Review Article

Volcanism, Past and Present – The Indian Scenario

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Indian geoscientists continue to study volcanism in the sub-continent under three distinct theme-based time periods i.e. Archean-Proterozoic volcanism, Late Mesozoic Deccan Traps and Prehistoric Barren Island volcanism. The physical volcanology, geochemistry, isotopic systematics and economic potential constitute thrust areas for komatiites research in the Dharwar and Singhbhum cratons. Similarly, the geochemistry and geochronology of basalts and boninites from Chitradurga, Veligallu, Kutti, Gadwal, Jonnagiri and Kolar greenstone belts continue unabated. The Mesozoic Deccan Trap lavas and interflow boles have captivated the attention of a small but significant group of Indian geoscientists. Papers related to several aspects such as the physical volcanology, geochemistry, geochronology and magnetism of basalts, rhyolites and boles have been published. A first time report of occurrence of pelletal lapilli from one of the world's largest crater-facies kimberlites at Bejripadar Tokapal Kimberlite field is significant. Radiogenic dating of kimberlite-lamproite magmatism from Mainpur, Wajrakarur and Kutch suggest a close spatio-temporal association between these deep-seated mantle messengers and large CFB provinces during the Cretaceous. A small group of dedicated Earth Scientists continue to work on the tuffs and basaltic andesite lavas from the prehistoric Barren Island Volcano.

Keywords: Volcanism in India; Komatiites; Deccan Traps; Cretaceous Kimberlites; Barren Island Volcano

The Indian subcontinent has witnessed several episodes of plutonism and volcanism in its geological past. In the Indian context, magmatism occurred since the Precambrian to Recent times and produced vast volcanic terrains such as the Archean komatiites, greenstone mafic volcanism, bimodal lavas of the Malani and the Dongargarh, the Pir Panjal Traps and related volcanics in the Himalayas, the classical continental flood basalt provinces of Deccan Traps and Rajmahals and the famous island arc volcanism at Narcondam and Barren Islands. In this report, we present and discuss the wealth of new data generated over the past four years on the various facets of volcanism and volcanic rocks in India. We have divided the contents of our synopsis into three theme-based time periods so as apprise National and International Earth Science community about the important developments in volcanology and identify knowledge gaps for further studies.

Archean-Proterozoic Volcanism

Komatiites are extrusive, ultramafic rocks containing

more than 18% MgO and were first described from the Barberton greenstone belt in the Kaapvaal craton, South Africa (Viljoen and Viljoen, 1969). Komatiites invoke considerable interest amongst geologists due to their antiquity, internal variation in structures, textures, geochemistry and their potential to host Ni-Cu and PGE mineralization. Their bearing on understanding Archean mantle dynamics makes komatiites one of the most sought after rocks in the Precambrian world. Recently, the komatiites have received the attention of the Indian geoscientists. In the western Dharwar craton (WDC) of southern India, Jayananda *et al.* (2016) and Prabhakar and Namratha (2015) have reported physical volcanology and geochemistry of the Paleoarchean komatiite lava flows from J C Pura and Banasandra greenstone belts (Fig. 1). These high-temperature (1450-1550°C), low-viscosity lavas produced thick, massive, polygonal jointed sheet flows with sporadic flow top breccias, pillows and quench fragmented hyaloclastites. J.C. Pura komatiite lavas represent massive coherent facies with minor channel facies, whilst the

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Banasandra komatiites correspond to compound flow fields interspersed with pillow facies. Tushipokla and Jayananda (2013) present field, petrographic, major and trace element data for komatiites and komatiitic basalts from the Nagamangala greenstone belt, WDC. According to them, geochemical characteristics of the Nagamangala komatiites indicate derivation from heterogeneous mantle (depleted to primitive mantle) at different depths within a rising plume. The widespread Paleoarchean deep depleted mantle-derived komatiite volcanism and sub-contemporaneous TTG accretion in the western Dharwar craton implies a major earlier episode of mantle differentiation and crustal growth during ca. 3.6–3.8 Ga.

