Review Article

Spatial and Temporal Distribution of Large Igneous Provinces in the Indian Shield – Highlights of Recent Investigations

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This report highlights investigations since 2016 on the Large Igneous Provinces (LIPs), particularly based on their mafic dyke swarms (MDSs) and continental flood basalts (CFBs), from the Indian Shield. Recent research, particularly geochemistry, geochronology and paleomagnetism, allow identification and characterization of distinct generations of LIPs in space and time in the Indian Shield. This could be the basis for critical new tests of paleogeographic reconstructions of supercontinents and paleocontinents of the Earth's history and the position of India in different ancient supercontinent/supercratons. The high-quality data generated in recent years also helped significantly to understand the nature, composition and evolution of the sub-continental lithospheric mantle beneath the Indian Shield, which aims at resolving important geological aspects, such as the role of plume tectonics, ancient subduction events, extent of the LIPs paleo-supercontinent reconstructions, etc., and has received considerable national and international attention.

Keywords: Large Igneous Provinces; Geochemistry; Geochronology; Paleomagnetism; Mafic Dyke Swarms; Continental Flood Basalts; Indian Shield

Introduction

Large Igneous Provinces (LIPs) represent large volume ($>0.1 \text{ Mkm}^3$), mainly mafic (–ultramafic) magmatic events of intraplate affinity that occur in both continental and oceanic settings and are typically of short duration ($<1 \text{ myr}$) or consist of multiple short pulses over a maximum of a few 10s of myr (cf. Bryan and Ferrari, 2013; Ernst, 2014). LIPs may comprise continental flood basalts (CFBs), and a plumbing system of mafic dyke swarms (MDSs), sill complexes, layered intrusions, and crustal magmatic underplating, although erosion and deformation over time means that an individual LIP may incompletely preserve some of these components. LIPs can also be associated with silicic magmatism (known as Silicic LIPs, or SLIPs; when the size reaches LIP-scale),

carbonatites and kimberlites and could be linked with continental breakup, regional domal uplift, global climate change including extinction events (e.g. Ernst and Youbi, 2017). Moreover, it represents significant reservoirs of energy and metals that can either drive or contribute to a variety of metallogenic systems, and also affect hydrocarbon and aquifer systems as well (cf. Ernst and Jowitt, 2017). The relationships between LIPs and the generation of multiple different types of mineral, water and hydrocarbon resources are only useful to industry if exploration strategies can be developed that take advantage of the LIP record and variations in the characteristics (e.g. geochemistry) of individual LIPs (Ernst and Jowitt, 2017). ‘Barcoding’ the geological record, particularly identifying LIP events, allows, in principle, the

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possibility of a full reconstruction of Earth's paleogeography of continents, back to ca. 2.7 Ga (cf. Bleeker and Ernst, 2006; Ernst, 2014).

LIPs are primarily represented by large volume mafic magmatic events, particularly MDSs and CFBs. However, for many reasons including their great vertical depth and lateral extent, MDSs in shield areas provide the most complete record of such magmatism through time and space (cf. Srivastava *et al.*, 2010, 2019a; Ernst, 2014; Peng *et al.*, 2016, 2019; Sensarma *et al.*, 2018). CFBs are more common in Phanerozoic LIPs, but are present only as erosional remnants during the Precambrian where the LIP plumbing system of MDSs provides a robust record of the rhythm of intraplate mantle melting events; this includes rift-related events to the largest known igneous events on the planet (cf. Ernst, 2014). More importantly, if such MDS events are linked with precise ages, they become an incomparable source of information on several geological and geodynamic aspects, such as tectonics, secular evolution of the mantle, age and location of igneous centres, paleo-stress directions, key paleomagnetic poles, paleo-intensities of the core dynamo, plume frequency, mantle sources, etc. and subsequently reconstruction of ancient supercontinents (cf. Srivastava *et al.*, 2010, 2019a; Srivastava, 2011; Ernst, 2014; Ernst and Jowitt, 2017; Ernst and Youbi 2017; Sensarma *et al.*, 2018; Peng *et al.*, 2016, 2019).

