Large igneous provinces – global perspectives and prospects in India

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The origin and emplacement of Large Igneous Provinces (LIPs) is a challenging research frontier in earth sciences that has implications for understanding: (a) the dynamics and evolution of the earth's mantle, (b) atmosphere and climatic shifts, (c) redistribution of land and oceans, (d) biosphere involving transfer and migration of flora and fauna and mass extinctions, (e) metallogeny, and (f) source of hydrocarbons. In this review, we appraise contemporary models for the origin of LIPs (plume versus non-plume) to evaluate their strengths and limitations. We also examine vexed issues (e.g. nature and extent of mantle heterogeneity, role of fluids in LIP genesis, relation amongst carbonatites, kimberlites and LIPs, linkage of dyke swarms to LIPs and continental reconstruction and metallogeny) which are not readily explained by any of the models. Pursuable research frontiers in Indian igneous provinces (e.g. identification of new LIPs in the Precambrian, Fe-enrichment, fertility and thermal state of mantle below India, detailed study of lava stratigraphy and palaeomagnetism, assessment of duration of LIP activities, irrespective of compositional variability) are identified for future study. Despite large-scale magma generation, crust–mantle interaction and geodynamic evolution of South Asia through the Phanerozoic, research on modern lines on Indian LIPs is limited. Research on LIPs deserves a major thrust in India for better understanding of the evolution of large magmatic provinces in the Peninsular and Extra-Peninsular regions.

Keywords: Crust-mantle interaction, India, large igneous province, plume, precambrian.

IN the last few decades, the plate tectonics theory has provided explanation for distribution of both the surface and subsurface igneous activity in the Earth's crust. But, it has not provided satisfactory explanation for the origin of all intra-plate large-volume magmatic features. Continental flood basalts and their oceanic equivalents–giant oceanic plateaus, and aseismic ridges are known as Large Igneous Provinces (LIPs)[1].

Magmatism associated with LIPs represents large-scale mass and heat energy transfer from the Earth's deep interior to its surface, affecting the lithosphere and atmosphere on which life is sustained. Magma fluxes in LIPs show some periodicity, in contrast to the relatively steady-state crustal accretion over geologic time. LIPs are generally believed to be in intra-plate setting covering $> 100{,}000\ \mathrm{km}^2$ area[1–3]. However, it was suggested that igneous provinces covering area $\geq 50{,}000\ \mathrm{km}^2$, independent of tectonic setting, composition or emplacement mechanism, can be classified under LIPs[4]. With this modification, igneous provinces occurring both in the subduction zone or mid-ocean ridge (MOR) setting may qualify as LIP.

LIPs are recently considered[5] to have been formed in a span of 50 Ma (ref. 5), and not 1–5 Ma as envisaged earlier[6]. However, more than 75% of their total volume must be emplaced either by a single eruptive event or by several pulses in 1–5 Ma duration[5]. LIPs were initially defined as large mafic volcanic provinces with rocks having < 55 wt% SiO_2 (MLIP; e.g. Deccan Traps, India). Subsequently, the term silicic LIP (SLIP) was introduced to include LIPs having rocks with > 65 wt% SiO_2 (ref. 7), such as the Malani Province, NW India[8] (Figure 1) and the Whitsunday Province, Australia[9]. In addition, bimodal LIPs with sub-equal proportions of both mafic and silicic volcanic rocks have been reported[10,11]. Therefore, LIPs represent a compositional continuum between MLIP and SLIP end-members. Currently, ~150 LIPs are known globally, mostly from the Phanerozoic, and occurring primarily in oceanic setting[5].

It is plausible that during Precambrian, which represents more than 80% of the Earth's geologic time, a mechanism similar to Phanerozoic relating to generation and emplacement of LIPs prevailed. However, deformation, metamorphism, crustal melting and recycling accompanied by accretion, prolonged weathering and erosion of rocks render recognition of Precambrian LIPs a formidable task. LIP emplacement is also linked with major climatic shifts, redistribution of land and sea with profound impact on biosphere, including mass extinction, and metallogenesis[12–15]. Therefore, understanding the origin of LIPs becomes a first-order problem in Earth sciences research and merits high priority.

