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Contemporary Researches and Issues Related to the Deccan Volcanism

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In the past few decades, late Cretaceous Deccan volcanism witnessed extensive researches, focused on nature, variety and genesis of magma, emplacement span [entail Cretaceous/Palaeogene (K/Pg) transition] and attendant faunal crisis; however several issues remain to be addressed. In this gamut, researches in the past five years have been reviewed, encompassing petrochemical, Nd-Sr-Pb isotopic, and geochronology studies to comprehend origin, age and duration of volcanism and attendant K/Pg transition events. Low/high TiO₂ tholeiites of Deccan Traps and associated rocks from a rifted basin revealed existence of varied mantle sources for synchronously formed tholeiitic and alkaline magma involved sub-continental lithospheric mantle. Moreover, later magma type ascended with faster rate through the lithosphere and subsequently led to rapid gaseous release, accounted for the Cretaceous/Palaeogene boundary (KPB) mass extinction. Flow-by-flow palaeomagnetic measurements for the Mandla basalt revealed multiple magnetic polarity events: implying for C29n-C28r-C28n magnetostratigraphy.

⁴⁰Ar/³⁹Ar ages for Mundwara and Sarnu-Dandali complexes assign polychronous emplacement, concomitant with the post-breakup of Indo-Madagascar. Both complexes show comparable evolution from early to late Cretaceous Period. U-Pb zircon age data based Deccan eruption rates when combined with the Chicxulub impact triggered seismicity, inferred four major eruptive phases, each lasted for ≤100 ka. In the second eruptive phase, Poladpur Formation eruption began tens of thousands of years before, but peaked out at K/Pg mass extinction event. Consequently, carbonate dissolution, climatic cooling and late Maastrichtian global warming attendant to Deccan volcanism, induced ocean acidification which led to high environmental stress worldwide. Present review also covers applied aspects, including CO₂ sequestration in Deccan basalt and suitability of silicic phase for nuclear waste disposal. Additionally, it ends-up with a note on future direction of researches in Deccan basalt.

Keywords: Deccan Volcanism; Cretaceous/Palaeogene Boundary; Palaeoenvironment; ⁴⁰Ar/³⁹Ar Ages; Infra-Inter-Trappeans

Introduction

The Deccan Volcanic Province (DVP) represents one of the largest Continental Flood Basalt (CFB) provinces in the world (cf. 1.6, Ernst, 2014), covering an area of 0.51×10^6 km² (Fig. 1), which records vast accumulation of basalt in a relatively short time span entailing the Cretaceous/Paleogene boundary (KPB). The Deccan volcanic activity initiated prior to the KPB, however, main episode occurred at ~300 ka prior to or at the KPB itself (Schoene *et al.*, 2015). Lithospheric versus asthenospheric contributions to Deccan Traps when compared to the Ethiopia-Yemen and Karoo continental flood basalt revealed similar parental magmas and fractionation trends (Natali *et*

al., 2016). Such continental flood basalt represents similar zonal arrangement for the hottest and deepest picrite-basalt magmas in the central area and cooler and shallower basalts at the peripheral areas. Further, superheated picrite-basalt supposedly coeval with the alkaline-carbonatite complexes and rhyolitic differentiates often lie at the intersection of extensional lineaments and at the top of picrite-basalt lavas, respectively. Additionally, more or less unaffected mantle Sr-Nd isotopic values of picrite-basalt together with the lithospheric values of the peripheral basalt marked common geodynamic setting (Natali *et al.*, 2016).

One of the thickest (~ 1.5 km) Deccan Traps

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Fig. 1: Studies on Deccan volcanic province (green shaded area) carried out in the past five years shown with bold numbers enclosed within the parentheses. Work responsibility: (1) Shrivastava *et al.* (2015), (2) Parisio *et al.* (2016), (3) Font *et al.* (2016), (4) Pande *et al.* (2017), (5) Sheth *et al.* (2017), (6) Schoene *et al.* (2017), (7) Shrivastava *et al.* (2017), (8) Sheth *et al.* (2018), (9) Cucciniello *et al.* (2018), (10) Schoene *et al.* (2019), (11) Chatterjee and Sheth (2015), (12) Petersen (2015), (13) Rani *et al.* (2015), (14) Richards *et al.* (2015), (15) Widdowson *et al.* (2015), (16) Ray *et al.* (2016), (17) Rani *et al.* (2016), (18) Natali *et al.* (2016), (19) Pathak *et al.* (2016), (20) Sheth (2016), (21) Shrivastava *et al.* (2016), (22) Alexander and Purohit (2019), (23) Mishra *et al.* (2017), (24) Sinha *et al.* (2017), (25) Kumar *et al.* (2017), (26) Vedanti *et al.* (2018), (27) Kumar and Shrivastava (2019), (28) Prasanth *et al.* (2019), (29) Pal *et al.* (2015a), (30) Pal *et al.* (2015b), (31) Puneekar *et al.* (2015), (32) Keller *et al.* (2017), (33) Chenming and Demin (2018), (34) Sprain *et al.* (2019) and (35) Renne *et al.* (2019). Note: references in italics refer to studies carried out on Deccan volcanism

accumulation occurs in the Mahabaleshwer area of Western Deccan Volcanic Province (WDVP). In Koyna-Warna-Panchgani area, Sinha *et al.* (2017) and Mishra *et al.* (2017) reported 932 and 1251 m thick sub-surface lava packages, comprised of 30 and 46 lava flows, respectively. Although, stratigraphy of the lava flows, age and duration of volcanism in the Koyna-Warna-Panchgani area needs to be correlated with special reference to the main WDVP. Petrophysical and elastic studies of Vedanti *et al.* (2018) on 338 m thick sub-surface basalt package from Killari (KLR-1) borehole revealed presence of FeO (~13.4 wt%) rich and SiO₂ (47.8 wt%) poor Ambenali and Poladpur-like lava flows, characterized by a mean density of 2.91 g/cm³ and P, S wave velocities of 5.89 and 3.43 km/s, respectively. Overall, low velocity of P, S waves observed in this sequence is ascribed to energy loss and intrinsic attenuation due to the prolific glass and high Fe contents and their intensely altered nature. Although, high order of attenuation is also noticed in few massive basalt types, either glassy or contain high proportion of chlorophaeite and other secondary silicates. Activities were mainly focused on Deccan volcanism and related fields (Fig. 1) and produced vast information (Table 1), however, to identify forthcoming research problems, an attempt has been made to review significant research contributions published in the journals of national and international repute in last five years. Outcome of the work is summarized and discussed under subsequent sections:

