmundry host the K-Pg Boundary based on isotopic (Iridium & Mercury concentrations) and paleontological data (Jaeger et al., 1989; Bajpai and Prasad, 2000; Bhandari et al. 1996; Keller et al., 2009, 2016a). The Deccan volcanic event had a role to play in creating an environmental crisis that led to the terminal Cretaceous mass extinction event (Self et al., 2008a; Renne et al., 2015; Keller et al., 2016b). Punekar et al. (2014) argued that the early Danian phase of Deccan volcanism was responsible for the delayed biotic recovery of marine planktons during the Paleocene times.

Paleomagnetism

While the fossils from the Trap-related sediments provided the broad framework of the age of these flows, paleomagnetic data provided the first level of refinement. The early paleomagnetic studies in the Mandla exposures of the DVP (Athavale, 1970; Wensink, 1973) demonstrated the contemporary proximity of the Indian subcontinent to the Reunion Hotspot in the southern latitudes. They recognized a normal - reverse - normal (N-R-N) sequence in the Mandla sequence. Shrivastava et al. (2015) recorded 5 normal polarity flows interbedded within flows with reverse or mixed polarity from a continuous sequence of 37 flows in the Mandla lobe.

The relatively thin sequence of basaltic flows exposed in Kutch (with Iridium anomaly bearing Late Maastrichtian intertrappeans: Bhandari et al., 1996) has yielded a R-N-R polarity sequence (Courtillet et al., 2000). Dhandapani and Subbarao (1992), Venkata

Table 1: Comparison of chemostratigraphy (Subbarao and Hooper, 1988) and lithostratigraphic (GSI, 2001) classifications of the DVP. Note that no lateral correlation of lithostratigraphic units is implied between the subprovinces, except a possible equivalence between the Karla - Indrayani Formations (from Western subprovince) and the Ajanta Formation from the Satpura subprovince, based on the order of superposition above the Upper Ratangarh Formation. The equivalence between chemo- and litho-stratigraphy of the western DVP is limited to the Kalsubai - Khandala Subgroups. The Bombay Subgroup was not within the purview of Subbarao and Hooper (1988) compilation.

Chemostratigraphy (after Subbarao and Hooper, 1988)			Lithostratigraphy (after GSI, 2001)										
			Western Subprovince			Satpura (Central) Subprovince		Malwa (Northern) Subprovince		Mandla (Eastern) Subprovince			
Group	Subgroup	Formation	Group	Subgroup	Formation	Group	Formation	Group	Formation	Group	Formation		
Deccan Traps			Sahyadri	Bombay	Borivali								
					Elephanta							Singarchori	
	Wai	Desur		Mahabaleshwar	Bargonda								
		Panhala		Diveghat	-- M4 (GPB) -- Purandargarh Diveghat	Karanja	Indore	Amarkantak	Kuleru Khamla / Khampla Amarwara Multai Linga Pipardehi Dhuma Mandla				
		Mahabaleshwar				Buldhana	Kankaria - Pirukheri						
		Ambenali				Chikhli	Kalisindh						
		Lonavala		Bushe	Lonavala	Karla	Ajanta			Mandleshwar	Gaganwara		Unclassified
	Khandala			Indrayani						Singarchori			
	Kalsubai	-- Giravali GPB -- Bhimashankar		Kalsubai	-- M3 (GPB) -- Upper Ratangarh	Satpura	Upper Ratangarh						
		-- Manchar GPB -- Thakurwadi			-- M2 (GPB) -- Lower Ratangarh		Karanja						
		-- Tunnel 5 GPB -- Neral			-- M1(GPB) --	Buldana	Chikhli						
		-- Kashele GPB -- Igatpuri			Salher								
		-- Thalghat GPB -- Jawhar

Figure 4. Locations of fossiliferous sediment associated with the Deccan Traps, along with representative district-wise litho-columns (plotted against their exposed elevations above msl) where geochronological and geomagnetic data is available. The flow-types (discussed later) are depicted in the litho-columns of Kutch, Mumbai, Raigad, Khargone, Nasik, Pune and Mandla districts. The units marked “M₋” represent the GPB flow fields in the respective sequences. The adjoining column gives the magnetic polarity (white = Reverse; black = Normal; grey with question marks = mixed on indeterminate). The weighted mean ages of each sector from available ^{40}Ar - ^{39}Ar ages (normalized to FCs standard) are given on the side, with black lettering for whole-rock ages and red lettering for mineral (plagioclase) ages. Other 55 districts underlain by Deccan Traps do not have paleomagnetic and/or geochronological data as yet.

