J. Earth Syst. Sci. (2022)131 237
https://doi.org/10.1007/s12040-022-01993-z
© Indian Academy of Sciences

Preface

The Deccan Trap eruption during the end-Cretaceous is one of the most conspicuous global-scale geological events witnessed in the Indian Shield. Despite more than a century of research, a number of fundamental aspects related to the Deccan Traps, such as their (i) duration of eruption, (ii) link to mass extinctions associated with the K–Pg boundary, (iii) influence on the contemporary sedimentary environments, (iv) relationship with the associated, less voluminous, alkaline magmatism, (v) transport mechanism of dykes and lavas in far off domains, (vi) original spatial extent, (viii) origin (mantle plume, bolide impact or passive rifting), (ix) influence on the Indian lithosphere, and (x) comparison with other volcanic eruptions through space and time still remain unclear, conjectural and also widely debated. This special volume entitled 'Deccan Traps and other Flood Basalt Provinces – Recent Research Trends' contains a collection of 32 peer-reviewed original and review articles addressing some of these issues.

Prof. Gautam Sen (born 1952), a renowned Igneous Petrologist and Volcanologist, breathed his last on June 25, 2019, in New York, USA.

Prof. Gautam Sen (1952–2019)

Throughout his teaching and research career, Prof. Sen worked extensively on the flood basalt provinces of several parts of the globe, including the Deccan Traps. He has produced many students who are now actively working and professionally contributing in their respective fields of research. Prof. Sen was an alumnus of the University of Calcutta (where he did his graduation in 1971 and post-graduation in 1973). After completing his PhD in 1981 (on the topic 'Petrology of the Ultramafic Xenoliths on the Koolau Shield, Oahu, Hawaii') from the University of Texas, Dallas, he joined the University of California, LA, as a post-doctoral fellow to work in the domain of experimental petrology. Subsequently, he started his career as an Assistant Professor at the Florida International University (FIU) in 1984. At FIU, Prof. Sen founded and served as the Director of the Florida Center for Analytical Electron Microscopy (FCAEM), which houses some of the most advanced electron microscopes and continues to support and serve academia and industries in the USA. He spent most of his academic and research career building the Earth Science Department at FIU before he was appointed as a founding Vice Provost, Research and Graduate Studies, American University of Sharjah, UAE, during 2010–2014. He then joined as a Dean, School of Natural & Social Sciences, Lehman College, City University of New York (CUNY) and served this school till he breathed last. Prof. Sen's research has significantly improved our understanding of Hawaii and Deccan volcanism, as well as the origin of Mid Ocean Ridge and Ocean Island Basalts. By studying the sizes and chemical profiles of plagioclase crystals in Deccan Traps, Prof. Sen was amongst the first to propose a very short duration of Deccan volcanism. This special volume is a humble effort to pay homage to Prof. Gautam Sen, and hence it has come as no surprise to us that it attracted considerable

This article is part of the Topical Collection: Deccan Traps and other Flood Basalt Provinces – Recent Research Trends.
Published online: 09 November 2022

response from the Deccan and LIP enthusiasts and a summary of the contents is provided under:

A Naik et al. provided a geological account of the late-stage Deccan volcanism and plutonism of the Thane–Vasai region in the Panvel flexure zone. Gabbroic plutons are the major rock type of the area with subordinate granophyres. The Chena pluton shows transition from gabbro, gabbro with interstitial granophyre, to transitional gabbro-granophyre. Through petrography and mineral chemical data, they demonstrate that the granophyres are the products of extensive fractional crystallisation.

Using high-resolution gravity data, *Prasad et al.* came up with a three-dimensional crustal density model of Narmada–Tapti region. The model suggests the presence of high-density magmatic intrusions at Navsari near the west coast and Junapani near Khandwa area. Signature of high gravity anomalies and positive residual geoid undulation, bounded by major tectonic faults, highlights the intense crust–mantle interactions through multistage Deccan magmatism.

Gupta and Kumar have studied the lithospheric variation across the Deccan volcanic province (DVP) and Eastern Dharwar craton (EDC) through joint modelling of teleseismic RFs and surface wave dispersion data as well as using teleseismic relative residuals collected from 18 seismological stations. Based on the models, they interpret the lithosphere beneath the DVP to be $\sim$50–60 km thinner in comparison to that of EDC. The thinning has been linked to the breakup of the Gondwanaland prior to its interaction with the Deccan plume.