Tholeiitic and Alkali Basalt-Carbonatite Associations

The DVP dominantly composed of tholeiitic basalts (with a minor amount of alkaline, carbonatite, and silicic rocks) and is sub-divided into low (TiO₂ < 2.5; Ti/Y < 500) and high (TiO₂ > 2.5; Ti/Y > 500) Ti basalt types and inferred involvement of multiple mantle components assigning derivation from the depleted mantle sources (Prasanth *et al.*, 2019). Alkaline rocks are commonly associated with the rift zones. Most of the researches carried out in the past five years were focused on the pericratonic rift basin in the Kutch area of northwestern India (Ray *et al.*, 2016; Cucciniello *et al.*, 2018). Both alkali and tholeiitic basalt types occur together in this area. Former is cropping out as an isolated, relatively small, eroded, cinder cone-like volcanic plugs within a linear belt in

central part, whereas, later occurs in the form of sub-horizontal flows in the southern part of the Kutch basin. Alkaline and tholeiitic magma types require varied degree of partial melting and mantle sources, however in a mantle plume scenario; alkaline magmatism precedes and possibly follows the main phase of tholeiitic magmatism. Parisio *et al.* (2016) established existence of varied mantle sources for the synchronously formed alkaline and tholeiitic magmas and require sub-continental lithospheric mantle involvement at the time of Deccan magmatism. Both alkaline and tholeiitic magmatism occurred during early and late phases, therefore, their derivation from same mantle source is highly unlikely. Ray *et al.* (2016) reported disc-shaped spinel peridotite mantle xenolith-xenocrysts (of spinel lherzolite and spinel wehrlite compositions) bearing monogenetic alkali basaltic plugs (few connected to feeder dykes) and tholeiitic basalt lava flows from the fault controlled uplifted block of the Kutch basin. These observations were supported by prolifically present feeder dykes (with greater width) which contain large xenocrysts and xenoliths with thick alteration aureole around olivine xenocrysts. Commonality in the chemico-mineralogical attributes of these isolated alkali basalt is suggestive of co-genetic nature, implying for a common source, age and eruption mechanism. Alkali basalt contains, fractured olivine (Fo>90) fragments (Figs. 2 and 3) with embayed margins as xenocryst and less forsteritic (~Fo⁸⁰) olivine grains as phenocrysts (compared to groundmass grains). Alkali magma ascended through

Fig. 2: Photomicrograph of olivine (Ol) with alteration veins and melt inclusions (MI). Source: Chatterjee and Sheth (2015)

Table 1: Location-wise summarized published work on Deccan volcanism and related fields

Locations	Summary of the work done	References
Dating		
1.	Post-K/PB younger ^{40}Ar - ^{39}Ar ages of the Mandla lavas: Implications for the duration of the Deccan volcanism,	Shrivastava <i>et al.</i> (2015)
2.	$^{40}\text{Ar}/^{39}\text{Ar}$ ages of alkaline and tholeiitic rocks from the northern Deccan Traps: implications for magmatic processes and the K-Pg boundary	Parisio <i>et al.</i> (2016)
3.	Mercury anomaly, Deccan volcanism, and the end-Cretaceous mass extinction	Font <i>et al.</i> (2016)
4.	$^{40}\text{Ar}/^{39}\text{Ar}$ dating of the Mumbai tholeiites and Panvel flexure: intense 62.5Ma onshore-offshore Deccan magmatism during India-Laxmi Ridge-Seychelles breakup	Pande <i>et al.</i> (2017)
5.	Recurrent Early Cretaceous, Indo-Madagascar (89-86 Ma) and Deccan (66 Ma) alkaline magmatism in the Sarnu-Dandali complex, Rajasthan: $^{40}\text{Ar}/^{39}\text{Ar}$ age evidence and geodynamic significance	Sheth <i>et al.</i> (2017)
6.	U-Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction	Schoene <i>et al.</i> (2015)
7.	Feeder and post Deccan Trap dyke activities in the northern slope of the Satpura Mountain: Evidence from new ^{40}Ar - ^{39}Ar ages	Shrivastava <i>et al.</i> (2017)
8.	Geochemistry and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of the Nandurbar Dhule mafic dyke swarm: Dyke sill flow correlations and stratigraphic development across the Deccan flood basalt province	Sheth <i>et al.</i> (2018)
9.	Mineralogy, geochemistry and ^{40}Ar - ^{39}Ar geochronology of the Barda and Alech complexes, Saurashtra, northwestern Deccan Traps: early silicic magmas derived by flood basalt fractionation	Cucciniello <i>et al.</i> (2018)
10.	U-Pb constraints on pulsed eruption of the Deccan Traps across the end-Cretaceous mass extinction	Schoene <i>et al.</i> (2019)
Petrology and Geochemistry		
11.	Origin of the Powai ankaramite, and the composition, P-T conditions of equilibration and evolution of the primary magmas of the Deccan tholeiites	Chatterjee and Sheth (2015)
12.	End-Cretaceous extinction in Antarctica linked to both Deccan volcanism and meteorite impact via climate change	Petersen (2015)
13.	Natural glass from Deccan volcanic province: an analogue for radioactive waste form.	Rani <i>et al.</i> (2015)
14.	Triggering of the largest Deccan eruptions by the Chicxulub impact	Richards <i>et al.</i> (2015)
15.	The geochemistry of Indian bole horizons: palaeoenvironmental implications of Deccan intravolcanic palaeosurfaces	Widdowson <i>et al.</i> (2015)
16.	Mantle xenolith-xenocryst-bearing monogenetic alkali basaltic lava field from Kutch Basin, Gujarat, Western India: Estimation of magma ascent rate	Ray <i>et al.</i> (2016)
17.	Long-term performance assessment of nuclear waste and natural glasses in the geological repository: A geochemical modelling	Rani <i>et al.</i> (2016)
18.	Comparison among Ethiopia-Yemen, Deccan, and Karoo continental flood basalts of central Gondwana: Insights on lithosphere versus asthenosphere contributions in compositionally zoned magmatic provinces	Natali <i>et al.</i> (2016)
19.	Tectonomagmatic setting of lava packages in the Mandla lobe of the eastern Deccan volcanic province, India: palaeomagnetism and magnetostratigraphic evidence	Pathak <i>et al.</i> (2016)
20.	Giant plagioclase basalts: Continental flood basalt-induced remobilization of anorthositic mushes in a deep crustal sill complex	Sheth (2016)
21.	Geochemical Modeling and Experimental Studies on Mineral Carbonation of Primary Silicates for Long-term Immobilization of CO_2 in Basalt from the Eastern Deccan Volcanic Province	Shrivastava <i>et al.</i> (2016)
22.	At last! Giant plagioclase basalt from Sagar district	Alexander and Purohit (2019)