Komatiites and high MgO volcanic rocks such as boninites have high Ni, Cr and platinum group elements (PGE) and as such could have great economic potential. Saha *et al.* (2015) studied samples from the Bababudan greenstone belt of western and Gadwal greenstone belt of the eastern Dharwar craton (EDC) and found that the Bababudan komatiites have Ni (509–1066 ppm) and Cr (136–3036 ppm) and low RPGE (9–42 ppb) contents and are geochemically analogous to Al-undepleted Munro type komatiites and their PGE compositions similar to Alexo and Gorgona komatiites. The sulphur undersaturated character of Bababudan komatiites is attributed to decompression and assimilation of lower crustal materials during magma ascent and emplacement. The Gadwal high-Ca boninite show higher concentration of Ni (821–1168 ppm) and Cr (2307–2765 ppm) and total PGE (82–207 ppb) and exhibit geochemistry that imply high degree melting of refractory mantle wedge under hydrous conditions in an intraoceanic subduction zone setting. Sulphur undersaturation of these boninites confirms to influx of fluids derived by dehydration of subducted slab resulting in high fluid pressure and metasomatism of mantle wedge. Mukherjee *et al.* (2014) studied the sill-like, chromitite-bearing layered ultramafic–mafic rocks from the 3.1 Ga Nuggihalli greenstone belt in the WDC. The chromitites show high PGE abundances (Σ PGE = 96–296 ppb), especially IPGEs (Σ IPGE = 63–223 ppb) due to the presence of IPGE-bearing inclusions. According to the authors, the REE patterns and incompatible elements negate the role of crustal contamination of the parental komatiitic magma and the immiscible sulfide segregated from

the Al-depleted komatiitic parental magma concentrating the PGEs during crystallization of the pyroxenes.

The Singhbhum craton is one of the oldest Palaeo-Mesoarchaeon cratons of the world. Chaudhuri *et al.* (2015) report the Tua-Dungri komatiites from the Iron Ore Group that are characterised by cumulate, platy and random spinifex zones with geochemical affinity to the Barberton type komatiite. Based on their findings and based on published geochemical, sedimentological and stratigraphic data from rocks of the Iron Ore Group, the authors suggest mantle plume activity during the Mesoarchaeon in the Singhbhum craton.

Jayananda *et al.* (2015) present SIMS U–Pb zircon ages and Nd isotope data for the felsic volcanic rocks from seven Neoarchean greenstone belts of the EDC and from the Chitradurga greenstone belt in the WDC. According to them, zircon ages show bimodal age distribution of felsic volcanism, consistent with two-stage growth of the Dharwar craton in the Neoarchean. The ca. 2.70–2.65 Ga felsic volcanic event is contemporaneous with 2.7 Ga mafic greenstone volcanism and emplacement of juvenile tonalitic to granodioritic crust, while 2.58–2.54 Ga felsic volcanics are coeval and spatially (and probably genetically in some cases) linked to the major episode of calc-alkaline magmatic accretion in the EDC. The Chitradurga and Veligallu greenstone belts host felsic volcanics of the first generation, the latter showing inheritance at ca. 2.95 Ga. Four of the five greenstone belts hosting the second generation of felsic volcanics (Chitradurga, Kolar, Kadirī, and Hutti) show crustal inheritance at ca. 2.6, 2.7, 2.9, 3.0, 3.1 and 3.3 Ga. Duraiswami *et al.* (2013) described the physical volcanology, morphometric and emplacement mechanism of pillow lavas from the ~2.8 Ga Chitradurga greenstone belt. The authors envisage that the pillow lavas exposed in the Chitradurga hills and at the National Geological monument at Mardihalli were erupted as tholeiites that variably interacted with sea water to produce distinct geochemistries and were emplaced in a shallow marine marginal inter/back arc basin.

Manikyamba *et al.* (2015) studied the geochemistry of the Neoarchaeon Jonnagiri greenstone belt in the EDC. According to them, the

Jonnagiri metabasalts were derived in a paired arc-back-arc setting marked by nascent back-arc rift system similar to the Mariana-type arc that developed in the proximity of an intraoceanic arc. Bhattacharya *et al.* (2015) produced SHRIMP U–Pb zircon dates of 1861 ± 6 Ma and 1631 ± 6 Ma for the Arkasani Granophyre and felsic Dalma volcanics respectively. Based on their new findings, they suggest that the different sub-basins in the North Singhbhum Mobile Belt evolved diachronously under contrasting tectonic environments and were juxtaposed during a later orogenic event. Singh and Slabunov (2015) discuss the geology, geochemistry and geochronology of the Central Bundelkhand greenstone complex and suggest that the volcanics formed in a subduction zone setting. SHRIMP-dating of zircon from the felsic Babina volcanics indicate that they were erupted in Neoproterozoic time (2542 ± 17 Ma).