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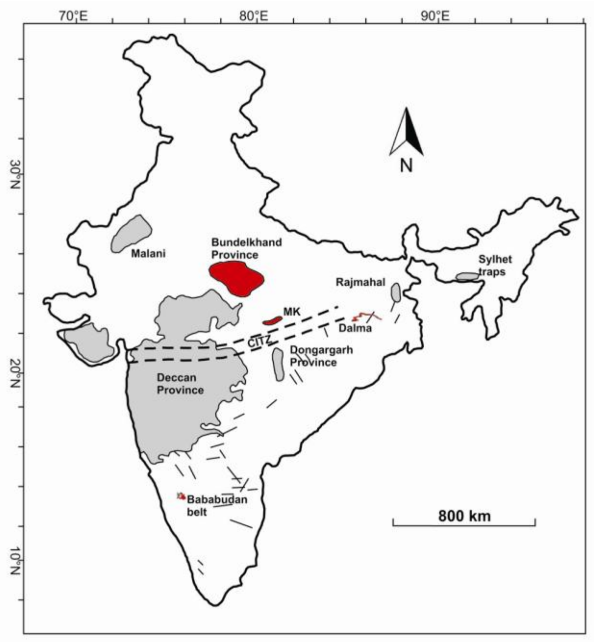

Figure 1. Distribution of Large Igneous Provinces (LIPs) in India; identified and recognized LIPs are shown in grey and some prospective ones in red. MK represents the Mahakoshal belt and its extention in the Central Indian Tectonic Zone (CITZ). Solid black lines represent dykes. (Modified after Ernst and Srivastava[106].)

A paradigm-shift is taking place in our understanding of the fundamental processes related to large-volume magma generation and mantle evolution leading to scientifically challenging new questions. Several models on the origin and emplacement of LIPs have been proposed and reviewed in recent years[3,5,6,16–19]. Concerted effort[20,21] has led to new interpretation and brought out several new fundamental questions. The purpose of this article is to: (i) appraise the present state of knowledge, (ii) evaluate gaps in our knowledge, and (iii) identify new and challenging frontiers in the context of large Precambrian magmatic provinces. This has relevance to the fact that the Indian subcontinent is endowed with an entire range of geological settings from the Archaean to recent times. Apart from the known Phanerozoic LIPs in India, e.g. the Rajmahal–Sylhet and the Deccan, notable magmatic provinces of smaller dimensions exist in the Precambrian volcano-sedimentary belts (Figure 1). The Precambrian volcano-sedimentary sequences in India as possible LIP relicts have not been adequately examined. Such a study opens a new avenue for active inter-disciplinary research. In the following, we discuss various contemporary LIP models, their strengths and weaknesses and their possible application, particularly to the Indian Precambrian provinces.

Plume model

Concept and predictions

Plume hypothesis was first proposed by Morgan[22] primarily to explain mantle 'hotspot' related volcanism producing a chain of volcanic islands located in the plate interior. He postulated that stationary 'hotspots' in the mantle, called mantle plumes, brought up thermally buoyant material as narrow cylindrical upwelling from deep interior to the surface of the Earth, that continually feed the anomalous surface volcanism. As lithospheric plates driven by mantle convection move on these stationary plumes, episodic volcanism gives rise to a chain of volcanic islands and seamounts, such as the Hawaiian volcanic chain. Globally, a number of these island chains, predominantly of basaltic composition, also known as ocean island basalts (OIB), can be traced to LIPs[3]. For example, the current Reunion 'mantle plume' and its volcanic products, Mauritius, Mascarene Plateau and Chagos–Maldive–Laccadive Ridge are extrapolated to the Deccan LIP in India[22,23]. Morgan listed a global constellation of 16, and potentially 20 plume-related hotspots, including Hawaii, Iceland, Yellowstone, Azores, Easter Island, Galapagos, Reunion and others. The number of postulated 'hotspot' and plumes have now risen to 50 or more[24,25]. Experimental and mathematical simulation models of mantle convection showed that the plume rises from the core–mantle boundary (depth of ~ 2900 km) and comprises of a bulbous head with a narrow tail[26–28].

The plume hypothesis was expanded to include plume head–tail hypothesis[26,29], suggesting that the mushroom-shaped plume heads erupt to form LIPs. Subsequently, the plume tail acts as a continuous feeder of volcanic material giving rise to thousands of kilometres long volcanic chains. This simple explanation, although fits well for the formation of several island chains, fails to explain the absence of LIP in others. To reconcile the absence of LIPs in several present-day plumes, two classes of plumes have been proposed – 'thermochemical'[30] and 'splash'[31] plumes, which may not begin with large heads as predicted earlier and such plumes may originate from a shallow mantle.

At the outset, the predictions of the contemporary plume model include: (1) fixity relative to other hotspots (at least for ~ 50–100 Ma)[32]; (2) long period of precursory uplift (topographic swells)[25,33,34], followed by eruption of plume head to form LIPs; (3) large eruptive volume ($1–2 \times 10^6$ km^3) in short duration (1–5 Ma)[5]; (4) linear space and time progressive volcanic history; (5) high-temperature magma eruptions and decrease in magma volume with time[16] and (6) enriched incompatible trace element abundances, high radiogenic Sr and Pb isotope ratios, and high ^{3}He/^{4}He in the OIB[35]. Although the plume model is accepted by many workers[33,36,37], a number of studies have argued against it[4,17,38,39].