23.	A 1251m-thick Deccan Flood Basalt Pile Recovered by Scientific Drilling in the Koyna Region, Western India	Mishra <i>et al.</i> (2017)
24.	The Subsurface Megascopic Characteristics of Basalt and Basement Rocks from Koyna-Warna Area of Maharashtra, India	Sinha <i>et al.</i> (2017)
25.	Mineral carbonation reactions under water-saturated, hydrothermal-like conditions and numerical simulations of CO ₂ sequestration in tholeiitic basalt of the Eastern Deccan Volcanic Province, India	Kumar <i>et al.</i> (2017)
26.	Ultrasonic P- and S-Wave Attenuation and Petrophysical Properties of Deccan Flood Basalts, India, as Revealed by Borehole Studies	Vedanti <i>et al.</i> (2018)
27.	Thermodynamic Modelling and Experimental Validation of CO ₂ Mineral Sequestration in Mandla Basalt of the Eastern Deccan Volcanic Province, India	Kumar and Shrivastava (2019)
28.	Tholeiitic basalts of Deccan large igneous province, India: An overview	Prasanth <i>et al.</i> (2019)
Lava-flow stratigraphy		
29.	Polycyclic aromatic hydrocarbon compound excursions and K/Pg transition in the late Cretaceous–early Palaeogene succession of the Um Sohryngkew river section, Meghalaya	Pal <i>et al.</i> (2015a)
30.	Physils and organic matter-basepalaeoenvironmental records of the K/Pg boundary transition from the late Cretaceous–early Palaeogene succession of the Um-Sohryngkew River section of Meghalaya, India	Pal <i>et al.</i> (2015b)
31.	A multi-proxy approach to decode the end-Cretaceous mass extinction	Punekar <i>et al.</i> (2015)
32.	Environmental changes during the Cretaceous–Paleogene mass extinction and Paleocene–Eocene Thermal Maximum: Implications for the Anthropocene	Keller <i>et al.</i> (2017)
33.	Study on the Relationship Between Deccan LIPs and Chicxulub Crater Based on “Collisions Aggregation Effect”	Chenming and Demin (2018)
34.	The eruptive tempo of Deccan volcanism in relation to the Cretaceous–Paleogene boundary	Sprain <i>et al.</i> (2019)
35.	State shift in Deccan volcanism at the Cretaceous–Paleogene boundary, possibly induced by impact	Renne <i>et al.</i> (2019)

Fig. 3: Photomicrograph of alkali basalt type from the Kutch area showing olivine xenocryst with fractures filled up with glassy groundmass. Microphenocrysts and groundmass olivine grains are also present along with the olivine xenocryst. Abbreviations: Ol(x)-olivine xenocryst; Ol(mp)-microphenocryst of olivine. Source: Ray *et al.* (2016)

Fig. 4: Giant plagioclase basalt from Bijasan Ghat showing well-developed, lath-shaped plagioclase megacrysts (5 cm in length). Source: Sheth *et al.* (2016)

the lithosphere with faster rate, where mantle xenoliths were broken-up into smaller fragments. These processes were considered as major causative factors for the K/Pg mass extinction. Chatterjee and Sheth (2015) studied ankaramite from Powai in the Bombay area which contains zoned olivine crystals. Primary magmas for this area as well as voluminous Ambenali and Mahabaleshwar Formation tholeiites in the

Western Ghats representing primitive tholeiites (MgO 8.74-11.77 wt%, Mg# 70-74). Such magma types last equilibrated with the mantle peridotite at a temperature and pressure ranging between 1268-1332°C ($\pm 12^\circ\text{C}$) and 8.0-13.0 kb (± 0.8 kb) corresponding to the depth between 30-49 km (± 3 km), respectively. Moreover, primary magmas originated by $\leq 5\%$ batch melting of the mantle and these magma types underwent olivine gabbro fractionation. As a result, mafic cumulate piles (Ol+Cpx+Opx) produced at the bottom of magma chambers. Later tholeiitic magma batches penetrated cumulate piles which led to the formation of cumulate rich ankaramite and underwent dissolution of the orthopyroxene and subsequent crystallization of augite, olivine, and plagioclase. The voluminous Ambenali and Mahabaleshwar tholeiites of the Western Ghats last equilibrated with the spinel lherzolite mantle which was neither Fe rich nor anomalously hot.

Giant Plagioclase Basalt

The Giant Plagioclase Basalt (GPB) containing long (~ 5 cm) plagioclase megacrysts (Fig. 4) attending as a marker horizon for the upper of the Deccan stratigraphic formational boundaries. These megacrysts form anorthositic mushes embedded within the ferrodioritic interstitial glassy groundmass. On the basis of unusual occurrence of such type of basalt, Sheth (2016) proposed a model, where residency period of ~ 15 ka in a deep crustal sill complex was postulated for the magma to grow plagioclase megacrysts before being erupted. Of late Alexander and Purohit (2019) reported GPB from lava flows in the northeastern basalt in the Sagar area of Madhya Pradesh. However, stratigraphic correlation between these two GPB horizons and details pertaining to lava flows (which lie immediately below as well as above) is lacking in the literature.

DVP Associated Anorogenic, Intra-plate Silicic Magmatism

Cucciniello *et al.* (2018) recognized advanced fractional crystallization of basaltic magmas, crustal assimilation coupled with fractional crystallization, partial melting of basalt and anatexis of old basement crust as important processes responsible for their formation. Sr-Nd-Pb isotopic data in conjunction with the geochemical data, assigned process of multiple magma injections to the ENE-WS trending Nandurbar-

Dhule tholeiitic dyke swarms (Sheth, 2018). These dykes served as feeders to few Western Ghats and Saurashtra lavas, located ~ 200 km away from the dyke swarms. Moreover, compositionally distinct (high TiO_2), but, majority of them are isotopically akin to Mahabaleshwar and Panhala Formations of the upper Western Ghats that lie within a narrow isotopic array and represent distinctive chemical signatures somewhat comparable to distant (~ 600 km) dykes, sills, and lavas of the Pachmarhi, Shahdol, and Mandla areas in the Satpura and Narmada regions in the eastern Deccan Traps. Distinctive isotopic signatures of Nandurbar-Dhule tholeiitic dyke swarms were somewhat similar to the dykes, sills, and lavas of the Pachmarhi (Shrivastava *et al.*, 2008; Kumar and Shrivastava, 2009) and Mandla (Shrivastava, 2014) areas, located ~ 900 km to the east, thus, justify a separate entity of eastern Deccan lava stratigraphy.