Vijaya Kumar *et al.* (2015) portray growth of the continental crust in the Proterozoic Eastern Ghats Belt, SE India. Mafic magmas within the Palaeoproterozoic Kondapalli–Kandra region illustrate subduction-related island arc basalt-type geochemical signatures and alkali basaltic magmas in the Mesoproterozoic Prakasam continental rift-zone displaying OIB-type characteristics. From their study, the authors demonstrate the dichotomy of continental crust produced by intra-plate processes exhibiting plate-margin signatures and advocate that we possibly have overestimated the proportion of continental crust generated above subduction zones. Azam *et al.* (2015) studied the mafic volcanics from the Bayana, Alwar and Khetri volcano-sedimentary basins, North Delhi fold belt and proposed that the Mesoproterozoic crust of NW Indian shield has evolved through the operation of a complete Wilson cycle at about 1832 Ma. The Bathani volcanics from the northern fringe of the Chotanagpur Granite Gneiss Complex were studied by Saikia *et al.* (2014) and consist of rhyolite, andesite, pillow basalt, tuff and mafic pyroclasts generated in an island arc setting. The authors are of the opinion that the belt probably marks the collision of the northern and southern Indian blocks during Proterozoic period.

The volcano-sedimentary sequences from the Purana Basins of India have also been studied. Sesha Sai (2014) discusses the hitherto unreported occurrences of two significant phases of pyroclastic

volcanic activity associated with the Vempalle Formation in Papaghni sub-basin of the Proterozoic Cuddapah basin of EDC. According to Sesha Sai (*op. cit.*), the pyroclastic zone present at the interface of the Vempalle Formation and Pulivendela quartzite in Vanambayi-Lingala-Lopatnutala section represents a significant tectono-magmatic event of explosive volcanic activity that is contemporaneous with the culmination of the precipitation of Vempalle dolomite and marks the termination of sedimentation in Papaghni Group during Paleoproterozoic times. Similarly, Saha and Tripathy (2012) have reported rhyolitic tuff beds from the Owk Shale in the Proterozoic Kurnool sub-basin similar to those described from other Proterozoic intracratonic basins like Vindhyan and Chhattisgarh basins in India (e.g. Chakraborty *et al.* 2011).

Kimberlites, orangites and lamproites are an important clan of diamond bearing rocks that have captivated the attention of Indian geologists. Both, diatreme (sub-plutonic) and crater facies (volcanic) kimberlites have been studied. The crater facies kimberlites are considered to be an extreme explosive product of kimberlite magmatism. The saucer-shaped Tokapal kimberlite and its satellite body at Bejripadar from the Bastar craton, central India, is one of the world's largest (>550 ha) crater-facies kimberlite. Although detailed characterisations of the pyroclastic crater facies has not been attempted, several papers (e.g. Chalapathi Rao *et al.* 2013; Dhote *et al.* 2013) dealing with the occurrence, volcanic textures (pelletal lapilli) and petrogenesis of the Tokapal crater facies rock have been published in recent years.

Late Mesozoic Deccan Traps and Associated Volcanism

Since the discovery of end-Cretaceous diamondiferous Group II kimberlites synchronous with the eruption of the Deccan flood basalts by Lehmann *et al.* (2010), in the Mainpur field of the Bastar craton of central India, renewed interest in the genesis of Group II kimberlites and diamond exploration activities have begun in India. Karmalkar *et al.* (2014) report the discovery of Mid-Cretaceous (~124 Ma) lamproitic dyke from the Kutch region, Gujarat and suggest close spatio-temporal association of this magma type with the Deccan Trap lavas. Similarly, Dongre *et al.* (2016) indicate that the Timmasamudram diamondiferous kimberlite cluster from the Wajrakarur kimberlite field,

show strong affinity with those from the Cretaceous Group II kimberlites from the Bastar craton, central India and Kaapvaal craton of southern Africa.

As the Late Cretaceous age (ca. 90 Ma) of the younger perovskites from the TK-1 kimberlite is indistinguishable from that of the Marion hotspot-linked extrusive and intrusive igneous rocks from Madagascar and India. The authors infer that they may be part of a single Madagascar Large Igneous Province and may have significant implications for SCLM evolution and diamond exploration programs in future.