Merits and limitations of plume hypothesis

Despite considerable acceptance of the plume hypothesis[22], some features of intra-plate LIPs are not convincingly explained by the plume model. The predictions intrinsic to plume hypothesis and their limitations are explained below.

Presence of time-progressive volcanic chains and relative fixity among melting anomalies on diverse plates are adequately explained[32,40]. Numerical convection models[41] explained the age progression observed in Hawaiian, Louisville and Easter hotspots in the Pacific Ocean. Tarduno and Cottrell[42] indicated that the locus of volcanism may not remain fixed relative to the palaeomagnetic pole; so hotspots are not necessarily stationary. Also, only 13 hotspots have time-progressive chain of islands[17]. Although surface tracks of time-progressive volcanic chains have been generally argued for Hawaii, Reunion, Easter, Society, St Helena, Tristan-Gough, Kerguelen, Galapagos and Louisville, it is not confirmed for other cases such as Austral-Cook, Cameroon and Samoa[25].

Abundances of incompatible trace elements and radiogenic isotope ratios suggest that plume-related OIBs are compositionally distinct and different from MORBs which have shallow mantle source. The former are enriched in incompatible elements and radiogenic Sr and Pb isotopes[25,35]. Isotopic compositions of noble gases, particularly $^3He/^4He$ in OIB ($12.2 \pm 5\ R/R_A$), relative to that in MORB ($8.75 \pm 2\ R/R_A$) have been used to argue that plumes originate from a less-degassed reservoir in the deep mantle (White[43] and references therein). However, recent experimental results[44] indicate the high $^3He/^4He$ ratios do not require an undegassed reservoir, and that differences in the He-isotope ratios may be related to the solubility and partitioning of He, and mantle processing rates.

The individual hotspots often sit atop broad topographic high of ~ 1 km elevation above the ocean floor (e.g. Hawaii, Iceland, Reunion, Azores). The presence of broad topographic high (e.g. the Hawaiian swell or Arch) in isostatic equilibrium led to the inference that the buoyant plume and its lower density column are the source of ‘hotspot’ volcanism. The best example of precursory domal uplift associated with LIP[45] is confirmed for the 258 Ma Emeishan LIP (2×10^6 km^2 area and 1×10^6 km^3 volume) in west China, where kilometre-scale domal uplift over a region 900 km wide preceded high-MgO basalt eruptions, by ~ 3 Ma. Such a pattern was also inferred for the Deccan LIP from drainage patterns[46,47]. However, evidence for a precursory uplift is not accepted unequivocally. In the type locality Hawaii, while 1000 km wide bathymetric swells are attributed to the mantle plume[33,34], Shapiro *et al.*[48] negate this observation. Topographic swells are also not observed above few hotspots such as the Madeira and Canary.

High mantle potential temperatures (temperature at atmospheric pressure after correcting for adiabatic decompression) of > 1200°C have been estimated for flood basalt provinces. Estimates using the olivine geothermometer strongly suggest present-day potential temperatures for the mantle near the hotspots being 200–300°C hotter than near MORs[49–51]. However, others[52] obtained crystallization temperature of parental liquids of MORB (1243–1351°C) and OIB (1286–1372°C) to be nearly the same. Recently, Presnall and Gudfinnsson[53] used comparable global seismic shear wave velocities and phase equilibrium data in glasses to estimate depths of maximum melting and production of tholeiitic magma at Hawaii and in MORs, including Iceland. They concluded that the volcanic melts come from low-velocity zone of 65–220 km depth, and not from ‘hot’ plumes.

Volcanic eruption of LIPs is considered to be of short duration, in the range 1–5 Ma (ref. 6). Studies on ^{210}Pb–^{226}Ra–^{230}Th radioactive disequilibria[54] and U-series disequilibria[55] infer that bulk of the melts from Earth’s mantle is transported, accumulated and erupted within a short time-span of few years or decade to < 1 Ma (ref. 16). In this case, it is expected that magmatic fluxes and eruptive volumes should be vigorous with the arrival of the plume head at the base of the lithosphere and then dwindle with time. However, magmatic fluxes and eruptive volumes have increased with time in some magmatic provinces that have satisfied several predictions in the plume model. For example, in much of the Hawaiian chain the magmatic rate grew from ~ 0.17 to ~ 0.25 km^3/year in recent years[56]. In Iceland, the magmatic rate of < 0.1 km^3/year for the first ~ 10 Ma increased to < 0.25 km^3/year since ~ 44 Ma, approximately the same rate as the present-day[17].