Age and Duration of Deccan Volcanism

Earlier reported Deccan basalt ages recognized that bulk of magma was emplaced within a period of 67 - 65 Ma, however, with the exception of some early alkaline activity in the Cambay graben at 69 Ma. But, Shrivastava *et al.* (2015) assigned significantly younger ages of 63-65 Ma (weighted mean age of 64.21 ± 0.33 Ma) to the stratigraphically controlled ~ 900 m thick Mandla lobe succession (which contains 37 lava flows) on the eastern margin of Deccan volcanic province. New ages are consistent, however, with the geochemical correlation of the Mandla lobe lavas with the uppermost succession (Poladpur-Ambenali-Mahabaleshwar Formations) of southwestern Deccan Traps, indicated that this post KPBY youngest phase of flood basalt activity erupted over much of the province. The Deccan volcanic activity occurred in several phases - an earlier phase was accountable for the formation of great western succession of lava flows, whereas, later phase resulted in the formation of terminal lava flows of the southwest region and entire succession of the Mandla lobe in the east (Shrivastava *et al.*, 2015). The post-KPBY younger ^{40}Ar - ^{39}Ar ages of the Mandla lavas have serious implications on the duration of Deccan volcanism (Shrivastava *et al.*, 2015). A large number of Deccan basalt dykes associated with the east-west trending Narmada-Tapti-Son lineaments are supposedly synchronous with Deccan volcanic eruptions. But, in the northern slope of Satpura

Mountain range (~800 km NE of the Western Ghats escarpment), Shrivastava *et al.* (2017) recognized feeder and post-Deccan Traps dyke activities solely on the basis of new ^{40}Ar - ^{39}Ar ages of 66.56 ± 0.42 and 56.95 ± 1.08 Ma from two distinct dykes (Fig. 5) which cut across the lava flows near Mohpani and Olini villages, respectively. The new age data on the Mohpani dyke yielded an age of 66.56 ± 0.42 Ma, which is earlier to or contemporaneous with the nearby Mandla lavas. It is evident that the lava flowed through major fractures/faults and emplaced as dykes and served as conduits for the lava flows. Thus, dykes possibly served as feeders. The new ages are also consistent with geochemical correlation of the Mandla lavas and with uppermost Poladpur, Ambenali and Mahabaleshwar Formation lavas of the southwestern Deccan (Shrivastava *et al.*, 2014). The dyke near

Olini village represents an age of 56.95 ± 1.08 Ma which is much younger and represents the terminal stage of dyke activity.

Recent ^{40}Ar - ^{39}Ar ages from the northern portion of the DVP provided new constraints on the relationship between two magma series and on the evolution of Deccan magmatism (Parisio *et al.*, 2016) and further assigned an age of 65.86 ± 1.68 Ma for the first stage of magmatism in the Rajpipla area. Besides this, the Rajpipla basalt and Pavagadh rhyolite (64.9 ± 0.8 Ma) represent a maximum and minimum duration of the tholeiitic Deccan magmatism of 3 Ma and <1 Ma, respectively. Conversely, alkaline magmatism lasted within 4 Ma, starting from 69.62 ± 0.08 Ma to 65.25 ± 0.29 Ma. Significantly, recalculated ^{40}Ar - ^{39}Ar ages suggested that the magmatic activity started at the boundary between magnetic chrons C31r and C31n with the emplacement of the Sarnu Dandali and Mundwara complexes, and Deccan magmatism lasted at least 4 Ma. Moreover, ^{40}Ar - ^{39}Ar ages of Parisio *et al.* (2016) for the Pavagadh complex and Phenai Mata alkaline rocks indicated incidence of late-phase of magmatism in the northern Deccan volcanic province. ^{40}Ar - ^{39}Ar ages of Pande *et al.* (2017) for the Mumbai tholeiitic and Panvel flexure flows, and post-flexure dykes yielded similar ages of 62.5 Ma and suggested rapid formation of Panvel flexure at 62.5 Ma. These observations are congruent with the Dongri rhyolite flow ages of 62.5 Ma from the uppermost part of Mumbai volcanic sequence. Post-rift magmatism ages of 60.8-60.9 and 60-61 Ma assigned to the Manori trachyte and Gilbert Hill basalt in the Mumbai area, respectively. Thus, these units were coeval with the rift-to-drift transition of breakup between the Seychelles and the Laxmi Ridge-India, thus clearly recognize pre-, syn- and post-rift Deccan magmatism associated with the breakup of Seychelles from the Laxmi Ridge and India. The longest (~79 km), Nandurbar-Dhule tholeiitic dyke swarms in the Deccan Traps represent ^{40}Ar - ^{39}Ar ages of 67.06 - 63.43 ± 0.48 Ma, suggestive of ≥ 2.5 emplacement span under regional crustal extension (Sheth *et al.*, 2018).

Sheth *et al.* (2017) reported new ^{40}Ar - ^{39}Ar ages of 88.9-86.8 Ma from the Sarnu-Dandali alkaline complex, Rajasthan and suggested that the syenite, nephelinite, phonolite and rhyolite rocks were much older than Deccan basalt (66 Ma) rock types present

Fig. 5: Field photographs showing dykes located (a) near Olini (sample P7) and (b) Mohpani villages (sample P18) in Betul area. Chilled contact zones vary in thickness from 3 to 8 cm, lying between the dyke and lava flows marked in the photograph. Source: Shrivastava *et al.* (2017)

within the complex, thus, assigned two diverse emplacement episodes entailing a time lag of ~ 20 Ma in the late Cretaceous Period (for these two distinctive rock groups). Pande *et al.* (2017) on the basis of $^{40}\text{Ar}/^{39}\text{Ar}$ ages suggested polychronous emplacement for the Mundwara alkaline complex, located ~ 120 km southeast of Sarnu-Dandali in Rajasthan. Moreover, 84-80 Ma ages obtained from the Mundwara alkaline complex represents post-breakup stages of the Indo-Madagascar. Thus, akin to the Mundwara complex, Sarnu-Dandali complex is also polychronous in nature and characterized by

periodically replenished alkaline magma. Temporally, both the complexes show comparable evolution from early to late Cretaceous period and spatially record Indo-Madagascar flood basalt volcanism to northwestern India. Of late, Schoene *et al.* (2019) estimated Deccan eruption rates using U-Pb zircon as chronometer. They recognized four major eruptive phases (Fig. 6); each lasted for ≤ 100 ka and separated by periods of relative volcanic quiescence. Moreover, one of the phases initiated tens of thousands of years prior to both the bolide impact and the K/Pg extinction. Coincidental with the second major eruptive phase,