The Deccan Traps – an important continental flood basalt (CFB) province of the world continues to draw attention of several workers in the field of petrochemistry, physical volcanology and geochronology. Several interesting papers related to various aspects of the Deccan Traps appeared in the special volume on Asian Flood Basalt (Sheth and Vanderklusen, 2014). Krishnamurthy *et al.* (2014) compare clinopyroxene compositions in the Deccan and Rajmahal Traps and their bearing on magma types and evolution. According to them, pigeonite is absent in mild or strongly alkalic basalts from Rajpipla, Navagam and central Kachchh. However, they report co-existence of augite and pigeonite in subalkalic basalts/dykes and picritic basalts. Based on host-rock chemistry, total alkalis-silica plot, CIPW norms, estimated temperatures of eruption and augite–pigeonite thermometry, they inferred that clinopyroxene compositions, especially the incidence of pigeonite, appear to be very sensitive to bulk chemistry of host rocks, especially their Na₂O, K₂O, SiO₂, total iron and TiO₂ contents. Evaluation of host-rock compositions in the ternary olivine–clinopyroxene-quartz plot indicates polybaric conditions of crystallization and evolution especially in samples that are picritic and which could also breach the olivine–clinopyroxene-plagioclase thermal divide that exists in part between alkalic and subalkalic basalts under atmospheric conditions. Ray *et al.* (2014) compared geochemical and Sr–Nd–Pb isotopic compositions for Deccan Continental Flood Basalts and Central Indian Ridge (CIR) and discuss the possible parental linkages between the two regions. The rocks from these regions do not share common parentage, and are therefore genetically unrelated to each other (Ray *et al.*, 2014). The authors infer that

the northern CIR MORB were derived from a depleted mantle source contaminated by upper continental crust, probably during the break up of Gondwanaland.

Sheth and Pande (2014) report Danian age (62.6 ± 0.6 Ma and 62.9 ± 0.2 Ma) for the Dongri rhyolite flow from Mumbai and discuss the late-stage Deccan rhyolitic volcanism, inter-volcanic sedimentation, and the formation of Panvel flexure. Baksi (2014) reports new ⁴⁰Ar/³⁹Ar ages for lava flows from the Deccan Traps and Rajahmundry basalts and critically assesses reliability of other dates available in the published literature. According to him, only six ages of lavas from the composite Western Ghats are found to be reliable estimates of the time of crystallization. The age of the upper flow at Rajahmundry defines its formation during chron 29n and a single age from the lower reversed polarity flow appears somewhat dichotomous when plotted against the geomagnetic polarity time scale. Based on his findings, Baksi (2014), is of the view that the hypothesis of faunal extinctions at the Deccan Trap–Cretaceous–Paleogene boundary (KPgB) remains plausible, but must compete with the latest report, favouring a very close temporal connection (0.03 Ma) between the Chicxulub Impact Crater and the KPgB. Bolide impact and flood volcanism compete as leading candidates for the cause of terminal-Cretaceous mass extinctions. In an interesting paper, Renne *et al.* (2015) suggest that the existing Deccan Traps magmatic system underwent a state shift approximately coincident with the Chicxulub impact and the terminal-Cretaceous mass extinctions, after which ~70% of the Traps' total volume was extruded in more massive and more episodic eruptions. Initiation of this new regime occurred within ~50,000 years of the impact and is consistent with transient effects of impact-induced seismic energy. According to the authors, post extinction recovery of marine ecosystems was probably suppressed until after the accelerated volcanism waned.

The physical volcanology of lava flows from Deccan Traps continued unabated. Basaltic lava flows are traditionally classified as pahoehoe and aa according to their surface morphology and style of emplacement but some transitional-types such as rubbly pahoehoe, slabby pahoehoe and toothpaste lavas share morphologies akin to the two end-

members have been described from active and old volcanic terrains. Changes in effusion rates, apparent viscosity and shear rate, slope and crystallinity are some of the reasons for transitions in lavas. In their paper on pahoehoe–aa transitions in the lava flow fields of the western Deccan Traps, Duraiswami *et al.* (2014) demonstrate that flow fields with transitional tendencies cannot travel great lengths despite strong channelisation. Accordingly, the authors doubt the long distance flow of Deccan Traps lavas to Rajahmundry and suggest a polycentric eruption at ~ 65 Ma in Peninsular India. Earlier, Sheth *et al.* (2011) have reported field and geochemical evidence, particularly Nd–Sr isotopic ratios for formation of breccia-cored rosettes. According to them, the features formed due to the sinking of the flow-top breccia crusts into molten interiors and the radial joints formed due to warping of isotherms around these “cold anchors”.