Sangode et al. combined rock magnetic and AMS studies over the paleo-lava channel body within the Deccan volcanic province to examine the lava flow-related fabric. AMS studies demonstrate that a combination of processes such as gravity settling, grain imbrications, viscous shear and competitive mineral readjustments penultimate to cooling are the deciding factors to impart the final petrofabrics in lava flows.

The Koyna dam in the western Deccan Traps, since its impoundment in 1962, has witnessed repeated artificial water reservoir-triggered seismicity. The triggered earthquakes continue until now and the region has experienced 22 events of M $\sim$5, over 200 events of M $\sim$4 and several thousand smaller events. *Gupta* provides a summary of the preliminary investigations leading to drilling of a 3-km deep pilot borehole at Koyna for near-field studies of earthquakes, and a few recent findings are also reported in this article.

Rama Rao et al. provide a comprehensive picture of the subsurface geology and structures beneath the Deccan Traps using gravity anomalies. Regional Bouguer gravity data of southern and central India indicates presence of granite–greenstone terrain akin to that from eastern Dharwar Craton. Similarly, gravity signatures indicate imprints of the Godavari rift zone and possible presence of Betul-like supracrustal belt in the eastern and central part of the Deccan volcanic province.

Chattopadhaya et al. have studied the peridotite xenoliths hosted in alkali basalts from the northwestern part of the Deccan volcanic province. Mineral chemical characters accord an upper mantle origin of the xenoliths. Trace element signatures of both silicate and carbonate metasomatism have been recorded from xenoliths. High heat flow and multiple metasomatic imprints demonstrate that the lithospheric mantle beneath western India suffered a complex multistage evolutionary history followed by rifting towards the end of the Mesozoic era.

Khanna and Arora have carried out detailed petrographic, bulk rock geochemical and Nd isotopic studies of basaltic tephra in the two deep borehole well-cores KBH-8 (Paneri) and KBH-10 (Udgiri), in the Koyna–Warna region of the Deccan volcanic province. Their trace element and isotopic characters are similar to those from the intra-plate tholeiitic flood basalts but differ from those of the Reunion plume and Deccan lava flows. Significantly, higher magnetic susceptibility and the corresponding induced-magnetic field in tephra compared to the underlying Deccan Traps further make the origin of tephra inexplicable.

Venkateshwarlu and Sangode, through anisotropy of magnetic susceptibility (AMS) record generated from KBH 07 borehole in Deccan Traps of the Koyna region, illustrate episodic variations in magnetic fabrics. The changes in magnetic mineralogy and fabrics are attributed to be controlled by density, lava thickness pattern and shift in the magmatic composition. These episodic variations characterised by multiple rock-magnetic and magnetic fabric parameters are suggested to constitute a robust tool for correlation to larger stratigraphic intervals.

Subba Rao et al. have acquired audio-magnetotelluric and magnetotelluric data across Aravalli and

Tural hot springs to generate geoelectrical structure beneath the geothermal zones. Different conductive anomalies have been observed, where shallow ones are related to upward propagation of meteoric water through faults/fracture zones. While mid-crustal conductivity anomalies are either associated with carbonate fluids released/trapped from the Deccan Traps or major fracture/fault zones through which the Deccan lavas have erupted.

Vasanthi has analysed the satellite gravity data over the Deccan volcanic province and the adjacent Dharwar Craton of the southern Indian Shield to understand the seismicity of the Koyna–Warna region and its relation with the subsurface structures existing beneath the thick lava flows. Several gravity-low areas have been identified as rift zones which contain metasomatised mantle and underplated magmatic materials. It has been proposed that seismic events are related to the metasomatic mantle episodes during magmatic underplating.

Kumar et al. report petrography, mineralogy, and geochemistry along with Sr–Nd isotopic compositions of tholeiitic dykes of the Multai area of central Deccan volcanic province. The Sr–Nd isotopic ratio of the dykes suggests contribution of a depleted mantle source in their origin and resemblance to those from the Mahabaleshwar and Poladpur formations of the southwestern Deccan volcanic province. P–T estimates of minerals indicate that fractionated melt for these dykes last equilibrated at P = 0.2–4.4 kbar and T = 1128–1169°C.

Sensarma and Gaur provide results of their study on rhyolite conglomerate hosted within the Bijli Rhyolite in the Dongargarh large igneous province of the Bastar Craton to constrain their origin. New field and petrography evidences support a pyroclastic origin related to Bijli volcanism, contrary to the initially suggested epiclastic or reprocessed origin. It has been suggested that rounding of pyroclasts may have taken place due to surface tension of hot crystallising molten magma and mechanical interactions of particles on steep slopes in such volcanic settings.