Fig. 6: Major eruptive phases, timing of the K/Pg transition events and organo-molecular compounds (associated with the marine Um-Sohryngkew river section) calibrated with respect to biozonation and GSSP El kef (Tunisia) sections (as a reference) further correlated with the Jhilmili and Anjarintertrappeans and EDVP bole beds successions. **Data Source:** Bhandari *et al.* (1987); Mukhopadhyay (2008, 2009, 2010, 2012a,b, 2013); Shrivastava *et al.* (2013); Pal *et al.* (2015a-c), where, * = *Parvularugoglobigerinaeugubina*, ** = *Guembelitraetacea*, *** = *Plummeritahantkeninoides*, **** = *Pseudoguembelinahariaensis*, 1 = Schoene *et al.* (2019); 2 = Shrivastava *et al.* (2015), 3 = Puneekar *et al.* (2016), 4, 5 = Pal *et al.* (2015 a,b), 6 = Shrivastava *et al.* (2013), 7 = Keller *et al.* (2009), 8 = Pal *et al.* (2013), 9 = Pal *et al.* (In press a), 10 = Bhandari *et al.* (1987), 11 = Shrivastava and Ahmad (2005); 12 = Pal *et al.* (In press b), 13 = Keller and Lindinger (1989), 14 = Gross (2017). **Abbreviations:** Geol. Periods = Geological Periods, Mag. Chrons = Magnetic chrons, Erupt. = eruption, Bus. = Bushe, Ocean acid. = Oceanic acidification, Carb. crisis = carbonate crisis, LMW PAH = low molecular weight polycyclic aromatic hydrocarbon compounds, SA = short chain n-alkanes, HMW PAH = high molecular weight polycyclic aromatic hydrocarbon compounds, Ce anom. = Ce anomaly, Dec. = Deccan, Vol. = Volcanism, GH effects = Greenhouse effects, *P. elegans* = *Pseudotextulariaelegans*, Brack.-Marine = Brackish-Marine, Intert. = Intertrappean, Ostro. = *Ostrocod*, Plank. Foram. = Planktonic foraminifera, incur. = incursion, Mont. = montmorillonite, Lacust. = Lacustrine, Ir. anom. = Iridium anomaly, Aliph. = aliphatic, NAP = naphthalene, A = anthracene, Pyr = pyrene, +ve = positive. Symbols: and denotes transgression and regression, respectively

Poladpur Formation eruption began tens of thousands of years before, but, peaked out at the K/Pg mass extinction event which continued after it, but in a subdued manner. Finding out Chicxulub impact signature (if any) may provide a precise stratigraphic reference point within Deccan stratigraphy.

Palaeomagnetism and Magnetostratigraphy

In the Mandla area of Eastern Deccan Volcanic Province (EDVP), flow-by-flow palaeomagnetic measurements (Pathak *et al.*, 2016) for the 37 lava flows (from the ~ 900 m-thick, isolated lava pile) revealed multiple magnetic polarity events: implying for the C29n-C28r-C28n magnetostratigraphy. However, based on recent palaeomagnetic data from Deccan dyke swarms of the Mumbai area, Basavaiah *et al.* (2018) suspected more reversals than three Chrons (n-r-n) flow magnetostratigraphy. These results when traced out from section to section, maintaining the order of superposition, resolved that the lava packages of contrasting characters are juxtaposed near Deori area. In Dindori and also towards south, the distinct lava packages are juxtaposed and explained by the presence of four normal post-Deccan faults in the Nagapahar, Kundam-Deori, Dindori and Badargarh-Amarkantak sectors, thus, justify structural complexity with the vertical shifts of 150-300 m. To some extent, observed magnetic polarity bias (transitional direction) might be the result of combined effects of tectonic disturbance in the area, lesser availability of the unaltered lava flows and their altitude based correlation. Considering the highly wavy palaeo-surfaces and faulting due to post-Deccan isostatic adjustments over a distance of ~ 800 km along the strike length, there is a possibility of disorder in the stratigraphic heights of lava packages, which, therefore, constrains the altitude-based correlation of lava packages over such a vast area.

Magnetostratigraphic correlation of the Mandla lavas with that of the main DVP is mainly based either on: (a) magnetic polarity correlation as a function of altitude or (b) available $^{40}\text{Ar}/^{39}\text{Ar}$ ages of the Mandla lava flows. Later correlation is solely based on new $^{40}\text{Ar}/^{39}\text{Ar}$ ages (Shrivastava *et al.*, 2015) which are consistent with the GPTS (Cande and Kent, 1995; Gradstein *et al.*, 2012), thus, pointing to the idea that the entire Mandla lava package were laid down in the chron C29n-C28r-C28n. The later correlation

seems to be more reliable as it lies well within the GPTS of Gradstein *et al.* (2012). As compared to the southwestern lavas, Mandla lavas erupted at different times. In view of the palaeomagnetic results, it is suggested that the Mandla lavas erupted from different feeder system(s). Proposed C29n-C28r-C28n magnetostratigraphy of the Mandla lavas revealed that they are significantly younger than the majority of main DVP lava sequences documented from the Western Ghats.

Magnetic chron reversals in conjunction with field and chemical data supported these findings (Pathak *et al.*, 2016). Further, compositionally these lavas are akin to Bushe, Poladpur, Ambenali and Mahableshwar Formational lavas, and follow the same stratigraphic order as in the Western Ghats. Alternating field (AFD) and thermal demagnetizations (THD) isolate the normal mean direction of the Mandla lobe. The Virtual Geomagnetic Pole (VGP) position determined for these lavas, when compared to the Deccan Super Pole, indicates concordance with the main DVP, thus, assigning eruption ages close to the KPB for the eastern and western Deccan Traps.