The geochemistry of lava flows from the Deccan Traps also saw some interesting papers. Hegde *et al.* (2014) studied the geochemical characteristics of the youngest lava flows belonging to the Desur Formation in the Western Ghats and inferred that they are derived by partial melting of a peridotite source that underwent subsequent fractionation. Krishnamurthy (2015) discusses the chalcophile element depletion in Lower Deccan Trap Formations and implications for Cu–Ni–PGE sulphide mineralization akin to those of Norilsk–Talnakh, Siberian Traps, Russia. Sequential ore genetic processes envisaged for such depletion at Norilsk include, crustal contamination with country rocks, sulphur saturation, sulphide liquid immiscibility and finally enrichment in the tenor of Ni, Cu and PGE in the sulphides. According to the author, identification of such enriched zones in magma plumbing systems (chonoliths) and intrusions (dykes and sills) near the source regions within the Deccan Traps is a huge challenge for exploration geologists in India.

Dykes and sills form an important part of the plumbing system in the Deccan Traps. Duraiswami and Shaikh (2013) present the geology of the saucer-shaped sill at Mahad and discuss the geodynamics involved in its emplacement. Sheth, (2016) provides a new model for the formation of Giant plagioclase basalts from the Deccan Traps. According to him, plagioclase megacrysts grow over long (15 k.y.) time periods in a deep crustal (possibly Moho-level) sill complex, which forms tens to hundreds of thousands

of years before the continental flood basalt eruptions. Sheth *et al.* (2014) present field, petrographic, major and trace element and Sr–Nd isotopic data on the tholeiitic flows and dykes from the Ghatkopar–Powai area, Mumbai. The geochemistry of flows closely resembles the Mahabaleshwar Formation and most dykes are distinct from any of the Western Ghats stratigraphic units except two dykes that resemble the Ambenali Formation. Cucciniello *et al.* (2015) report few picrites, several sub-alkalic basalts and basaltic andesites, and an andesite dyke from Central Saurashtra mafic dyke swarm. Mineral chemistry and whole-rock major and trace element and Sr–Nd isotopic data show that fractional crystallization and crystal accumulation were important processes. $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 65.6 ± 0.2 Ma, 66.6 ± 0.3 , and 62.4 ± 0.3 Ma (2σ errors) for three of the dykes, indicates emplacement of the swarm over several million years. The tectonic significance of dykes from the Sarnu–Dandali alkaline complex, Rajasthan, northwestern Deccan Traps was also undertaken by Vijayan *et al.* (2015).

Recently, studies related to interflow clayey material commonly referred to as boles (Fig. 2) from the Deccan Trap has been in the limelight. In his paper, Sayyed (2015) referred to these boles as ‘intrabasaltic palaeosols’ and gave a concise account of the Deccan Trap boles *vis-a-vis* selected examples from the other ‘continental flood basalts’. According to him, the red boles have potential as palaeoclimatic indicators of global climate change. The paper however falls short of elucidating the paleoclimate during the Deccan Trap volcanism. Earlier, Srivastava *et al.* (2012) studied some of boles from the same Pune area and concluded these to be of sedimentary origin formed by frequent recycling and re-deposition by surface run-off, infiltration and ponding of shallow streams or laterally migrating channels. Subsequently, Srivastava *et al.* (2015) studied the iron oxide characteristics of these lava flow hosted sediments and concluded that green, brown and red boles represent the transitional baking environments under various hydrous–anhydrous conditions and pedogenic processes. According to them, the complex genesis of the iron oxides in the Deccan Trap bole beds offers great scope as ‘Martian analogues’ (after Greenberger *et al.* 2012; Gavin *et al.* 2012) and thus need to be subjected to advanced rock magnetic techniques and spectroscopic analyses. Srivastava *et al.* (2016) also