The different cratonic regions of the Indian Shield have an extensive record of large magmatic events (LIPs) from Precambrian to Paleogene, and are also thought to be an integral part of several ancient supercontinents (cf. Ernst, 2014; Sensarma *et al.*, 2018; Roy and Purohit, 2018; Samal *et al.*, 2019a,b). Precambrian mafic magmatic events are mostly represented by extensive emplacement of mafic dyke swarms (Srivastava *et al.*, 2016a; Samal *et al.*, 2019a). A number of recent publications (since 2016) provide comprehensive information on geochemistry, geochronology, and paleomagnetism of the different components of LIPs from the different Indian cratons, mobile belts and sedimentary basins of the Indian Shield (see Fig. 1). Similar to the known LIPs of the globe, LIP events of the Indian Shield can also be correlated with distinct metallogenic systems (cf. Srivastava *et al.*, 2018; Nehru and Sikka, 2018). Glimpses of all these findings, into two major groups

i.e. (i) Precambrian and (ii) Phanerozoic LIPs, are summarized in the subsequent sections.

Precambrian LIPs

Broadly, the Indian Shield comprises twelve LIP events during Precambrian (cf. Ernst and Srivastava, 2008; Ernst, 2014; Samal *et al.*, 2019a,b; see Table 1). Based on the recent investigations, salient geochronological, geochemical and paleomagnetic highlights of these LIPs are described below.

Geochronology

A number of recent publications report geochronological data, mostly precisely dated, particularly using the U-Pb methods, of distinct magmatic events of the Indian Shield (Kumar *et al.*, 2017; Samom *et al.*, 2018; Shellnutt *et al.*, 2018, 2019; Nagaraju *et al.*, 2018a,b; Srivastava *et al.*, 2019b; Söderlund *et al.*, 2019; Liao *et al.*, 2019) and these are well summarized in Samal *et al.* (2019a,b).

Söderlund *et al.* (2019) have refined the LIP record of the Dharwar craton through ID-TIMS U-Pb baddeleyite ages of different generations of mafic dykes. On the basis of these new eighteen Paleoproterozoic ages together with ages reported in other recent publications (Nagaraju *et al.*, 2018a,b; all other available ages are compiled in Söderlund *et al.*, 2019; Samal *et al.*, 2019a,b), they identified eight different dyke swarms with emplacement ages between 2.37 and 1.79 Ga across the eastern Dharwar Craton (see Table 1 for their respective LIPs). These include:

1. NE–SW to ESE–WNW trending ca. 2.37 Ga Bangalore-Karimnagar swarm,
2. N–S to NNE–SSW trending ca. 2.25 Ga Ippaguda-Dhiburahalli swarm,
3. N–S to NNW–SSE trending ca. 2.22 Ga Kandlamadugu swarm,
4. NW–SE to WNW–ESE trending ca. 2.21 Ga Anantapur-Kunigal swarm,
5. NW–SE to WNW–ESE trending ca. 2.18 Ga Mahbubnagar-Dandeli swarm,
6. N–S, NW–SE, and ENE–WSW trending ca. 2.08 Ga Devarabanda swarm,

Fig. 1: Generalized geological map showing distinct Precambrian and Cretaceous mafic dyke swarms (MDSs) and Cretaceous continental flood basalts (CFBa) in different Cratons of the Indian Shield (Figure modified and taken from Samal *et al.*, 2019a,b). Other major geological features: Ch, Chattisgarh Basin; CIS, Central Indian Shear Zone; CGC, Chhotanagpur Gneissic Complex; GR, Godavari Rift; M, Madras Block; Mk, Malanjhand; MR, Mahanadi Rift; N, Nilgiri Block; NS, Narmada-Son Fault Zone; PCSZ, Palghat-Cauvery Shear Zone; R, Rengali Province and Kerajang Shear Zone; SGC, Singhbhum Granite Complex, SMB, Singhbhum Mobile Belt; V, Vindhyhan Basin

7. E–W trending ca. 1.88–1.89 Ga Hampi swarm, and
8. NW–SE ca. 1.79 Ga Pebbair swarm.

Besides the identification of these Paleoproterozoic mafic dyke swarms and their respective LIPs, Söderlund *et al.* (2019) have also observed and offered reasons for bending of several

Archean-Paleoproterozoic geological features such as (i) ~450-500 km long N-S dyke (part of the ca. 2.22 Ga Kandlamadugu swarm), (ii) 2.62-2.52 Ga Closepet Granite batholiths, and (iii) 3.4-2.7 Ga greenstone belts, which have experienced a 30° relative rotation between northern and central-southern parts of the eastern Dharwar craton. They suggested that this tectonic bending observed between

the northern and southern Dharwar craton could be related either to orthogonal extension of its eastern convex side or a zone of pervasive dextral shearing affecting its southern portion. The three major dyke swarms in the eastern Dharwar craton (EDC) viz. ca. 2.37 Ga Bangalore-Karimnagar, ca. 2.25 Ga Ippaguda-Dhiburahalli, and ca. 2.21 Ga Anantapur-Kunigal, which become approximately linear swarms after correction for the tectonic bending (see Fig. 2), and if correct, then previous interpretations of plume centre location as well as paleoreconstructions, based on a radiating pattern for these swarms are probably incorrect (Söderlund *et al.*, 2019).