Finally, the Hawaiian basalts in many cases have elevated SiO_2 (48 wt%) at given high MgO (≤ 20 wt%) and very high Ni (≤ 1000 ppm) contents, which was used to argue for an olivine-free mantle source[57]. Abundant differentiated ferro-basaltic rocks are also reported from Iceland. These observations are not consistent with mantle peridotite (olivine + pyroxene + garnet) composition typically attributed to plume sources.

It is concluded that despite notable success of the plume model for the type localities, viz. Hawaii and Reunion, several volcanic/magmatic features do not exhibit all the traits universally. In short, clearly one model does not uniquely fit in all cases. It is pertinent to explore why other volcanic provinces, thought to be related to plume melting, do not consistently have typical plume signatures?

Melting of shallow mantle

Trace element and isotopic compositions of many continental flood basalts suggest contamination of primary plume magma with continental crustal material. Therefore, it is difficult to ascertain relative contributions of sub-lithospheric mantle reservoirs to LIP magmatism. To explain this, ‘passive mechanism’ involving shallow mantle has been invoked through partial melting of heterogeneous and fusible mantle during lithospheric extension[58].

Lithospheric delamination (role of crust and source fertility)

This hypothesis essentially envisages foundering of dense, unstable lithosphere (lower crust + lithospheric mantle/subcontinental lithosphere) into the asthenosphere and reaching thermal equilibrium with the surrounding, which in turn imparts mantle heterogeneity. The metamorphic reactions in the lower continental crust may lead to density increase (up to 3.8 g/cm^3) with the appearance of garnet (basalt–amphibolite–garnet–clinopyroxenite/eclogite) leading to gravitative instability of the overthickened lithospheric keel[18]. This may detach from the uppermost lithosphere and sink into the upper mantle, making the uppermost lithosphere more buoyant. In large-scale magmatic stoping, magma rises and shatters but does not melt the surrounding rock. The broken rock fragments sink, making more magma to rise. Addition of crustal material, having low melting temperature, may induce some fertility in the upper mantle (i.e. the ability to produce more melt at a lower temperature compared to plume melting) and continuously produce large-volume melts. Exhumation of deeper crustal material in several provinces is also perhaps related to crustal delamination and concomitant partial melting.

Melting of fertile mantle, interaction between melt and surrounding mantle

Enriched character of the 2.3 Ga komatiite (^{143}Nd/^{144}Nd = 0.51311– 0.51252) in the basal Aravalli volcanic rocks (northwestern India) is attributed to shallow subcontinental lithospheric fertile mantle melting, though heat and fluid were advected by the mantle plume[59]. Further, metasomatic reaction, between SiO_2-rich lower crustal and the uprising asthenospheric melts may form orthopyroxene-rich layers with strong crustal signatures. For example, lherzolite, garnet pyroxenite and granulite xenoliths in the Neogene basalts in North China Craton show difference in the extent of metasomatism[60]. The garnet pyroxenites occurring as veins/layers within lherzolite show gradual decrease in olivine and an increase in orthopyroxene. These are rich in incompatible elements, but with high Ni (≥ 1000 ppm) and Mg$^{\#}$ (100*Mg/Mg + Fe: 83–90). On the other hand, granulite xenoliths are of intermediate to mafic composition with high Mg$^{\#}$ (54–71) and Ni (21–147 ppm). The continuous melt–rock interactions between more incompatible element-rich crustal melt and lherzolite mantle imparts more fertility to the heterogeneous mantle and produces large volumes of magma at a lower temperature. This hypothesis has implications for the pre-volcanism surface domal uplift and post-eruption subsidence as LIPs are carried away from the hot plume by plate motion. But lithospheric subsidence due to delamination and detachment precedes the volcanism that occurs as astheospheric mantle material from greater depths flows in to replace the lost lithosphere.

Existence of piclogitic and pyroxenitic mantle

Piclogite is a continuum assemblage that includes eclogite (having low solidus) and peridotite (high solidus) in the mantle. Piclogite has less olivine and orthopyroxene than peridotite, and is characterized by variable fertility and density. Piclogite thus represents heterogeneous mantle, in contrast to both homogeneous peridotite mantle and homogeneous pyrolite mantle (with one part basalt to three parts dunite)[61]. The upper mantle may comprise 2–5% pyroxenite with variable bulk compositions and modal proportions that play an important role in controlling the composition of the mantle-derived partial melts.