Fig. 1: Komatiite outcrop from Kunikenahalli, Banasandra (3.15 Ga) greenstone belt showing spinifex texture

studied the weathering characteristics of interflow, 'color differentiated' volcanic boles from Mandla lobe, Eastern Deccan volcanic province. According to them, the significant presence of primary parent magnetic minerals (i.e. coarse SD–MD titanomagnetite and magnetite) in the majority of boles depict incipient to moderate weathering owing to limited time intervals during successive eruptions. In few red and brown boles, the combination of hematite and SP particles present depicts baking effect rather than pedogenesis. They conclude that the boles from western and eastern Deccan Traps indicate similar first order paleo-environmental conditions without any major regionally correlated pedogenesis. Despite these rigorous works, the true identity of the boles in terms of their origin, either as paleosols, sediments, pyroclastics, peperites or weathered lava selvages, remains enigmatic.

Prehistoric Barren Island Volcanism

The Mile Tilek Tuff is one of several consolidated volcanic ash deposits in the Andaman and Nicobar Islands that has preserved evidence of a large-scale volcanic eruption in southeast Asia. Assumed to be of Mio–Pliocene age (~25–2 Ma), the tuff was thought to have been generated by the Andaman–Indonesia volcanic arc. Little was known about its source volcano because of absence of critical isotope and geochemical data. Awasthi *et al.* (2015) present ^{40}Ar – ^{39}Ar plateau age for the whole rock at 0.73 ± 0.16 (2σ) Ma and exhibit geochemical characteristics of subduction zone magmatism. Based on this, the authors speculate that the Ranau volcano in south Sumatra could have been the source of the Mile Tilek Tuff.

The Barren Island from Andaman Sea is India's

Fig. 2: Interflow 'red bole' from the Deccan Trap lavas from Ambegaon, Pune

only active volcano and has a long prehistoric eruptive history with previous eruptions in 1787, 1789, 1795, 1803, 1852, 1991 and 1994–95. Barren Island volcano has displayed explosive Strombolian eruptions for more than two decades (1991–2009) making it a favourite topic of research. Recently, several Indian researchers have worked on different aspects of volcanism and volcanological evolution on this island. Bandopadhyay *et al.* (2014) re-evaluate the existing knowledge and incorporate new information and interpretations of the recent and past volcanic activity on the Barren Island. According to the authors, the volcanic landforms of the Barren Island such as a prehistoric mafic stratocone with a central caldera, a central scoria cone with summit crater and abundant basaltic lava flows of historic eruptions and the scoria cones of the recent activity bear testimony to the alternating effusive and explosive activity during prehistoric times. Sheth

(2014) christened the central polygenetic scoria cone on Barren Island as “*Shanku*” and compares it to those at Anak Krakatau (40 eruptions since 1927), Cerro Negro (23 eruptions since 1850), and Yasur (persistent activity for the past hundreds of years). According to him, these are an important category of volcanoes, gradational between small “monogenetic” scoria cones and larger “polygenetic” volcanoes. Ray *et al.* (2014) dated plagioclase separates from two tephra (ash) layers older than 42 ka from the Barren eruptions in marine sedimentary core. The $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages of plagioclase separates from two successive tephra layers, 65 cm wide, are 1.8 ± 0.4 (2 σ) Ma and 1.5 ± 1.8 (2 σ) Ma respectively. Based on concordant plateau and isochron ages, Ray *et al.* (2015) establish that the oldest sub aerial lava flows of the volcano are 1.58 ± 0.04 (2 σ) Ma, and some of the plagioclase xenocrysts have been derived from crustal rocks of 106 ± 3 (2 σ) Ma. Renjith (2014)

presented a systematic account of micro-textures and a few compositional profiles of plagioclase from high-alumina basaltic aa lava flows erupted during the year 1994-1995, from Barren Island Volcano. According to these authors, the magma generated has undergone extensive fractional crystallization of An-rich plagioclase in stable magmatic environment at a deeper depth. Subsequently, they ascend to a shallow chamber where the newly brought crystals and pre-existing crystals have undergone dynamic crystallization via dissolution-regrowth processes in a convective self-mixing environment. Such repeated recharge-recycling processes have produced various populations of plagioclase with different micro-textural stratigraphy in the studied lava. Earlier, Sheth (2011) has described the spectacular occurrence of highly viscous toothpaste lavas that are associated with the aa lava flows on the Barren Islands.

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