Pivaranus *et al.* (2018) dated a mafic dyke from NW of the Krishnagiri, Northern Granulite Terrain (NGT) that yields crystallization age of 2363 ± 6.6 Ma. This work supports the extension of ca. 2.37 Ga LIP towards the southern region of the eastern Dharwar craton. One additional dyke swarm i.e. ~ 1.85 -1.86 Ga Dharmapuri swarm is now recognized (cf. Shellnutt *et al.*, 2019; Samal *et al.*, 2019b), which could be potentially a part of the previously recognized ca. 1.88-1.89 Ga Hampi swarm. This is based on magmatic events recorded in the entire Dharwar craton, which includes NW-SE trending mafic dykes (Belica *et al.*, 2014; as described in Shellnutt *et al.*, 2019) and felsic tuffs from the upper part of the Tadpatri formation of the Cuddapah basin (Sheppard *et al.*, 2017).

In recent years, the record of Paleoproterozoic mafic dyke swarms has also expanded in the Bastar craton (Shellnutt *et al.*, 2018, 2019; Liao *et al.*, 2019). Shellnutt *et al.* (2018) obtained a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1882.4 ± 1.5 Ma on a NW trending tholeiitic dyke in the Bhanupratappur region and linked it with the Bastanar swarm of the Bastar craton and the Hampi swarm of the Dharwar craton (cf. Samal *et al.*, 2019a). This enabled a linkage between the Bastar and Dharwar cratons has been established (Shellnutt *et al.*, 2018). Another dyke from the same area, i.e. near Bhanupratappur, yields an older age (Liao *et al.*, 2019); they obtained a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2365.6 ± 0.9 Ma on a boninitic dyke that is now termed the Bhanupratappur swarm (Samal *et al.*, 2019b). Further, the chemical and temporal similarities between the Bhanupratappur swarm of the Bastar craton and the ca. 2.37 Ga Bangalore-Karimnagar swarm of the Dharwar craton have been established,

which suggest connection between these two swarms as a giant dyke swarm. However, it is further explained that although these two cratons were adjacent to each other that they likely had a different configuration at 2.37 Ga than the present day (cf. Liao *et al.*, 2019).

A slightly younger dyke swarm, viz. Sonakhan swarm was also discovered from the NW part of the Bastar craton; a NW mafic dyke exposed near Sonakhan yielded a weighted-mean $^{207}\text{Pb}/^{206}\text{Pb}$ baddeleyite age of 1851.1 ± 2.6 Ma (Shellnutt *et al.*, 2019). An apparent connection between the Paleoproterozoic mafic dyke swarms i.e. (i) the ca. 1.88-1.89 Ga Bastanar and ca. 1.85 Ga Sonkhan swarms of the Bastar craton, (ii) the ca. 1.88-1.89 Ga Hampi and ca. 1.85-1.86 Ga Dharmapuri swarms of the Dharwar craton, and (iii) the ca. 1.89 Ga Boonadgin and ca. 1.85 Ga Yalgoo dykes of the Yilgarn craton has been suggested (Stark *et al.*, 2019; Shellnutt *et al.*, 2019; Samal *et al.*, 2019b). These swarm correlations are supportive of India and Western Australia being in connection during the Paleoproterozoic (see Fig. 3) and all these magmatic activities together with poorly dated ca. 1.80-1.90 Ga mafic intrusive rocks within the Himalayan Mountain Range are also thought to be part of the shared ca. 1.85-1.90 Ga LIP event (Srivastava and Samal, 2019; Samal *et al.*, 2019a,b).

Besides mafic dykes, other units of LIPs from the Bastar craton have also been dated. Santosh *et al.* (2018) reported a U-Pb zircon age of 2473 ± 8 Ma for a syenitic body exposed near the Nuapada, which probably represent thermal events associated with the ca. 2.4-2.5 Ga Dantewara LIP event (Samal *et al.*, 2019a). Chalapathi Rao *et al.* (2016) have reported $^{40}\text{Ar}/^{39}\text{Ar}$ whole-rock age of 1045 ± 9 Ma for a lamproite intrusion, which is thought to be related with the widespread alkaline and mafic magmatism of the Indian Shield ~ 1.05 -1.11 Ga (cf. Samal *et al.*, 2019a,b).