Pandey et al. provide a comprehensive review of a wide variety of Pre-, syn- and post-Deccan alkaline rocks by grouping these occurrences into seven subprovinces. Distinct shoshonitic characters for some of these alkaline rocks are also highlighted. Authors have also brought out the role of mixed mantle sources ranging from spinel to garnet stability depths along with the involvement of the lower degrees of partial melting in the genesis of Deccan alkaline rocks from the available geochemical and isotopic data. Source modification by subduction and depth of the lithosphere–asthenosphere boundary was also evaluated.

Nagaraju and Roy report the results of thermal conductivity measurements carried out for 55 thick core samples of the Deccan basalts recovered from various boreholes from the Koyna–Warna region. They demonstrate that the thermal conductivity values of basalts from the Koyna–Warna region are not only consistent with the basalts from the other parts of the Deccan volcanic province but also with those from other flood basalt provinces of the world, such as Parana–Etendeka, Columbia River, Karoo, etc.

Chandra et al. report petrography and geochemistry along with C and O isotopic compositions of carbonatite clasts in breccias from the Amba Dongar carbonatite complex of the Deccan volcanic province. Based on the $\delta^{13}C$ and $\delta^{18}O$ values, their mantle origin is postulated. The authors propose a genetic model that includes a liquid immiscibility of a parental silicate-carbonate melt at crustal depths followed by the intrusion of dykes and crustal doming, ultimately leading to the subsidence of caldera and extensive brecciation and the formation of the carbonatite ring dyke complex.

Shilpa Patil-Pillai et al. have assessed the geometric features and emplacement ages of the basaltic dykes exposed along the Bhetkheda–Mohana lineament within the central Narmada valley. They provide a $^{40}Ar/^{39}Ar$ age of 66.6 ± 0.5 Ma, which suggests these dykes were contemporaneous with the Deccan Trap eruption and would have acted as the feeder dykes for the emplacement of the Malwa Traps. A fissure-fed eruptive model for the Deccan flood basalts is proposed, which was not hitherto recorded previously.

Shukla et al. present petrographic and geochemical study on the basement granitoids from the drill core samples of the Koyna region. Based on the major minerals present, the granitoids have been classified as granitic gneisses and tonalities and recorded the signatures of brittle deformation and shearing effects. Geochemically, these basement granitoids are peraluminous with sodic character and fractionated rare earth element patterns indicating a strong control of fractional crystallisation in their genesis.

Baksi provides a summary of the geochemical and geochronological investigations on the Rajmahal Traps. He has critically commented on the problems with dating surface samples of the continental flood basalt provinces that are severely altered. He has attributed the isotopic heterogeneity in the lavas of the Rajahmundry Traps and Sylhet Traps, possibly owing to the various degree of chemical alteration.

Arora and Srinu used airborne LiDAR survey and derived a high-resolution digital elevation model to trace major lineaments representing fault zones. The Donachiwada Fault, which is one of the major causative faults for the Koyna earthquakes, is identified as a N–S trending arcuate feature extending to the south of the Warna reservoir. It is suggested that the frequent and largest earthquakes with $M \geq 5.0$ have epicentres at the junction of the southern end of the Koyna–Warna Fault and the South Warne Fault.

Misra et al. have studied the deformation features in the basement granitoids as deep as 1.5 km recovered from four different drill cores in the Koyna region. The presence of brittle deformational features such as fault breccias, fault gouge, slickensides and pseudotachylites revealed the proximity to a fault zone. They inferred the extension of the still-active Donichawadi fissure zone and provided evidence for multiple fracturing episodes and fault rock formation in a water-saturated intraplate fault zone.

Dhote et al. report wehrlite xenoliths hosted in the lamprophyre dykes from the Sarnu–Dandali alkaline igneous complex. Three mantle modification events have been identified wherein initially, the carbonate-rich fluids from the upwelling mantle metasomatised the mantle leading to the formation of secondary olivine and clinopyroxene. This event was followed by phlogopite veining as a result of the crystallisation of silica-undersaturated alkaline fluids. Subsequent melting of the metasomatised mantle led to the generation of alkaline magmas at the terminal phase of the Deccan basalts eruption.

Baksi provides a critical assessment of geochronological data and eruptive history of various sections of Deccan traps. His analysis highlights that bulk of the Deccan volcanic eruptions are confined to <1 Myr. This brief period of volcanic activity seems to be also valid for the tholeiitic material forming the Mandla lobe, the Malwa plateau and the Rajahmundry traps, and some of the felsic and alkaline rocks in the Deccan volcanic province.