Deccan Volcanism and K/Pg Transition Events

Punekar *et al.* (2016) discussed excessive amount of CO_2 and SO_2 release during the most violent phase of Deccan volcanism introduced into the atmosphere which was the causative factor for carbonate crisis in the oceans and severe stress to the marine calcifiers, ultimately led to the mass extinction (Fig. 6). Highly stressed environment initiated for planktic foraminifera is evidenced by ~50 cm below the KPB layer at Bidart (France) and Gamsbach in Austria and ~ 4.5 m below the KPB at Elles in Tunisia. Moreover, corresponding interval in India documented stronger carbonate dissolution effects in the intertrappean sedimentary units which lie between the longest lava flows and culminated with the mass extinction. Based on these observations, Punekar *et al.* (2016) inferred that the widespread dissolution event stratigraphically matches with the climatic cooling and followed by the late Maatrichtian global warming. These major events perhaps were attendant to Deccan volcanism induced ocean acidification (Fig. 6). Further, late Maatrichtian CF1 zone in the former two areas revealed events within the latest ~160 ka of late Maatrichtian and considered as critical as far as role

of the Deccan volcanism in global high stress environments is concerned. Sudden rise in temperature ($>140^{\circ}\text{C}$) during the formation of illite in the upper part of biozone CF3 is comparable to the KPB layer of Caravaca section of Spain (Pal *et al.*, 2015a). Moreover, humid tropical to arid-semiarid climatic and thermal variation across the succession were linked to the contemporaneous Deccan volcanic activities. Total organic carbon together with the short chain *n*-alkane and fatty acid spikes (Fig. 6) are concomitant with the sudden rise in the palaeotemperature ($>140^{\circ}\text{C}$) of the yellowish brown organic rich clay layer in biozone CF3 (Pal *et al.*, 2015b; 2019a). These organic macro-molecules reflected global fire, induced by the heat supplied by late Cretaceous Deccan extrusions initiated prior to the KPB, however, the main episode of Deccan volcanic activity occurred ≥ 300 ka earlier or after the KPB itself. Punekar *et al.* (2016) provided evidence of Deccan-related environmental changes at the onset of K/Pg mass extinction from Bidart section (France). In this area, the sedimentary layer which lie immediately ~ 80 cm below and ~ 50 cm above the KPB layer contains anomalously high Hg concentrations (>2 orders of magnitude) coincidental with the low magnetic susceptibility interval (Font *et al.*, 2016). The K/Pg mass extinction is universally attributed to the Chicxulub impact; however Deccan volcanism contributed to as a major factor (Keller *et al.*, 2017). Although, the Hg anomalies pointed out that the major Deccan eruptions accelerated during last 10 ka and reached to its maxima which led to mass extinction. Thus, Chicxulub asteroid impact (Mexico) and gigantic Deccan volcanic eruptions were proposed as the major causes for the end-Cretaceous mass extinction, including sudden demise of nonavian dinosaurs. But, high resolution U-Pb zircon ages determined by Schoene *et al.* (2015) provided an idea that the main phase of eruptions initiated ~ 250 ka prior to the KPB, where >1.1 million km^2 of basalt erupted in ~ 750 ka. These results are consistent with the idea that the Deccan volcanism contributed to the latest Cretaceous environmental change and the biologic turnover that culminated in the marine and terrestrial mass extinctions. However, the main phase of Deccan volcanism occurred at 66 Ma, but, its activity started ~ 0.5 Ma prior to and terminated after the KPB and the Chicxulub impact dated at 66.04 ± 0.09 Ma and 66.04 ± 0.05 Ma,

respectively (Sprain *et al.* 2019). A noticeable $7.8 \pm 3.3^{\circ}\text{C}$ warming which was synchronous with the onset of Deccan volcanism, however, a second, smaller warming was at the time of meteorite impact (Petersen *et al.*, 2016). Although, eruption pattern, as well as rate of Deccan volcanism at the KPB was primarily affected by the Chicxulub impact (Renne *et al.*, 2015; Richards *et al.*, 2015). To understand relationship of the Deccan volcanism across the KPB at Um Sohrynkew and Jhilmili sections in India, Sial *et al.* (2017) employed Hg, Hg/TOC and Al_2O_3 as proxies for volcanism and recorded true Hg anomalies and three prominent Hg/TOC spikes: (1) within the CF2 planktic foraminiferal biozone, (2) at the KPB, and (3) within the P1a planktic foraminiferal sub-zone of the former as well as in the Jhilmili sections. They further concluded that Hg anomalies possibly attributed to strong volcanic incidences of the Deccan phase-2 (started 250 ka before the KPB and lasted for 750 ka). These incidences were accountable for prolific sulfuric aerosols and carbon dioxide emissions. Moreover, Hg isotopic spike 2 in Meghalaya KPB layer, spike 1 in CF2 biozone and spike 3 in Jhilmili are consistent with the peak volcanic Hg emissions, thus Hg enriched in paleoenvironment at three distinct stages during the Deccan phase-2. However, Mukhopadhyay *et al.* (2017) pointed out that the KPB reported by Sial *et al.* (2016) is not compatible with the existing planktonic foraminiferal succession across K/Pg boundary in the Um Sohrynkew River section, Meghalaya India. Owing to the meteorite impact and the Deccan Traps formed by the collisions, aggregation effect of the Chicxulub crater impact triggered massive mass extinctions (at 65 Ma of the K/Pg boundary) and accelerated the Indian Plate drift (Chenming *et al.*, 2018). The eruptive pulse of Deccan volcanism studied with reference to the KPB concluded that the late Cretaceous records of climate change coincided temporally not with the major and most violent phase, but, with the eruption of smallest Deccan Trap phases (Sprain *et al.*, 2019). They opined that either the release of climate-modifying gases was not directly related to eruptive volume or Deccan Traps volcanism, therefore, Deccan volcanism was not the source of late Cretaceous climate change. However, diverse ideas emerged out of the studies (Sprain *et al.* 2019; Schoene *et al.*, 2019) on relative timing of Deccan Traps emplacement and mass extinction. On the basis of

age data-sets, the stratigraphic position of KPB was assigned within Deccan Traps stratigraphy. But the subtle difference in placement significantly alters the balance of accountability between the bolide impact and the Deccan volcanic events (Burgess, 2019). Thus, finding out Chicxulub impact signature (if any) may provide a precise stratigraphic reference point within Deccan stratigraphy.

Infra-/interflow Volcanic Bole Beds

Widdowson *et al.* (2015) discussed Deccan intra-volcanic bole horizons, representing weathered products formed at the time of major hiatuses between two successive major volcanic episodes. Both bole beds and altered lavas represent a comparatively early stage of weathering because residual elements, such as Al and Fe are closer to the fresh basalt than the laterite. Nevertheless, there is clear evidence in support of significant chemical alteration as the more mobile elements such as Ca and Na have been substantially removed. Several Deccan Traps associated bole beds are in fact weathered pyroclastic material, where pyroclastic content of the basaltic succession is very large. A significant pyroclastic input during Deccan eruptions has important palaeoenvironmental implications for the fate of late Cretaceous fauna and flora that existed in the Peninsular India.