Rao et al. (1996) recorded a R-N-R-N sequence in the Satpura region north of the Tapi rift. Subsequent studies recorded only a N-R-N sequence (Khadri, 2003; Chenet et al., 2009; Schöbel et al., 2014) from this region and the northern Malwa plateau.

The +2000 m thick pile exposed in the WGE displayed reverse polarity with a small capping sequence of normal polarity. Courtillot et al. (1986) and Duncan and Pyle (1988) suggested that this R-N sequence may be equated with the magnetic chrons 29R and 29N respectively and provided the paleomagnetic and geochronological validation of the linkage of the DVP with the K-Pg Boundary. This was subsequently reaffirmed by recent studies (Jay et al., 2009; Chenet et al., 2009). Paleomagnetic studies of dykes exposed south of Mumbai have recently indicated the record of a 3-Chron N-R-N sequence of polarity (Basavaiah et al., 2018), although they all intrude flows with reverse polarity.

The real problem across the DVP is the fact that while the western sequence has been well studied and replicated by multiple workers

over the years, paleomagnetic data from the other subprovinces is sparse. Generalized correlations with Chron 29 across the province are seriously suspect in light of the emerging geochronological data discussed below. More data is required before any concrete conclusions can be arrived at for the DVP in this context. The paleomagnetic data is definitely consistent with the paleo-latitude position of the Indian plate over the Reunion hotspot around 68 - 66 Ma, and its northward flight in the ensuing period, coinciding with the growth of the Indian Ocean in the Tertiary - Quaternary times (see Inset Fig.1).

Geochronology

Besides the paleomagnetic techniques, radiometric (mainly ^{40}K - ^{40}Ar and ^{40}Ar - ^{39}Ar) techniques have been used to constrain the age and duration of the Deccan volcanism. The most recent high-precision U/Pb ages (Schoene et al., 2015) and ^{40}Ar - ^{39}Ar (Renne et al., 2015)

also use sampling of the Western DVP. The high precision U/Pb ages of zircons are an indirect means of establishing the chronology since they depend on provenance and pre-eruptive residence times of the zircons. ^{40}Ar - ^{39}Ar ages provide robust age constraints for basaltic rocks from the DVP. Most of the geochronological studies are from the Western Ghats sequence, with few samples from the Mandla, Malwa and Kutch subprovinces.

^{40}Ar - ^{39}Ar ages reported from different laboratories are not directly comparable because of the different ages of these monitor samples that have been used by them for calibration and computations. To enable this, we have recalculated and normalized to the Fish Canyon Sanidine (FCs) age of 28.294 ± 0.036 Ma (Renne et al., 2010, 2011) all previously published ^{40}Ar - ^{39}Ar plateau ages (Duncan and Pyle, 1988; Venkatesan et al., 1993; Hofmann et al., 2000; Pande et al., 2004, 2017; Bakshi, 2014; Schöbel et al., 2014; Renne et al., 2015; Shrivastava et al., 2015; Parisio et al., 2016). The recalculated high quality ^{40}Ar - ^{39}Ar plateau ages (both whole rock and plagioclase) for seven districts based on the District Resources Map (DRM) series data (GSI, 2001) are plotted in the Fig 4 along with the available paleomagnetic information of the sequence. We also take cognizance of the recent revision in the age of the KPg Boundary to 66 Ma (Gradstein et al., 2012; Renne et al., 2013) in this context.

The sequences around Nasik, Pune and Raigad in the Western DVP show indistinguishable whole rock ages with the weighted mean age of 67.5 ± 0.2 Ma and exhibit reverse magnetic polarity. The upper flows in the Raigad district that have normal polarity have a weighted mean age of 63.2 ± 0.7 Ma. This suggests that there may be a gap in the volcanic events between the lower and upper sequence in the Western DVP, unlike the continuity assumed in current literature (e.g. Renne et al., 2015; Sprain et al., 2019). The ages of lava flows in Mumbai (63.1 ± 0.1 Ma) compares well with the ages of the dykes reported earlier from the southern tip of the DVP around Goa (Widdowson et al., 2000). This phase perhaps represents the youngest volcanic pulse of the DVP.