The Singhbhum Granite Complex (SGC), an integral part of the Singhbhum craton, also witnessed extensive mafic magmatism, including 'Newer' dolerites, during the Precambrian and geochronology of some of these events are reported recently (cf. Srivastava *et al.*, 2019b; Samal *et al.*, 2019a). Kumar *et al.* (2017) reported Pb-Pb baddeleyite ages for the

Fig. 2: The Dharwar craton shown in present day orientation (right) and prior to two tectonic models (left) to explain a 30° clockwise rotation from north to south of basement geological features and dyke swarms: orthogonal extension of its eastern convex side (upper left) or pervasive dextral shearing within its southern portion (lower left). Rose diagrams on top of the figure show the change before and after dykes have been adjusted by 30° relative rotation. The effect of dextral shearing is exemplified by two dykes of the N-S and NW-SE trending Ippaguda-Dhiburahalli (red) and Kandlamadugu swarms (blue), respectively (lower right). Figure taken from Söderlund *et al.* (2019)

Fig. 3: Conceptual model of rift propagation from 1.88 Ga to 1.85 Ga. The left diagram shows the initial rift and magmatism begin at ~1.88 Ga as Peninsular India and Western Australia are proximal and the right diagram shows that extension continues and rift propagates NE-ward and the younger dykes are emplaced at ~1.85 Ga (Figure taken from Stark *et al.*, 2018; Shellnutt *et al.*, 2019)

NNE-SSW trending mafic dykes exposed in the entire SGC, which are grouped into two dyke swarms i.e. (i) the ca. 2.80 Ga Keshargaria swarm and (ii) the ca. 2.75-2.76 Ga Ghatgaon swarm (Samal *et al.*, 2019a,b). These two swarms are comparable with similar magmatic events recorded in the Kaapvaal and Pilbara cratons during the Neoproterozoic (Kumar *et al.*, 2017) and represent part of a ca. 2.75-2.80 Ga global LIP event. Later, a U-Pb ID-TIMS emplacement age of 2256 ± 6 Ma was reported for the NE-SW to ENE-WSW trending Kaptipada mafic dyke swarm (Srivastava *et al.*, 2019b). Earlier, Shankar *et al.* (2014) obtained a ca. 1.77 Ga U-Pb age for WNE-ESE mafic dykes belonging to the Pipilia swarm. On the basis of integration of dyke trends, cross-cutting relationships, and available geochronological data, the mafic dykes of the SGC have been classified into seven distinct swarms, which interpreted to represent LIP events (Srivastava *et al.* 2019b; Samal *et al.*, 2019a,b). These include –

1. NE-SW trending ca. 2.80 Ga Keshargaria swarm,
2. NNE-SSW to NE-SW trending ca. 2.75-2.76 Ga Ghatgaon swarm,
3. NE-SW to ENE-WSW ca. 2.26 Ga trending Kaptipada swarm,
4. WNW-ESE trending ca. 1.77 Ga Pipilia swarm,

5. E-W to ENE-WSW trending early-Paleoproterozoic Keonjhar swarm,
6. NW-SE to NNW-SSE trending middle-Paleoproterozoic Bhagamunda swarm, and
7. N-S to NNE-SSW trending late-Paleoproterozoic Barigaon swarm.

Srivastava *et al.* (2019b) successfully correlated the ca. 2.26 Ga Kaptipada and ca. 1.77 Ga Pipilia swarms of the SGC with the ca. 2.26-2.25 Ga Ippaguda-Dhiburahalli and 1788 Ma Pebbair swarms of the eastern Dharwar craton and suggested that these two blocks were nearby during this interval. They also inferred that these two swarms should be present in the intervening Bastar craton too (see Fig. 4). Furthermore, these two swarms also match globally to ca. 2.25 Ga swarms in Antarctica, Kaapvaal and Zimbabwe cratons, and at ca. 1.79-1.77 Ga with LIP events in North China, Northern Australia, Amazonia and Sarmatia cratons suggesting a reconstruction connection with these ca. 2.25-2.26 Ga and ca. 1.77-1.79 Ga global LIP events, respectively (cf. Srivastava *et al.*, 2019b).