Red bole horizons formed by pervasive sub-aerial weathering of the previously exposed igneous materials together with the locally associated lacustrine and fluvial sediments. Yet, unlike the lava sequences, intertrappean bole horizons have received little geological attention, although, it is accepted that the formation of these weathering horizons temporally represents greater part of the history of CFB provinces. Geochemical study of the weathered bole horizons established the role of elemental mobilization during chemical weathering, but indicated that the geochemical data cannot always be reconciled with the established patterns of elemental depletion (typical of alteration of a basaltic precursor). In addition, thin sections indicate that the fine-grained portions of some boles contain glass shards and fresh phenocrysts of a pyroclastic origin. Though, the Deccan intertrappean surfaces, all that resulted from the same endogenetic process (namely the development of lava fields during flood basalt volcanism), the saprolitic and pyroclastic

boles recorded two different types of palaeoenvironmental conditions. The former group formed by protracted, in-situ alteration of the lava surfaces during the periods of volcanic quiescence. By contrast, the cherty boles resulted from a 'blanketing' of the lava landscape by extensive ash fall-out which possibly led to the widespread destruction of established fauna and flora. Weathering studies of Shrivastava *et al.* (2017) on interflow volcanic boles from Mandla lobe, EDVP were primarily focused to trace out paleoenvironment and degree of pedogenic/non-pedogenic conditions that existed during the Deccan volcanism. Owing to limited time intervals during successive eruptions, majority of the bole beds represent incipient to moderate weathering. However, few red and brown bole beds show baking effects rather than pedogenesis. Moreover, comparison of magnetic properties of bole from EDVP and WDVP shows significant differences in the weathering intensity, duration and heating related alterations from the upper flows. But, both EDVP and WDVP bole beds indicate similar first order paleoenvironmental conditions without any major pedogenesis. Crystallographic defects in the smectites of the Jhilmili intertrappean provided evidence of KPB transition induced environmental changes which include global warming, acid rains and pCO₂ rise in the atmosphere (Pal *et al.*, 2019b).

Applied Aspects

CO₂ Sequestration in Deccan Basalt

Shrivastava *et al.* (2016) reported CO₂ sequestration under natural conditions as evidenced by abundant thick limestone and inter-calcareous lithofacies that occur as infra (visibly below lava flows)/inter (between two lava flows) - trappean beds. On the basis of field observations, Shrivastava *et al.* (2016) considered tholeiitic basalt lava flows of the Mandla area as a suitable matrix for mineral carbonation reactions and for long-term storage of CO₂ as they contain high amount of reactant minerals such as Ca, Mg and Fe rich silicates. Computer based basalt-water-CO₂ interaction modeling and laboratory induced reactions under hydrothermal-like conditions form the basis of study. A series of experiments performed at accelerated conditions and post-experimental residues indicate formation of calcite, aragonite, siderite and magnesite. They observed that the basalt dissolution

rate was faster and reaction is primarily driven by the secondary mineral replacement and growth of minerals. Formation of carbonates is largely due to the breakdown of pyroxene, feldspar and glass.

Kumar *et al.* (2017) performed Deccan basalt-water-CO₂ saturated interaction experiments and numerical simulations under hydrothermal-like conditions. Data revealed appearance of calcite, aragonite, ankerite, huntite and siderite along with the secondary silicates. Moreover, tiny calcite crystals were developed over larger calcite crystals (Fig. 7A), incipient-disordered calcite formed with imperfections on its crystal faces (Fig. 7B) and cubic chabazite crystals surrounded by chlorite grains (Fig. 7C). Formation of disordered rhombic calcite in these experiments is ascribed to a partial carbonation reaction, whereas well-defined rhombic calcite crystal faces (Fig. 7A) formed over basalt is suggestive of a complete carbonation reaction. Experiments run for shorter time periods show formation of secondary carbonates which predominated over the silicates; however, with increased reaction times, carbonates no longer persisted in the system as they were

dissolved and replaced by silicates. As a result, thin layer of neo-formed SS form adjacent to the basalt grains. Thus, basalt grains restricted to form carbonates. In this manner, neo-formed SS act as barrier. As a result, basalt-water-CO₂ interaction rate is also reduced considerably and limiting availability of Ca, Mg and Fe cation to form carbonates (Kumar and Shrivastava, 2019a). Mixing trends (Kumar *et al.*, 2017) between basalt and Ca-Mg-Fe carbonates and chlorite/smectite were observed in case of phyllosilicates. However, ankerite, calcite and siderite recorded enrichment of (i) Ca, (ii) Fe-Mg and (iii) Fe. Secondary silicates formed adjacent to the basalt grains clog basalt-water-CO₂ interaction pathways, thus, reduced the amount of CO₂ mineralization. Formation of carbonates and secondary silicates is mainly influenced by time; however, pressure, pH and temperature play subordinate roles. Kumar and Shrivastava (2019b) further validated modeling results by the experiments run in laboratory time framework and resolved that the negative entropy (ΔS) and enthalpy ($\Delta_f H$) suggested feasibility of plagioclase, pyroxene and magnetite dissolution. The negative

Fig. 7: SEM images of secondary minerals showing (a) stepped growth of calcite and chlorite coatings on basalt, (b) siderite and incipient-disordered rhombic calcite grain with imperfections on crystal faces and (c) chlorite coatings over chabazite grain. Abbreviations: Cal = Calcite, Ch = Chlorite, Chb = Chabazite, DB = Deccan Basalt and Sm = Smectite. Source: Kumar *et al.* (2017)

Gibb's free energy ($\Delta_f G$), $\Delta_f H$ and ΔS values for calcite, dolomite and magnesite indicated spontaneous reaction, whereas, positive $\Delta_f G$ and negative $\Delta_f H$ and ΔS values of the siderite suggested non-spontaneous and opposing reactions. Calcite was the first carbonate mineral to form, but, at a faster rate. Magnetite dissolution begins after a time lag (not initiated along with the plagioclase and pyroxene). Kumar and Shrivastava (2019a) concluded that largely, thermodynamic models do not agree well with the experimental results as numerical models indicate larger carbonate growth. Additionally, transition state theory based models worked well to predict dissolution rates for most of the minerals, but, they over-predict growth of the secondary minerals. Rietveld refinement (RR) results indicate that, weakened Ca-O and C-O bond length led to calcite degeneration after 80 hours of experiments; therefore, no calcite persisted in the system. Further, the crystal structure of experimentally and naturally formed calcite and chabazite was alike to each other (Kumar and Shrivastava, 2019c). The mass balance estimates after each experiment run revealed that the maximum 30.75 mol % of ions from parent basalt reacted during carbonation reaction. As a result, 22.88 mol % of CO_2 mineralized in the form of carbonates (such as calcite and dolomite) at 100°C under 5 bar CO_2 for 70 h of experiment (Kumar and Shrivastava, 2019d).