A study by Anderson[58] showed that significant amount of piclogite dispersed in the mantle partially melts at lower temperature to produce large-volume magma. This view is also supported by experimental findings[52]. Because of the difference between the peridotite and more pyroxene-rich and olivine-poor mantle lithologies (e.g. pyroxenite, garnet pyroxenite and eclogite), large volume of low-solidus material comprising more pyroxene-rich and olivine-poor mantle (> 50% depending on trace element concentrations) undergoes partial melting as the peridotite solidus is approached during decompression[62]. This implies pyroxene-rich and olivine-poor mantle source is likely to produce large volume of partial melt to form LIP. Interactions of pyroxenite-derived melt and peridotite have been modelled as an important process in the magma genesis at MORs[63].

The canonical notion that mantle is homogenous having peridotitic or pyrolitic compositions may thus not be entirely correct. A heterogeneous mantle, including fertile source is plausible. The possible mechanisms for imparting mantle fertility and heterogeneity include subduction of plates, which recycle crustal material, thereby refertilizing the shallower mantle.

Vexed problems

At present there is no model, plume or otherwise, which is without unresolved issues. It would be premature to accept any one model without questioning its fundamental validity and subjecting it to rigorous tests[17]. Brief accounts of some inter-connected petrological problems in large magmatic provinces that still remain unexplained are discussed in the following sections.

Fe-enrichment and mantle heterogeneity

The global upper mantle FeO concentration is estimated at 8.07–8.18 wt% (ref. 64). The high-MgO rocks

(> 10–12 wt%) in LIPs in many cases have higher FeO 9–16 wt% at a given MgO < 15 wt%. For example, mantle source regions below some LIPs (e.g. Paraná-Etendeka and Iceland) with melts of lower Mg$^{\#}$ (FeO ~ 15 wt%, Mg$^{\#}$ 64) than lherzolite (Mg$^{\#}$ 73) are reported. The higher concentrations of FeO in Archean and Palaeoproterozoic picrites compared to the Phanerozoic picrites is attributed to either Fe-sink in core or isolation of Fe in the lower mantle[65], or the presence of Fe-rich streaks in the mantle plume heads[66].

The FeO enrichment (FeO ~ 10 wt%) in the Palaeoproterzoic high-Mg basalts across the Indian Shield (i.e. Dalma in Singbhum, Mahakoshal in Central Indian Tectonic Zone, Dongargarh in the Bastar Craton) and even higher FeO (> 10 wt%) in Neoarchean Sandur high-Mg basalts (Dharwar Craton) are ascribed to mantle source[67]. Similarly, a Fe-enriched mantle below the Kolar and Ramgiri belts in the southern Dharwar Craton is envisaged in terms of asthenospheric–lithospheric mantle interactions[68]. On the other hand, lower Fo contents (MgO/MgO + FeO) in Hawaiian olivine (also with high NiO) is attributed to low-pressure (1–1.5 GPa) crystallization of parental picritic magma having high MgO and NiO, where D_{Ni} is high[49], and is not related to Fe-rich eclogite or pyroxenite mantle source.

Duration of LIP magmatism

Longer duration of total magmatic activity is obtained for all three compositional types of LIPs in contrast to the maximum duration of ~ 50 Ma attributed to them. Eruptive history of ~ 70 Ma is established for the Caribbean mafic LIP (139–69 Ma)[69], 60–70 Ma for silicic LIP (e.g. Chon Aike Province in Patagonia; the Malani in NW India)[8], ~ 73 Ma for the bimodal Dongargarh LIP, India[10], 50–80 Ma for komatiitic volcanism in Finland[70], and 60 Ma (between 2125 and 2067 Ma) mafic dyke swarm activity in the Marathon LIP in the Lake Superior Province[71]. Rift-related LIPs are perhaps of longer duration (> 25 Ma)[72]. Even in the Deccan LIP, most recent geochronological ages indicate that its duration is relatively long-lived than hitherto believed spanning from 69.7 Ma (ref. 73) to 61 Ma (ref. 74) with the main eruptive event at ca. 65 Ma. Thus the time-span of LIP may not be as short as the 1–5 Ma envisaged in the plume model[6] and requires reconsideration.

Compositional diversity of LIPs

In some provinces (e.g. Dongargarh, Rajmahal, Iceland, Snake River Plain), occurrences of a wide range of melt compositions (e.g. high-Mg basalts/picrite, basaltic andesite, dacite, trachyte, rhyolites) have been reported[7,10,17], not expected in contemporary plume or shallow mantle melting models. Compositional diversity of magmatic products (both in compatible trace elements and isotopic composition) are explained in terms of mixing of compositionally diverse magmas having distinct source characteristics[10,75]. Also, petrography of rocks from large magmatic systems (e.g. MORB) reveals different crystals in the same thin section having different histories[76]. Near-coeval successive magma recharge as part of the same large magmatic event is invoked to explain these observations. This also helps sustain the required thermal condition of the system to trigger a large eruption. The repeatedly changing physical and chemical environments in such open-systems seem a more common and plausible explanation for production of large-volume magmas having wide compositional range.