The mafic volcanic rocks exposed in the SGC are also thought to be associated with some of the SGC mafic dyke swarms (Srivastava *et al.*, 2016b; Srivastava *et al.*, 2019b,c; Mazumder and Chaudhuri, 2019). The ca. 2.80 Ga Dhanjori mafic volcanic rocks could be correlated with the ca. 2.75-2.80 Ga LIP.

Fig. 4: Present day configuration of ca. 2.7 Ga, ca. 2.25 Ga, ca. 1.88-1.89 Ga, ca. 1.77-1.79 Ga and ca. 1.10-1.12 Ga mafic dyke swarms and sills and associated kimberlite/lamproite intrusions in the Dharwar (EDC), Bastar, Singhbhum and Bundelkhand cratons. NSRZ = Narmada-Son Rift Zone. Figure taken from Srivastava *et al.* (2019b) and Söderlund *et al.* (2019)

The Dalma mafic volcanic are estimated be ca. 1.7 Ga and therefore, could be correlated with the ca. 1.77 Ga Pipilia swarm and also be part of the ca. 1.77-1.79 Ga LIP (Srivastava *et al.*, 2019b,c; Mazumder and Chaudhuri, 2019). The age of two other basic volcanic units, namely the Jagannathpur and the Malangtoli, have been estimated ca. 2.25 Ga (Pb-Pb age) and, therefore could be connected with the ca. 2.26 Ga Kaptipada mafic dyke swarm, which can be a part of ca. 2.25-2.26 Ga LIP of the Indian Shield and other blocks noted above (Srivastava *et al.*, 2019b,c; Mazumder and Chaudhuri, 2019).

Based on available ages and trends, the mafic dykes of the Bundelkhand craton have been classified into two distinct mafic dyke swarms viz. (i) NW-SE trending ca. 1.98 Ga Jhansi swarm, and (ii) ENE-WSW trending ca. 1.11 Ga Mahoba swarm, the latter is part of the ca. 1.05-1.11 Ga LIP event (cf. Pradhan *et al.*, 2012; Ernst, 2014; Samal *et al.*, 2019a). Samom *et al.* (2018) have presented Sm-Nd mineral-whole rock age of 2104 ± 23 Ma for a gabbroic sill from the Proterozoic Gwalior basin (sitting north to the Bundelkhand craton). On the basis of its age similarities with the radiating Devarabanda mafic dyke

swarm of the Dharwar craton, Samal *et al.* (2019a) interpreted Gwalior gabbroic sill as a part of ca. 2.08 Ga Devarabanda LIP. The Neoproterozoic Malani Igneous Suite (MIS) is identified as a silicic LIP (SLIP) and recently a representative sample of this suite from the Mirpur Granite has yielded a U-Pb zircon age of 753 ± 9 Ma (de Wall *et al.*, 2018). Several other Precambrian LIP events are also present in the Indian Shield (Samal *et al.*, 2019a,b), however there is no recent work available to share.

Geochemistry

Mineralogical and geochemical characterization of LIPs and their magmatic components helps in solving petrogenetic aspects of these rocks and allows assessment of the nature and evolution of deep mantle. An earlier review of the geochemistry of Paleoproterozoic mafic dyke swarms of the eastern Dharwar craton (EDC) was provided by Srivastava *et al.* (2015). Not much subsequent geochemistry has been done on the EDC mafic dykes except for Liao *et al.* (2019), who studied boninitic dykes of the Bhanupratappur region, central Bastar craton and the Karimnagar area, NE Dharwar craton; both these swarms emplaced ca. 2.37 Ga. These authors (Liao *et al.*, 2019) have also discussed the petrogenesis of the boninitic dykes of the central Bastar craton and suggested that fractional crystallization was the likely cause of major element variability in these rocks. However trace element modeling result indicates their derivation from a pyroxenite mantle source near the spinel-garnet transition zone (Liao *et al.*, 2019).

Rai *et al.* (2019) studied the geochemistry of undated NE-SW to ENE-WSW trending Palaeoproterozoic mafic dyke swarms from the western Dharwar craton (WDC) and identified three distinct groups, which may represent three different swarms. They compared geochemistry of these WDC mafic dykes with the dated swarms of the eastern Dharwar craton (EDC). However, apart from one geochemical Group, which has close similarities with the ca. 1.88-1.89 Ga Hampi swarm, the other two geochemical groups from the WDC cannot be geochemically correlated with any of the known mafic dykes of the EDC. It is therefore a high priority to get these WDC dykes dated as these may represent new swarms for the Dharwar craton. Sesha Sai *et al.* (2019) have studied petrology and mineral chemistry

of a porphyritic mafic dyke from the Jonnagiri Schist Belt, EDC and based on magnetite-ilmenite solid solution pair yielded an equilibrium temperature of ~ 756 °C and oxygen fugacity of $10^{-15.6} \text{atmf}_{\text{O}_2}$.