Impact glass and Obsidian: A Natural Analogue of Nuclear Waste Glass

Rani *et al.* (2015) and Kumar *et al.* (2019) discussed Deccan basaltic glass (associated with the differentiation centers of vast basaltic magmas) for its suitability as a standard reference for radioactive waste containment. The suitability primarily depends upon alteration behavior under hydrothermal-like conditions. Alteration results when compared to the naturally altered glass show partial to complete release of all the ions; however, abundant release of Si and Na ions is noticed. Altered residue shows morphologies of smectite, montmorillonite and illite inside as well as outside of the secondary layers. Octahedral cation occupancies of smectite were found consistent with the dioctahedral smectite. The secondary layer composition indicates retention for Si, Al, and Mg cations, indicating their fixation, but remarkably high retention of Ti, Mn and Fe cation suggested release of very small amount of these

elements into the solution. By evolution of secondary layer and retention of less soluble ions, the obstructive effect of secondary layer increases and constant release rate initiated slowly to diminish with time. Process of devitrification along the cracks and formation of spherulite-like structures, yellowish brown palagonite, chlorite, calcite, zeolite and finally white coloured clay minerals largely correspond to altered obsidian that existed in the natural environment since inception (~ 66 Ma ago). Moreover, low elemental release rate from the glass matrix is suggestive of high order of chemical durability of glass. Obsidian, a natural analogue for the nuclear waste glass is durable enough to withstand natural environmental conditions for a period of ~ 300 years till the radioactivity of Ce isotopes is ceased. The chemico-mineralogical attributes of the obsidian are analogous to radioactive waste form; therefore, obsidian is suitable for safe disposal of high-level nuclear waste in the geological repository. Process and extent of palagonitization and the formation of smectite are comparable to the experimentally altered as well as naturally weathered glass. The microtextures and microchemistry of altered glass revealed evolutionary changes partly to complete alteration and growth of palagonite, smectite, illite, montmorillonite, calcite and zeolite.

Future Directions

Present review discusses several important findings covering almost all the aspects related to Deccan volcanism, however, a few important issues that remain to be addressed include:

1. Most of the new bulk, mineral chemistry, Nd-Sr-Pb isotopic and ^{40}Ar - ^{39}Ar age data-sets restricted to differentiation centers, located in the western part of Deccan volcanic province; however, such data is rare for the peripheral areas.
2. Comprehensive flow by flow stratigraphic framework, age and duration of volcanism for the peripheral areas and sub-surface Koyna-Warna-Panchgani sections are required with special reference to their stratigraphic correlations with the main DVP to understand source, eruption mechanism, and rate of host magma ascended, age and duration of Deccan volcanism.

3. To find out possible link (if any) between the Sagar GPB and the type GPB section of the western DVP.
4. Parental magmas and the fractionation trends for various basalt suites required to be assessed particularly for the central and peripheral areas.
5. Mechanism to understand derivation of alkaline and tholeiitic magma from the mantle sources
6. To understand geodynamic setting of the magma suites with contrasting characters.
7. Lherzolite mantle equilibration trends need thorough investigations.
8. Timing of the dykes such as pre, syn or post to the lava flows is required to be resolved.
9. Inconsistency in the ages with southward migration of volcanism due to northward journey of the Indian plate above the Reunion hotspot need to be re-visited.
10. More age data is required to ascertain accurate timing of the periodically replenished alkaline magma with respect to Mundwara and Sarnu-Dandali complexes.
11. Flow-by-flow palaeomagnetic measurements and magnetostratigraphic correlation are required to understand structural complexities with special reference to palaeo-surfaces and faulting due to post-Deccan isostatic adjustments.
12. To find out possible link between the main phases of Deccan volcanic eruptions and the timing of the K/Pg transition events.
13. To understand late Cretaceous palaeoenvironmental implications (for the fauna and flora), pyroclastic input needs to be accessed thoroughly.
14. To establish Chicxulub impact signature as a precise stratigraphic reference point within the Deccan stratigraphy.

Conclusions

Present review on late Cretaceous Deccan volcanism and related issues concluded with the following remarks:

1. Petrography, mineral chemistry, whole-rock major, trace elemental and Nd-Sr-Pb isotopic data in conjunction with the ^{40}Ar - ^{39}Ar ages, revealed that the Deccan Traps associated silicic magmatism post-dates flood basalt eruptions. The Barda granophyre intrusions pre-dated intense and most prolific 66-65 Ma Deccan flood basalt phase by 3 to 4 Ma, thus, entailed a total duration of ~ 8 Ma. These observations are in conformity with the finding of Salil *et al.* (1997) and supportive of prolong duration of the Deccan volcanism (Shrivastava *et al.*, 2012).
2. Moreover, the 69-68 Ma Barda granophyre plutonism took place within-plate tectonic setting (Bhattacharya and Yatheesh, 2015). The voluminous basalt fractionation-derived silicic magmatism in Barda and Alech complexes suggested temporal evolution of the Deccan flood basalt volcanism. Further, magma evolution represents a pulsating mantle melting regime, where such activity continued for > 1 Ma. The Deccan volcanism is constrained by these ages and belongs to the magnetic chrons C31-C29. But, recalculated ages pointing towards initiation of the first phase of alkaline Deccan magmatism in Sarnu and Mundwara complexes in northern Deccan (Basu *et al.*, 1993) was coincidental with the boundary between the magnetic chrons C31r and C31n.
3. New U-Pb zircon age data (Schoene *et al.*, 2019) recognizes four major eruptive phases (Fig. 6); each lasted for ≤ 100 ka and separated by periods of relative volcanic quiescence. Moreover, one of the phases initiated tens of thousands of years prior to both bolide impact and the K/Pg extinction. Coincidental with the second major eruptive phase, Poladpur Formation eruption began tens of thousands of years before, but peaked out at K/Pg mass extinction event which continued after it, but in a subdued manner. Finding out Chicxulub impact signature (if any) may provide a precise stratigraphic reference point within the Deccan stratigraphy.
4. Stratigraphically, widespread dissolution event, climatic cooling, followed by the late Maastrichtian global warming (Punekar *et al.*, 2016) attendant

to Deccan volcanism induced ocean acidification and high stress environments.

5. Both modeling and experimental results revealed that maximum amount of carbonation of Deccan basalt is possible under short-term hydrothermal-like conditions. Suitability of silicic phase for nuclear waste disposal is also discussed.

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