Plagioclase from lava flow sequences in the Mandla have weighted mean age of 64.1 ± 0.4 Ma for both lower flows that show reverse magnetic polarity and the upper flow sequences characterized by normal polarity. The whole rock ages of the Mandla Province (Shrivastava et al., 2015) are comparatively younger than the ages of the Western Ghats sequence. The plateau of these dates show the evidence of argon loss, indicating that the whole rock ages here constrain only the minimum age. Based on this, Pathak et al. (2017) concluded that the N-R-N sequence from the Mandla subprovince may be younger than Chron 29 that hosts the K-Pg Boundary.

In the Malwa Province, the lower flows exhibit normal magnetic polarity and whole rock ^{40}Ar - ^{39}Ar age of 67.7 ± 0.2 Ma. Ages for the upper lava flow sequences that have reverse magnetic polarity are not available. Normal polarity of the uppermost flows in this region has also been reported (Sreenivasa Rao et al., 1985; Dhandapani and Subbarao, 1992) suggesting an N-R-N sequence of magnetic polarity. The magnetic polarity and radiometric data in the Kutch area are of variable quality and do not allow an unambiguous interpretation. The available whole rock age ranges from 66-68 Ma and the whole rock weighted mean age is 67.3 ± 0.2 Ma. Only a few lava flows in the middle show distinct R-N-R sequence.

It may be summarized that volcanism in the DVP occurred in not less than three distinct phases. Contrary to existing models (Renne et al., 2015; Richards, et al., 2015; Scheone, et al., 2019) these phases were not province-wide but restricted in their geographic spread. The

oldest eruptive phase is Maastrichtian in age (68 - 66 Ma), corresponding to magnetic chrons 30N - 29R. Eruptions during this phase occurred in the Kutch, Malwa and Western subprovinces and represent arguably the largest volumes of eruptions. This widespread volcanism must have contributed significantly to the environmental stresses leading to mass extinctions. The next phase occurred during the Danian times. The lava sequences in Mandla and Satpura subprovince; besides the youngest sequence (with normal polarity) in the Western subprovince erupted during this phase that occurred between 65.8 Ma and 64.0 Ma corresponding with the magnetic chrons 29N-28R-28N. Some of the younger flows in the Malwa subprovince may belong to this episode as also the dyke-swarms occurring in the Narmada and Satpura belts. The youngest phase of Deccan volcanism occurred in the western edges around Bombay and the offshore region, approximately in the period of 63.5 - 62.0 Ma. (Pande et al., 2017). Some of the younger lavas from the Mandla subprovince may have been erupted during this phase as well. It is also evident that volcanism did not occur across the entire province at the same time, but was limited to only some subprovinces during each of the three phases.

The recalibration of the available ages from the DVP demonstrates that the traditionally assumed 'continuity' of eruptive sequences (e.g. Renne et al., 2015; Sprain et al., 2019) is invalid. Also, chemically correlated lavas from different parts of the province yield distinctly different high-resolution ages. This poses serious doubts regarding the efficacy of the chemostratigraphic correlations that are the cornerstones of earlier models of the Deccan volcanism.

Volcanology

Volcanological aspects of lavas deserve a central place in the knowledge of this volcanic province but is seriously lacking. Published literature on the DVP appears to focus more on the chemistry than the physical volcanology of the components of this province. While the former has enabled a fairly good understanding of the primary petrogenetic nature, the mode and style of eruption of the lavas remains relatively less understood. These chemical correlations led to the model of a monocentric eruptive system (north of Nasik) akin to a large shield volcano developed over a plume head (Cox, 1989; Richards et al., 2015). Basic observations on the volcanological aspects of the lavas, which were not given due cognizance in this model, pose severe challenges to this model and the implicit long-distance correlations (see: Gupte et al., 1974; Kale et al., 1992; Deshmukh et al., 1996; Kale, 2020).

The spilitic pillow lavas from Mumbai (Sukheswala, 1974) suggest their eruption in submarine / subaqueous conditions. A recent study by the GSI has recorded the presence of similar pillow lavas from the Mandla subprovince as well. They are exceptions to the general agreement in literature that the Deccan lavas were erupted in subaerial conditions. Localised lakes may have temporarily developed due to volcanism-related precipitation in some parts of the DVP, yielding the lacustrine intertrappean sediments.