In this context, occurrences of silicic volcanics in LIPs, e.g. Deccan Traps[77], Rajmahal Traps[75], Malani and Dongargarh, India[10], North Atlantic Volcanic Province[78], Chon Aike Province of Patagonia[79] and Whitsunday in east Australia[7]; deserve further attention. Here, the role of crust and crust–mantle interactions seems significant in large-volume melt generation and emplacement irrespective of plume and other competing hypotheses.

An apparently disparate yet connected issue is the occurrence of large-volume silicic to high-silicic volcanic rocks coeval with large granitoid plutons in SLIPs and bimodal LIPs[80,81]. This is an ongoing debate and seems promising in breaking new ground for understanding the origin and emplacement of SLIPs.

Role of volatiles

The role of volatiles such as water and CO_2 in LIP magmatic processes has not been adequately addressed. This stems perhaps from the general observation that LIPs are characteristically associated with within-plate anhydrous system. An exception is a case of komatiite magma generation by melting of wet mantle in a subduction environment[82]. Inventory of water in different portions of the mantle remains a major challenge in solid earth studies. MORB-source mantle has 0.01 wt% water, OIB-source in the lower mantle has 0.05 wt%, whereas mantle near subduction zones is relatively wet having 0.1 wt% water[83]. The amount of dissolved water in nominally anhydrous mantle minerals has been quantified[84]: cpx: 342–413 ppm, opx: 160–201 ppm, olivine: 3–54 ppm and garnet: 0 – < 3 ppm. Deep crustal rocks, for example, eclogite, contain no hydrous phases, though omphacite and garnet may still contain ~ 1300 ppm and 0–300 ppm dissolved H_2O respectively. In short, presence of volatiles can drastically reduce the melting temperature and can generate a large pool of melts. This aspect surely deserves attention in detail.

Presence of fluids even at sufficiently low concentrations can have significant effects in reducing the solidus considerably and in producing large volume of melt[85].

Experimental studies[86] indicate that carbonated eclogite with fertile lherzolite could give rise to OIB. The super criticality of water and CO_2 vis-á-vis hydrous silicate melts and their immiscibility can lead new knowledge.

Tectonic processes and LIP

Large-scale melting and deformation in mantle/crust are linked in a positive feedback relationship[87,88]. Close spatial and temporal relations between large-volume silicic plutonic provinces and crustal-scale shear zones are therefore significant. On the one hand, intruded melts, whether crust-derived or mantle-derived, weaken the deep crust sufficiently promoting ductile deformation, a process called melt-enhanced deformation[89]. On the other hand, presence of low-degree melt on grain boundaries may induce extensive microcracking and reactions in deep crust and upper mantle leading to shear failure, which in turn becomes a promising environment for large-scale melt formation and transfer[90,91]. This aspect of deformation-assisted large volume melt generation and emplacement is not included in the contemporary models of LIP genesis. In this regard, the Precambrian Bundelkhand Province in north-central India could be a potential case to pursue[92], because close spatial and temporal relations between ductile to brittle–ductile deformation and large-scale melt generation and emplacement covering tens of thousands of square kilometres of the size of a LIP exist in this Province.

Relationship between carbonatites, kimberlites and LIPs

Since long, many researchers[93] have argued for a relationship between carbonatite and kimberlite, though the nature of this relationship remains controversial. Evidences suggest carbonatites and LIPs may be linked to common magmatic processes, although they may have followed different evolutionary pathways[94]. Additionally, slab break-off in subduction setting or lithospheric delamination processes have been proposed for the origin of some rare carbonatites[94]. Surely, this suggestion on carbonatite genesis and recent finding of LIP emplacement in subduction environment[85] has opened a new research frontier. In this context, the role of volatiles in the formation of LIPs, as discussed above, is significant.

Kimberlites are small-volume, volatile-rich potassic–ultrapotassic, ultramafic, ultrabasic and occasionally diamondiferous igneous rocks that are sourced from depths > 150 km. Xenoliths in kimberlites provide direct information about petrology and chemical composition of the crust and mantle. A compelling link between diamondiferous kimberlites, flood basalts and mantle plumes for the Deccan LIP is suggested[95]; kimberlites (orangeites) in Bastar (Central India) are synchronous with the Deccan flood basalt eruption at ca. 65 Ma (refs 96, 97). The kimberlite–lamprophyre–carbonatite–alkaline rock spectrum in the Deccan LIP is inferred to reflect variable thickness of the pre-Deccan Indian lithosphere with a thinner lithosphere along rift zones of northwestern and western India, and a thicker lithosphere underlying the Bastar Craton. High pressure (3–8 GPa) melting of CO_2-bearing garnet lherzolite may yield from low-degree ($< 0.5\%$) magnesiocarbonatite melts at low temperature, through kimberlitic to melilititic compositions ($< 1\%$ melting) to komatiite or picritic basalts at higher temperature where the CO_2 content is low[98].