Baksi presents new $^{40}Ar/^{39}Ar$ ages for the Grande Ronde and Wanapum basalts of the Columbia River continental flood basalt province and proposes that the Columbia River basalt eruption commenced at $\sim$16.6 Ma and continued for almost 700,000 years. The problems with previous geochronological results and methodology showing a relatively large duration of eruption (ca. $\sim$17–15 Ma) have been highlighted in this study.

Dey et al. have carried out multivariate statistical analysis on the basalts from the Khandwa region of the eastern Deccan volcanic province. The bulk level of crystallisation is demonstrated to have been broadly controlled by the ambient temperature. Early quenching is observed for the chilled dykes, whereas the crystallisation of the feeder dykes is found to be prolonged because the feeding dykes fed the lava flows. The compositional difference between the intercumulus liquid and cumulus crystals has been attributed to the rising magma and sudden transfer below the solidus.

R R Naik et al. have studied the morphology, composition, texture and crystallisation history of the plagioclase ultraphyric basalt from the Abor volcanics of the Eastern Himalaya. Based on the textural study, they proposed that the plagioclase and clinopyroxene macrocrysts crystallised from batches of plagioclase and plagioclase-clinopyroxene rich mush formed in the sub-volcanic magma chamber as a result of slow cooling. The occurrence of plagioclase ultraphyric basalt has been attributed to prolonged magma storage in the sub-volcanic chamber with variable amount of magma supply.

Singh et al. have probed the giant and small-size plagioclase crystals in the giant plagioclase basalt to understand the magmatic evolution of such rocks from the Kalsubai Subgroup of the Deccan volcanic province. They proposed that the anorthite component-rich plagioclase cores nucleated at mid-lithospheric depth at a higher temperature, which was followed by the crystallisation of anorthite component-poor rims at much lower temperatures and shallower depths. The authors have inferred the presence of supercharged feldspar-rich magma with a residence period of 3.2–17.4 ka.

Sangode et al. report a paleomagnetic inclination anomaly of +10 degrees during the Deccan main phase eruptions using a compilation of a large paleomagnetic database. The anomaly is interpreted to be a result of northward tilting during C29r followed by its restoration in C29n at $\sim$65 Ma. The authors have explained the anomaly and its application over the lithosphere of the Indian Shield through a plume–lithosphere evolutionary model.

More et al. have demarcated five zones within the Deccan volcanic province to evaluate the spatial geochemical variations. Applying geochemical modelling, they postulated that the plume–lithosphere interaction led to the mixing of plume-derived melts and the subcontinental lithospheric mantle melts. The authors argue that the mixing between the plume-derived melts and subduction-modified subcontinental lithospheric mantle-derived melts played a key role in geochemical heterogeneity observed in the Deccan volcanic province.

Pattabhiram et al. demonstrate that the giant phenocrysts basalts (GPBs) in the Deccan volcanic province are easier to be mapped and can be traced across several kilometres. As a result, the authors advocate for the efficiency of the GPBs to be used as marker horizons and highlight their significance in stratigraphic correlation. Accordingly, the stratigraphy of the sequence of lava flows in the western Deccan volcanic province has been revised, considering giant phenocrysts basalts as marker horizons.

Dey et al. from the cooling experimental data available in literature and also from their studies on olivine-depleted basaltic rocks from Khandwa, Eastern Deccan Volcanic Province, suggest $\sim$2–4% of olivine crystallisation in tholeiitic basalts world over. This insignificant level of olivine crystallisation has been ascribed to 'olivine decadence' and the authors provide petrographic support by way of its 'skeletal nature' with crystallographically oriented geometry.

Mukherjee et al. report petrological and geochemical studies on Bhanjada Bet hill, dominated by phonolites within the Great Rann of Kutch, western India. The phonolite has higher abundance of MgO (2.21–3.5%) over FeO (2.43–2.6%) and very high Mg# (65–69%), suggesting its primitive nature. Authors propose that Bhanjada Bet phonolite represents alkali magmatism of early Deccan age.

All the papers in this special volume have been reviewed at least by two or, at times, by even four reviewers. We sincerely thank the contributing authors and reviewers for their time and effort. We also thank the Editor of Publications (Indian Academy of Sciences, Bengaluru), publication staff of the Academy and Springer, and Dr Indra Sen (IIT-Kanpur) for their enthusiastic support at various stages. We trust that this special volume would be useful for the researchers interested in Deccan volcanism in particular and the large igneous provinces in general.

N V Chalapathi Rao
Banaras Hindu University, Varanasi
and
Jyotisankar Ray
University of Calcutta, Kolkata