Flow geometry and internal structures

Individual lava flows and flow fields in the Deccan essentially display a sheet-like geometry with the lateral spread being 50 - 100 times larger than the thickness. Individual flows range in thickness between 5 - 25 m, although exceptionally thick flows (~ 100 m) have been recorded. Uninterrupted lateral continuity across several tens of

km is evident along the escarpment face of the WGE. Choubey (1973) traced lava flows across distances of almost 100 km in the Malwa subprovince. Closer examination of many of the thick, widespread 'flows' indicate that they flow-fields comprising of several flows and lobes, rather than singular lava flows. Each lava flow normally consists of three internal layers, namely the crust, core and base (Keszthelyi, et al., 1999) from top to bottom respectively. They display a wide spectrum of internal structures and geometry as depicted in Fig. 5.

A thin reddened tachylitic rind representing the chilled outermost rim of the lava is not uncommon in the Deccan lavas. The crust is rich in vesicles and has a fine grained aphanitic texture that has significant proportions of glass yielding it a tuffaceous appearance in weathered exposures. Flows showing a domed-up geometry of the inflated crust which is cracks at the crest are recognized as hummocky flows. Others display a fragmented (brecciated) crust with clasts of vesicular basalt embedded in a tuffaceous, aphanitic matrix. Earlier workers have described them as rubbly pahoehoe or 'simple' flows. The crust grades downwards into a compact, crystalline basaltic core. The core is relatively depleted in vesicles and generally shows columnar (entablature) jointing. Some flows display vesicle bands

within the core, which normally also contains vesicle cylinders in its lower parts. Pipe vesicles interspersed with irregular shaped vesicles mark the base of the flow, which may display chilled lower margins. Large gas cavities (with domed-up roofs and irregular to flat base) are often encountered at the transition between the basal part of the flow and its core.

Interflow horizons of variable thicknesses separate successive flows, often generalized as (red, green, grey) 'boles'. They comprise of volcanoclastic tuffaceous material, which may or may not be baked and oxidized. Some of them may be pedogenic altered powdery layers derived from the flow-top breccia or the chilled crusts (Sayyed, 2014; Srivastava et al., 2018). Others, including the fossiliferous intertrappeans display evidences of sedimentary reworking and stratification. It is therefore inappropriate to generalize all the interflow horizons as boles and it is necessary to recognize each horizon independently. The presence of such interflow horizon is an indication of a gap between the emplacements of the successive flows. It is significant that intertrappean sediments are more prolific in the fringes of the DVP, but the thick basaltic successions exposed on the edges of the plateaus display very thin impersistent interflow horizons. In

some flow-fields, individual flows may not display a distinctive interflow horizon, suggesting that the lava emplacement occurred in quick succession and the capping flow spreads over while the earlier unit is cooling down.

Lava morphologies and classification

The Deccan basaltic flows were described elaborately in the memoirs of Blanford - 1867 & 1869, Bose - 1884, Fermor and Fox - 1916 (partly reproduced in Subbarao (Ed), 1999 pp 5 - 101). Earlier view of their being fissure-fed eruptions, was revised based on their comparisons with the Hawaiian lava types (West, 1958, 1959; Walker, 1971; Sheth, 2006).

Based on their geometry and internal structure (relative proportions of the upper crust, core and base, distribution of vesicles, etc), the flows in the Deccan were classified into (i) compound (with multiple units of pahoehoe lobes), (ii) simple and (iii) áa types. The distribution map of simple and compound flows compiled by Deshmukh (1988) became the cornerstone of the shield volcano model of the DVP in collaboration with the chemostratigraphic classification. Subsequent workers on the volcanological aspects of the flows, including the compilations by

Figure 5. Major morphological types recognized in basaltic flows from the DVP (modified after Duraiswami et al., 2014). 'Lobate flows' display the internal structure and geometry of the hummocky and typical pahoehoe, while the 'sheet flows' include all other morphological types according to Kale (2020).

the Geological Survey of India in their DRM and Quadrangle map series (GSI, 2001), used this classification with minor variations in the last 20 - 30 years.

Keszthelyi et al. (1999), Bondre, et al. (2000, 2004), Duraiswami et al. (2001, 2003, 2004, 2008, 2014), Sheth et al. (2011), Brown et al. (2011), Sen (2017), Sheth (2017) are examples that have documented the presence of a wide spectrum of morphological types and their lateral transition across the province. It is important to recognize that they reflect the emplacement and cooling history of the lava after it erupted on the surface. Self et al. (1998) had highlighted the importance of pahoehoe lavas in the flood basalt provinces across the world. Variations in the internal structure and geometry of the pahoehoe flows essentially reflect the differences in volumetric rate of emplacement, lateral spreading dynamics, cooling and vapor loss (consequent viscosity) history. Even in Hawaii, the pahoehoe and aa flows do not represent different 'types of lavas', rather they are variations in the morphology of the cooled lava. Similarly, in the DVP, lateral transition from one type to another occurs within a single flow or within a flow-field without changing the compositional characters of the flow. Fig. 5 gives a snapshot of the major morphological types of lavas recognized from the DVP.