Pandey and Chalapathi Rao (2019) modeled published geochemical data on 2.37, 2.21, 2.18, and 1.89 Ga mafic dyke swarms of the EDC (cf. Srivastava *et al.*, 2015) and suggested that their 'arc signals' resulted from coupled assimilation and fractional crystallization (AFC) processes that modified these mantle-derived melts. They also supported the involvement of thermal plumes in their genesis. However, several other workers have also supported genesis of these distinct Paleoproterozoic mafic dykes of the EDC emplacement in an intracratonic setting, but instead of crustal contamination favoured a role of metasomatized lithospheric mantle that had been modified during an earlier ancient subduction event (cf. Ernst 2014; Srivastava *et al.*, 2015; Rai *et al.*, 2019).

Shellnutt *et al.* (2018, 2019) presented geochemical and Nd- and Sr-isotope data on the Bastar tholeiitic dykes emplaced ca. 1.85 Ga and ca. 1.88 Ga, mostly emplaced in the northern parts of the craton. They suggest that these mafic magmatic rocks show chemical variability due to crystal fractionation and crustal contamination and do not represent primary melts. Sr and Nd isotopes and trace element data suggests derivation from partial melting of a mantle source in the spinel-garnet transition zone, which, in general, matches earlier interpretations (cf. Srivastava and Gautam, 2015). Geochemistry of these ca. 1.88-1.89 Ga dykes is comparable with the ca. 1.88-1.89 Ga NW trending Bastanar dyke swarm from the southern Bastar craton and the ca. 1.89 Ga Boonadgin dykes from the Yilgarn craton of Western Australia (Shellnutt *et al.*, 2018).

Srivastava *et al.* (2016) and Srivastava and Gautam (2016) have discussed Nd-isotope and litho-geochemistry of an early Palaeoproterozoic (ca. 2.4-2.5 Ga) high-Si high-Mg boninite-norite-diorite suite of rocks from the Bastar craton, which show the effect of crustal contamination; however, the possibility of mantle metasomatism during ancient subduction event cannot be ignored. Geochemically three varieties viz. high-Ca boninites, high-Mg norites, and high-Mg diorites are identified; the high-Ca

boninites crystallized from a magma generated by a comparatively greater percentage of melting of a lherzolite mantle source than the source for the other two varieties. It is likely that the high-Ca boninite rocks are derived from an Archean subduction process (the Whundo-type), whereas the other two types could be products of the interaction of subduction-modified refractory mantle wedge and a plume. Hazarika *et al.* (2019) studied a boninitic dyke and suggested preservation of subduction-related signatures in the lithospheric mantle beneath the Bastar craton. All these boninitic dykes are thought to be associated with the Dantewara mafic dyke swarms (cf. Samal *et al.*, 2019a,b).

Geochemical characteristics of the ca. 0.76–0.77 Ga Malani Igneous Suite (MIS), identified as a SLIP, suggest a two-stage evolution model with initial and late stage rifting and crustal extension events (de Wall *et al.*, 2018). It is also suggested that mafic rocks of the MIS are derived from a depleted continental lithospheric source, whereas the silicic component shows low-pressure high-temperature melting. The bimodal association is due to mantle upwelling which leads to the melting of thin crust.

Srivastava and Samal (2019) studied the geochemical characteristics of Paleoproterozoic mafic intrusive rocks from the western Arunachal Himalaya, which is thought to be a part of the ca. 1.85–1.90 Ga LIP, to understand their petrogenesis and tectonic environment. Two suites of rocks identified as high titanium mafic and low titanium mafic intrusives, which were originally spatially separated at the time of their emplacement, but were tectonically juxtaposed during the Himalayan orogeny. It is suggested that these two distinct geochemical groups of the intrusive rocks were derived from discrete mantle melts; one group from ~20–25% melting in the spinel stability field (thinner lithosphere), whereas the other group was derived from ~5–10% melting of a similar mantle source but in garnet stability field (thicker lithosphere). Rashid *et al.* (2019) have also studied metabasic rocks from Lesser Himalayan sequence, western Arunachal Pradesh, for their geochemistry and presented almost similar results as observed by Srivastava and Samal (2019).