Identification of Precambrian LIPs in the Indian subcontinent

Criteria for determination of LIPs in Precambrian terrains are a promising area for future research. Archaean greenstone belts comprising tholeiitic and komatiitic rock sequences are on the priority list for LIPs[16]. In this context, the Bababudan belt of the Dharwar Craton, and the Dalma–Dhanjori volcanics in the Singbhum Craton are encouraging. Neoarchean–Palaeoproterozoic association of subaerial flood basalts interlayered with fluvial sand (quartzites) in the Bababudan belt[99] is closely similar to subaerial basalt–arenite–basaltic andesite association in the ~ 2.5 Ga Dongargarh LIP[100]. Subaerial large-volume basalts are also described from the Uchi greenstone belts in Canada[101], basal volcanics of Aravalli, India[102], and the Ramgarh volcanics in the Himalaya[103].

However, records of ancient LIPs are likely to be fragmentary. Five LIP fragments [Karoo–Ferrar–Tasman (Bouvet plume), Parana–Etendeka (Tristan plume), Rajmahal (Kerguelen plume), Madagascar (Marion plume) and Deccan (Reunion plume)] have been linked with the progressive break-up of Gondwana from early Jurassic (200 Ma) to end-Cretaceous (65 Ma)[104]. The reconstruction of LIPs by stitching together the fragmentary evidences across continents in time and space may thus bring out fruitful results in the understanding of global geodynamic processes.

Dyke swarms and geodynamic linkage with LIPs

Precise U–Pb dating of the regional dyke swarms globally in recent years has established surprising linkage to the LIP events[105,106]. Giant diabase/dolerite radiating continental dyke swarms > 300 km long have been identified[105] in many continental LIPs (e.g. Mackenzie LIP, Canada), which acted as pathways for magma ascent. A set of dykes (~ 2.42–2.37 Ga) in the Dharwar Craton (India) and Widgiemooltha of the Yilgarn block (Australia) could have originated from a common plume centre[107]. Convergence to a common focal area and lack of apparent polar wander of three Palaeoproterozoic diabase dyke swarms – the Marathon, Kapuskasing and Fort

Frances in the Lake Superior province during 60 Ma magmatism (2125–2067 Ma) are attributed to a periodically active plume that gave rise to the Marathon LIP[71]. This likely formed as a result of pressure exerted by the plume head as it flattens at the base of the lithosphere. On the other hand, Ray *et al.*[108] suggest that the overpressure required for large, linear (< 79 km × < 62 m) tholeiitic dyke emplacement connected to the fissure-fed Deccan eruption could be linked to shallow magma chambers.

Relationship between metallogeny and LIPs

The link between flood basalts, Ni–Cu–PGE and diamond deposits in LIPs emplaced in cratons having older (Achaean and Proterozoic) lithosphere[13,97] is well established. The 2.6 Ga Bushveld LIP in South Africa, for example, has the largest known mafic–ultramafic intrusion producing significant amounts of platinum and chromite. The Ni–PGE-bearing Noril'sk Province in Russia in the 250 Ma Siberian LIP has the world's largest nickel deposit and contains a quarter of the known Ni and Pd resources. Likewise, the troctolite–gabbro–anorthosite-bearing Duluth Complex in the 1.1 Ga mid-continental rift LIP in North America contains 9% of the world's known nickel reserves[109]. The Insizwa complex of the 184–174 Ma Karoo LIP in South Africa hosts significant Ni–Cu–PGE mineralization, though no major deposits are known[110]. Silicic LIPs with A-type granitoid are potential targets for U, Sn and W deposits. The putative mantle plume responsible for the initiation of the 130–90 Ma High Arctic LIP has been linked to the hydrocarbon potential of northern Canada, northern Greenland, Svalbard and Franz Josef Land by the way of maturation of hydrocarbons[111].

Indian scenario and future research prospects

The LIP and associated features reviewed above illustrate divergent views to bring forth new challenges. The Indian subcontinent is a virtual testing laboratory not only for the existence of two large Phanerozoic LIPs of global importance, but also for a plethora of geological and geophysical and tectonic features linked with the break-up and dispersion of Gondwana land. India is also endowed with magmatic provinces practically spanning the entire geologic time, and therefore, an initiative must be taken for a better understanding of the origin of LIPs through geological time-span. The frontier areas identified for future research in India are summarized as follows:

Geochronology

The precise ages and duration are poorly known for Indian LIPs. This area of research needs immediate attention using different age-dating techniques (e.g. multi isotope radiometric dating), integrated with field-based study, petrological and geochemical results. The radiometric dating of successive lava flows interspersed by sedimentary horizons in the Precambrian LIPs holds promise for their better characterization and modelling.