Differences in volumetric rates, streaming v/s pulsed emplacement, cooling and vapour loss governed by local conditions during the lateral transfer of the extruded lava result in these morphological variations. Kale (2020) suggested that these morphologies represent a continuous variation series between two end-members, 'lobate' and 'sheet' flows. This working hypothesis of flow classification is based on the eruptive mechanism and the processes that operate after the lava has been vented from the edifice as elucidated by recent studies of lava emplacement (e.g.: Harris et al., 2007; Katterhorn and Schaefer, 2008; Guest, et al., 2012; Cashman, et al., 2013; Glaze and Baloga, 2013; Öskarsson and Riishuus, 2014; Bernardi, et al., 2015; Tarquini, 2017). Based on the logs generated from the DRM data, validated by limited field checks, it is possible to compile a province wide distribution of the morphological types as depicted in Fig.3 above.

The lobate flows (with a greater height:length ratio) are akin to the typical channel-fed pahoehoe flows with clearly defined cooling units that cool as individual lobes (as depicted in Fig. 5). Lobate flow fields are the result of pulses of relatively small volumes of lavas being erupted subaerially leading to their independent chilling and solidification. Such flows stack into a lobate geometry and do not travel far from their edifice. When such lobes are emplaced in rapid succession, they may be annealed together into a 'compound' flow. An early loss of vapour phase resulting in enhanced viscosity of the lava inhibits long distance spreading, leading to a pile up close to their eruptive edifice for these types of flows.

The sheet flows have a magnitude smaller height – length ratio, and may display internal structures comparable to sheet / slabby / rubbly pahoehoe along their length of exposures. A larger volumetric rate of semi-continuous emplacement is responsible for their development. The early formed rapidly chilled crust in such flows impedes vapour loss, retaining fluidity in the lava; and permits a relatively slower cooling of the core. The pulses of endogenous transfer of lava encased below the crust consolidate as an apparently unified core (unlike individual lobes in the former type). Separate pulses that fed such flows may be distinguished by multi-tiered columnar (entablature) joints, compositional variations and at places by horizontal bands of vesicles that separate the batches of lava in the

core. This mechanism (demonstrated by Hon et al., 1994; and refined in subsequent years by several workers (e.g. Self et al., 1998; Keszthelyi et al., 1999; Katterhorn and Schaefer, 2008; Glaze and Bolaaga, 2013; Cashman et al., 2013) allows a wider spread of the lava far from its eruptive edifice. Such flows (traceable continuously across long distances) were mapped as 'simple' flows (sensu-Deshmukh, 1988; GSI, 2001). However, they are unquestionably the result of multiple emplacements of lava enabling their larger aerial spread.

Stratigraphy and correlations

Based on the classification of the morphological type, with supplementary inputs from petrological studies and chemical characterization, Godbole et al. (1996) gave a lithostratigraphy of the western DVP that was differing from the chemical stratigraphy of the same region. Similar exercises were carried out by the Geological Survey of India in other parts of the DVP (see: Deshmukh and Nair, Eds., 1996). The compiled data of flow mapping by the Geological Survey of India (collectively cited as GSI, 2001) was published in the district-wise geology maps (DRMs). given above, compares subprovince-wise lithostratigraphic classifications with the chemostratigraphy of the DVP.

There are fundamental differences between the chemostratigraphic classification and the lithostratigraphic classification in the western and southern subprovinces where they geographically overlap. The Bombay Subgroup was unaccounted for in the chemostratigraphy and represents a distinctly separate set of volcanics both in terms of constitution and age as pointed out above. The Indrayani and Karla formations correspond with the Khandala and Bushe chemical types as mapped and therefore provide a datum for comparison.

It is important to note that although the names are the same, the 'Mahabaleshwar' units are distinctly different in the two classifications (Table 1). The Purandargarh Formation includes the lower flows of the Mahabaleshwar chemical type as well as the entire thickness of the Ambenali chemical type. Its upper boundary is marked by a distinct megaporphyritic flow field (M4) that was first described as a giant phenocryst basalt (GPB – sensu) by Karmarkar et al. (1971) but has been completely missed out in the chemostratigraphic classification. Significantly, the position of M4 at the top of the Purandargarh Formation is comparable to elevations where the magnetic polarity reversal (within the –chemical- Mahabaleshwar sequence) had been noted earlier (Chenet et al., 2009).