Paleomagnetism

There is a limited recent work on paleomagnetism of

the Precambrian LIPs. Nagaraju *et al.* (2018a) studied ca. 2252 Ma (part of the Ippaguda-Dhiburahalli swarm) and ca. 2207 Ma (part of the Devarabanda swarm) dykes of the Dharwar craton and reported paleomagnetic poles at 16°S, 299°E ($dp = 13^\circ$ and $dm = 15^\circ$) and 57°N, 113°E ($dp = 8^\circ$ and $dm = 10^\circ$), respectively. They have also refined the existing APW path for the Dharwar craton between 2367 Ma and 1886 Ma and reported that a major tectonic activity such as breakup of a supercontinent at 2.2 Ga may have been responsible for rapid drift of Dharwar craton between 2216 Ma and 2207 Ma. In another publication, Nagaraju *et al.* (2018b) studied the ~450 km long ca. 2216 Ma N-S striking Kandlamadugu dyke swarm and reported a paleomagnetic pole at latitude 36°S and longitude 312°E ($A95 = 7^\circ$) for this swarm. Babu *et al.* (2018) have also studied the ca. 2367 Ma Bangalore-Karimnagar dyke swarm and reported possible spatial link among the Dharwar dykes (India), Widgemooltha and Erayinia dykes (Australia), Sebang Poort dykes (Africa) and Karelian dykes (Baltica Shield). Pivarunaset *et al.* (2018) have also added new paleomagnetic results from mafic dykes exposed in the Salem Block of the Northern Granulite Terrain (NGT) and reported that ca. 2370 Ma Bangalore-Karimnagar dyke swarm is present in the NGT with a paleomagnetic pole at 2°N and 73°E ($A95 = 14^\circ$). In addition, this study also reveals that several of the reported paleomagnetic directions from NGT are matching with the 2.21 Ga, 2.18 Ga, and 1.88 Ga dykes of the Dharwar craton and hence support a juxtaposition of northern part of the southern India (i.e. NGT) with the Dharwar craton from at least 2370 Ma (see Fig. 5).

Radhakrishna and Chandra (2017) reassessed the palaeomagnetic data on Proterozoic mafic dykes in the Bundelkhand and Bastar cratons and estimated the 1.466 Ga paleopole, probably belong to the Lakhna event, at 49.4°N and 132.9°E ($A95 = 6.6^\circ$) and 1.65 Ga paleopole at 59.6°N and 47.9°E ($A95 = 8.1^\circ$). They have suggested a positive linkage between the Indian Shield and Western Australia and negated the juxtaposition of India with North China/Laurentia in Columbia (Nuna) reconstructions.

Kumar *et al.* (2017) reported a Neoproterozoic Keshargaria-Ghatgaon LIP from the Singhbhum Granite Complex (SGC) of the Singhbhum craton and reported at key paleomagnetic pole at ~2762 Ma 14N°,

Fig. 5: Comparison of the paleomagnetic pole calculated from primary 2363 ± 6.6 Ma paleomagnetic direction (green) with other studies from the Southern Dharwar craton (violet) (Figure taken from Pivarunas *et al.*, 2018)

78° ($dp = 11$, $dm = 12$). They have reported that the Singhbhum, Pilbara and Kaapvaal cratons were located at steep latitudes at ca. 2770 Ma and could have been proximal to each other during this time. They have also proposed that Singhbhum craton with similar Archean geology could also have had its ancestry in the Vaalbara supercraton. Paleomagnetic studies on the WNW-ESE and emplaced ca. 1765 Ma Pipilia swarm of the SGC have also been presented (Shankar *et al.*, 2018). They have reported the first key paleopole at 45°N , 311°E ($dp = 5.2$ and $dm = 9.9$) and proposed a paleogeographic reconstruction at ca. 1770 Ma, indicating a linkage between Baltica Craton and India for at least ~ 370 Ma (ca. 1770–1400 Ma) and they also supported India-North China craton spatial proximity at ca. 1770 Ma (see Fig. 6).

Phanerozoic LIP

Four prominent Phanerozoic LIP events are present in the Indian Shield, viz. (i) the early Permian Panjal, (ii) the early Cretaceous Greater Kerguelen (also named Comei-Bunbury), (iii) the late Cretaceous Madagascar, and (iv) the Cretaceous-Tertiary (Paleogene) Deccan (cf. Ernst, 2014; Shellnutt, 2017,

2018; Sensarma *et al.*, 2018; Vijay Kumar *et al.*, 2018; Roy and Purohit, 2018). These LIPs may or may not be associated with the Crozet, Kerguelen, Marion and Réunion hot spots (cf. Vijay Kumar *et al.*, 2018; Roy and Purohit, 2018).