LIP identification

LIP identification and research in the Himalayas and Pre-Himalayan basement should be considered. The reported ca. 132 Ma early Cretaceous Comei–Bunbury LIP[112] with an aerial extent of 40,000 km^2 consisting of basaltic lavas, mafic sills and dykes, and gabbroic intrusions ± subordinate ultramafic intrusions and minor silicic volcanic rocks and its equivalent in the Tethyan Himalaya, deserve detailed study, mapping and characterization. This has implications for the break-up of eastern Gondwana. The Panjal volcanics in western Himalaya and the Abor in the eastern Himalaya require a fresh look on modern lines of LIP research.

Petrology and geochemistry

Mantle source heterogeneity: Studies on the nature and extent of mantle source heterogeneity, including Fe and other incompatible trace element distributions below Indian LIPs should be undertaken. This aspect for the Deccan and Rajmahal–Sylhet LIPs is not adequately addressed, though some lithospheric contributions are suggested[113] for the Deccan basalts. Study of near-primitive samples would be of interest. Geochemical variations in incompatible elements, including REE and isotope compositions to understand source heterogeneity are of immense importance.

Estimation of magma temperature: Thermal state of mantle below Indian igneous provinces is still not well known. Estimation of magma temperature for Indian Precambrian LIPs (e.g. Dalma, Mahakoshal, Sandur, Dongargarh, Malani, Bababudan), using various robust thermometers available in the literature, should be compared with results for the Phanerozoic counterparts (e.g. Rajmahal–Sylhet, Deccan, Himalayan provinces). Because the performance of different geothermometers may largely differ for various partition coefficient used, it gives a fresh opportunity to experimental petrologist to determine and update mineral–melt partition coefficients relevant to mineralogy of a perceived heterogeneous mantle.

Crust–mantle interactions: Open system processes in LIP magma production and evolution, including crust–mantle contributions in the Deccan and Rajmahal LIP genesis deserve attention using micro-/nanoscale mineral chemistry and petrography, and numerical modelling. Establishing mafic LIP–kimberlite–carbonatite link holds much promise to break new conceptual model.

Mafic dykes: Magma plumbing system (including dykes) in LIP emplacement is not well understood. The existing models can be evaluated and new ideas may be tested in known provinces. High-resolution geochemical and isotopic compositional data (both bulk and individual minerals) and high P–T experimental studies are required for better constraints. Ancient provinces (e.g. Dharwar, Bundelkhand, Bastar, NE India) need to be re-examined in this regard.

Role of fluids: Fluid–rock interactions, fluids activity (particularly H_2O, CO_2), and dissolution–precipitation reaction processes are other promising areas that can be undertaken for Indian LIPs (e.g. large granitoids in the Bundelkhand Province).

Lava stratigraphy and paleomagnetism

Study of the known LIPs (e.g. Deccan) should be strengthened and extended for correlation of lava flows and for understanding physical conditions of eruptions. The knowledge can be utilized in developing much difficult lava stratigraphy in older and eroded LIPs.

Geodynamics

Understanding tectonic scenarios that give rise to LIP stratigraphy in older sequences as well as in the Himalayas is fundamentally important.

Metallogeny

Metallogenic aspects of the LIPs need to be thoroughly explored. Ongoing investigations and exploration for radioactive minerals and tungsten in the Dongargarh Province, Bundelkhand, and high Ni–Cr–PGE concentrations and gold in Archean and Palaeoproterozic volcanic-sedimentary sequences (e.g. Dharwar, Aravalli Craton, Dalma-Dhanjhori, Mahakoshal) are noteworthy.

Microorganisms

Distribution of microorganisms in bore-hole samples in Precambrain volcano-sedimentary basins (e.g. Krishna–Godavari basin) is another area that deserves attention.

Concluding remarks

Understanding the origin of LIPs constitutes a first-order problem in Earth Sciences and merits high priority. We have summarized the current state of LIP research highlighting competing views that are important from the Indian prospective. We propose that 'deep earth study' deserves a major thrust in India, with development of a national programme, solely devoted to this cause and augment research on all aspects of LIPs, including high quality data generation, which is essential to match global initiatives and make tangible contributions. Such an initiative will help in identifying strong integrated groups and subgroups in different fields towards a better understanding of the dynamics and evolution of crust–mantle system in the Indian subcontinent.

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