The mapping of individual flows had earlier recorded their pinch-and-swell geometry as well as variable thickness across their widths in field exposures as well as in aerial maps (Gupte et al., 1974; Kale et al., 1992). Recent flow mapping of individual flows and their lateral transitions by Chatterjee and Dash (2017) demonstrates this unequivocally, besides showing that the direction of lava movements may have been significantly different in successive flow fields. This exercise (Fig. 6) demonstrated the uncertainties in correlation as well as the undulating nature of the substrate on which each lava unit has been emplaced. On a regional scale, this is depicted by district-wise correlations across the WGE (Fig. 7) along the western subprovince. It shows progressive southward dip of the formation contact both above and below the WGE as was recorded in the chemostratigraphic models (Subbarao and Hooper, 1988; Jay et al., 2009). The inability to establish such correlations across subprovince boundaries is depicted in Fig. 8 across the Tapi Fault between the Satpura and

Figure 6. West - East (left to right) logs of sections measured southeast of Pune bring out the lateral geometry and correlation of flows from the Diveghat, Purandargarh and Mahabaleshwar formations (adapted from Chatterjee and Dash, 2017). Note the pinch and swell geometry of the individual flows and the undulating geometry of the Formation contacts. The reversal of the inferred direction of spreading in successive flows is significant. Diveghat flows were emplaced eastwards. The lower flows in the Purandargarh Formation (P1 & P2) suggest westerly movement of the lava, notwithstanding the undulations in their substrate. The younger flows again display an eastward spreading in the Purandargarh Formation. Vertical scale is exaggerated.

Western subprovinces. This also shows that the lithostratigraphic resolution is poor in the central (Satpura) subprovince in the available data.

Assumption of a singular eruptive edifice provided justification and the framework for the chemostratigraphic classification and correlation across the DVP. Using the distribution of the (simple & compound) flow-types compiled by Deshmukh (1988), this eruptive head was postulated to be north of Nasik (Watts and Cox, 1989; Jay et al., 2009; Richards et al., 2015). Absences of identifiable unambiguous eruptive centers as well as lack of exposures that display a feeder relationship between the dykes and flows were arguments against the erstwhile fissure-fed eruption model. As discussed above, correlations based on chemistry alone have severe limitations in light of the geochronology and paleomagnetic data. The chemical affinities

of Poladpur - Ambenali - Mahabaleshwar Formations assigned for the Mandla sequence (Shrivastava et al., 2014) would require them to be not less than 3 million years older than their computed ages (Shrivastava et al., 2015) nor are their paleomagnetic characters the same (Pathak et al., 2017) as depicted in Fig. 4. This and other examples demonstrate the limitations of the chemostratigraphic correlations; and also make out a case for a polycentric eruptive history of the DVP (Srinivasan et al., 1998; Sheth and Canon-Tapia, 2015; Kale and Pande, 2017).

The subprovince-wise lithostratigraphic classification (Table 1) is far more robust than the chemostratigraphic classification across the DVP (Kale et al., 2019). It is evident from the correlations indicated in Figs 6 and 7 that structural breaks and the possibility of multiple eruptive centers are better addressed. Several problems in the chemical characterization of the lava flows (e.g. Deshmukh et al., 1996; Sheth et al., 2018) are avoided. In addition, this being a field-based classification, it can be studied, refined and (if required) suitably modified easily by subsequent workers as more data is available. It does not suffer from the fundamentally 'probabilistic' mode of the chemostratigraphic parameters.

Eruptive mechanism

Taking cue from these contradictions, if one were to review the volcanological characters of the lava pile, a working model of the eruptive mechanism emerges that is significantly different from the Hawaiian analog currently in vogue for the DVP. Fig. 9 (modified after Self et al., 1998; Kale, 2020) gives a pictorial representation of how the endogenous transfer of lava in sheet flows can progressively yield the observed morphologies in the DVP. This also assumes that the eruption of the Deccan lavas was a fissure-type eruption, analogous to the Icelandic volcanism (e.g.: Grimsvötn volcanic field or Laki eruptions through multiple vents aligned along a dyke-fed fissure) rather than the Hawaiian volcanism.

Lava transfer proceeds endogenously through a series of lobes that emerge out and grow in successive pulses. Often, the lobes sourced from adjoining vents merge and spread further with a sheet-like geometry (as depicted in Fig. 9) since the hot fluid lava continues to move endogenously under the insulating sheath of the early formed

S Figure 7. District wise logs based on the DRM sheets (GSI, 2001) plotted against the elevations of exposure above msl. The logs above the WGE (A) and in the coastal belt (B) are arranged in a sequence from North to South (left to right), except in case of the Mumbai log. Note that prima-facie, the southward younging of the successive formations is indicated in these logs, as suggested by Cox and Hawkesworth (1985) and Jay et al. (2009). It is significant that the elevations of the formation contacts along the coastal belt are significantly lower than the adjoining contact above the Western Ghats in the plateau region. The comparison of the elevations of exposures of M3 in Thane (~ 300 m above msl) and Pune (> 650 m above msl) is an example of this. Therefore, when correlating eastwards, the same overstepping of flow-contacts or formations does not hold. It is necessary to invoke either a pre-Trappean topography fed by different eruptive foci or post-Trappean uplift across the WGE or a combination of both to explain this variation.

E Figure 8. District wise logs based on the DRM sheets (GSI, 2001) plotted against the elevations of exposure above msl. The logs north (A) and south (B) of the Tapi river valley are arranged in a sequence from West to East (left to right). In the southern set, a broad eastward younging of the strata is indicated, but the same is not true north of the Tapi valley. In addition, the southern set appears to provide the connection between the lithostratigraphic units from the western subprovince of the DVP (Table 1) with those from the central subprovince. It is significant, that with the current level of data, it is not possible to suggest any correlation between the northern and southern sequences at all.

Figure 9. Cartoon depicting the progressive evolution of morphologies within a sheet-lava flow field through endogenous transfer of lava through one of the eruptive centers; based on Keszthelyi et al. (1999), Self et al. (1998), Eibl et al. (2017), Kale et al. (2019). This also suggests that lateral transitions of the different morphological types may enable interpretation of the direction of the lava propagation on the surface within a flow-field.

crust. It is evident that all the morphologies of lava (Fig. 5) can develop along the same spreading lava sheet, in response to local conditions of vapor release, shear stress and rigidity of the crust. Large volumes emplaced in pulses will eventually yield large sheet flows, with disrupted crustal fragments getting engulfed in the later tuffaceous encrustations (= flow top breccias).

Recent studies of active volcanic fields in Iceland have demonstrated that the feeder dyke network to such fissure eruptions rarely comes up to the surface, but remains underground (Annen, et al., 2001; Eibl, et al., 2017). Similar interpretations are applicable for Deccan dykes (e.g.: Lala, et al., 2011; Ju et al., 2017) and this may explain why flow-dyke feeder exposures are rare and also the fact that dykes are more frequently exposed where the flows have been eroded off in the low-lying areas of the Narmada valley and KCB.

Concluding Remarks

Summary

The available knowledge of the DVP -that continues to grow by the day – shows that

a) The DVP does not have a unified eruptive history as has been

modelled in some of the recent publications. Lava vented in different subprovinces at different times. The earliest eruptions were perhaps located along the Narmada valley (Malwa subprovince) and in the Western subprovince. These Late Maastrichtian eruptions (occurring between 68 Ma and 66 Ma) represent the largest volumes of lava. They are temporally linked with the environmental crisis leading to the terminal Cretaceous extinctions. The next major phase occurred in the Early Danian (between ~64.8 Ma – 63 Ma) is represented by volcanism in the Mandla, Satpura and the (uppermost sequence in) Western Subprovince. This and the ensuing third phase that was restricted to the KCB and off-shore region (< 62 Ma) could have contributed to the delayed biotic recovery in the Danian times as postulated from the fossil and allied data across the world.

- b) Each of the subprovinces has a unique basement through which the lava erupted, both compositionally and in terms of crustal thickness. Consequently, the contamination of the lava must reflect these differences, and erstwhile interpretation of the chemical proxies requires to be reworked.
- c) The eruptive history of the DVP is more akin to the dyke-fed fissure eruptions of Iceland than the Hawaiian models. The eruptive foci must have been distributed across the DVP and were

not centralized. The ancient zones of structural weakness underlying the DVP, may have provided easier conduits for the upwelling magma, and therefore are likely to host such centers of eruption.

- d) Taking cognizance of the limitations of the chemostratigraphy and the fragmented basement, a zonal stratigraphy of the DVP provides a more robust framework for correlating lava sequences. It is likely that (as in case of the Western DVP), the GPBs may provide marker units enabling this classification further. However, the details of this are rather sketchy at this instant and need to be enriched with future studies.

Gaps

Although the available data yields a deceptive perception that the DVP is rather well constrained in terms of its age, origin and disposition, its geographic distribution is significantly skewed in favor of the Western Subprovince. The studies of the Deccan volcanics by the Geological Survey of India (compiled in the State, District and Quadrangle Geological maps and enumerated in numerous unpublished reports by the GSI officers) are far more exhaustive than the studies carried out by the academia. This data is an integral component of the knowledge of this province, but unfortunately has not come into the scientific discourse on this igneous province. This shortcoming deserves immediate attention and resolution.

The overall granularity of the petrological, volcanological, geochronological and geomagnetic data across the province is poor, besides being geographically skewed. The detailed petro-chemical profiling and standardization of the sub-provincial stratigraphy (Table 1) is a pending agenda. As demonstrated by Chatterjee and Dash (2017), detailed field mapping with petrological data can yield fascinating data on the geometry, eruptive nature and long-distance correlation of flow fields. Similar studies are required across the province. Emerging modern geophysical techniques and scientific drilling can provide significant data on the subsurface extensions and the basement-trap relations.

Morphotectonic assessment of sectors of the province in association with the sediment-supply data from the off-shore petroliferous basins could yield critical data on the Tertiary and Quaternary uplift history and tectonism of the DVP. Very little information on those lines is available. The anomalous drainage patterns of mature wide river valleys, beheaded streams (all draining towards the east) located along the west-facing WGE on the crests of the plateaux could not have resulted without structural or neotectonic controls (Kale et al., 2017). Although seismicity at Koyna-Warna has been attributed to reservoir-triggered mechanisms (Gupta et al., 2017), microseismicity across the province remains unstudied. Can reactivation of ancient structures explain catastrophic events (e.g. Killari, Jabalpur, Bhatsa) of stable-continent-interior seismicity or are far-field stress systems resulting from the Indo-Asian collision along the Himalayan belt contributing to it? Is the microseismicity precursory to larger events or not remains unanswered by existing data.

Challenges

The field relations, volcanological parameters, structural features, chemical and petrographic data, geochronology and paleomagnetic data across large stretches of the province are undocumented. Younger

(fluvial sedimentary) cover, deep weathering profiles and soil cover and anthropogenic activity have impeded this to a large extent. A multidisciplinary approach is required to gather this data. The existing geographically skewed data needs to be supplemented by a well distributed data granularity across the entire province for any confirmation of the various working hypotheses that are in vogue.

Although the above compilation has focused on the geological aspects of the DVP, its impact on human endeavors is not small. The DVP occupies more than 25% of the area of the Indian Peninsula and is a host to almost 20% of the Indian population. Availability of water, landuse, infrastructure and habitable areas are great in demand in these parts of the country. Landslides, earthquakes and droughts are common natural disasters that have affected the local population time and again. As an example, the distribution of aquifers in these basalts has to do with the porosity (dominantly dependent by the vesicularity) of the basalt. In light of this, understanding the distribution of vesicle within the basaltic flows has a direct impact on the groundwater potential of the area underlain by them. Similarly, the structural characters (including cooling joints and superimposed fractures) have a direct bearing on the stability of the slopes that these basalts support. In context of regional infrastructural seismic hazards, an elaborate understanding of the active structural elements in the province is essential.

A detailed multifaceted documentation and analysis of the scientific characters of the Deccan Basalts is therefore the need of the hour. The impact on the volcanological aspects of large continental flood basalt provinces, magmatic evolution, and tectonics of the Indian peninsular region are low-hanging fruits of this scientific enquiry. It will also have a wider impact on the livelihood, progress and safety of the (> 150 million) population that resides on this basaltic province.

Acknowledgements

The authors thank Dr. Fareeddudin for inviting us to contribute this manuscript. Constructive reviews by two anonymous reviewers and Anne Jay helped improve its contents significantly. MB and PC thank the Director General, GSI for permission to publish this material. Financial support from DST and IRCC, IIT Bombay (to KP) and DST and MoES (to VSK) is gratefully acknowledged. Authors thank the participation in field studies and discussions of Seema Dash (GSI), Gauri Dole (SPPU), Priyanka Shandilya (IIT-B) and several other students who helped synthesize the concepts presented here.

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