Magmatism of the Madagascar-India LIP is observed in the Madurai Block of southern India (Shaji *et al.*, 2018). Geochemical and zircon U-Pb geochronological studies have been done for the alkali leuco gabbros from Mundanmudi area. The zircon grains from the gabbro sample yield 84.6 ± 1.4 Ma, which is thought to be related with the rift-related tectonic setting. Another gabbroic/granophyric pluton exposed at the northern tip of the Nilgiri block, which emplaced ca. 93–94 Ma, is also associated to the Madagascar-India LIP (Marion hotspot) (Mohan *et al.*, 2016). They have further suggested that this magmatic event can be correlated with the post break up stage of the India-Madagascar flood basalt volcanism occurred between ca. 84 and 92 Ma (Mohan *et al.*, 2016; Shaji *et al.*, 2018).

The Permian Panjal LIP (Trap), consisting of basaltic, andesitic and silicic volcanics, is emplaced ca. 290–270 Ma, mostly recognized in the north-western Himalayan range, has been often linked with Gondwana break-up (Shellnutt, 2017, 2018; Sensarma *et al.*, 2018; Vijay Kumar *et al.*, 2018). It is suggested that the Panjal LIP was not derived from a mantle plume and its origin could be attributed from a passive rift system (Shellnutt, 2017, 2018). However, Shellnutt (2018) has recommended a careful study of Panjal Traps (particularly on their plutonic equivalents, geochronology, identifying the plumbing system, etc.) before having any definite conclusion regarding plume involvement or not.

The early Cretaceous Greater Kerguelen LIP covers a large area in SE Tibet, NE India, Western Australia and Antarctica and is thought to be associated with the break-up of East Gondwanaland ca. 132 Ma (cf. Zhu *et al.*, 2009; Olierook *et al.*, 2016, 2017; Singh *et al.*, 2019). The Greater Kerguelen LIP covers a huge area and one of the largest LIPs (cf. Bryan and Ferrari, 2013; Ernst, 2014); all the contemporaneous magmatism (initial Comei-Bunbury pulse at 130 Ma and subsequent Kerguelen pulses 118–100 Ma) of this LIP is shown in Figure 7 (Olierook *et al.*, 2016, 2017; Singh *et al.*,

2019; Srivastava, 2020). Activities related to the second pulse of this Kerguelen mantle plume are well recorded in the NE Indian Shield during ca. 118–100 Ma, particularly within the Chhotanagpur Gneissic Complex (CGC) of the Singhbhum craton and the Shillong Plateau-Mikir Hills (SPMH) Shield area, which include (i) ultrapotassic, (ii) silicate (ultramafic-alkaline)-carbonatite complexes, and (iii) mafic intrusions (Srivastava *et al.*, 2016d, 2019d; Srivastava, 2020).

Srivastava *et al.* (2016d) studied an early Cretaceous lamprophyre dyke exposed near Rongjeng, East Garo Hills, Shillong plateau and suggested its potassic affinity crystallizing in hydrous alkaline magmas, which is well comparable with the nearby Jasra potassic intrusion, but is distinctly different from the Damodar Valley lamproites as well as the Sung Valley carbonatitic-ijolitic intrusion. Several new *in-situ* U-Pb ages on zircon and perovskite, and Sr–Nd–Hf isotope data on zircon, perovskite, baddeleyite, apatite, titanite and calcite in Sung Valley and Jasra ultramafic alkaline-(carbonatite) intrusions have been reported (Srivastava *et al.*, 2019d). These high quality isotopic data suggest that the Sung Valley and the Jasra intrusions evolved through different petrogenetic processes. They were emplaced between ~102–109 Ma, well after the tholeiitic event (~117–118 Ma) recorded in the region, which suggest a different genetic history. Furthermore, the Sr–Nd–Hf isotopic compositions suggest low-pressure crustal contamination, crystal accumulation and fractional crystallization, rather than mantle-derived heterogeneity. It is recommended that different magmatic rocks of the Damodar Valley and the Antarctic ultramafic lamprophyres result from a variable extent of pre-Mesozoic metasomatism in the lithospheric mantle of eastern Gondwana (Srivastava *et al.*, 2019d). It is further explained that eruption of the Sylhet-Rajmahal tholeiitic basalts, mafic dykes and lamproites at ca. 112–118 Ma have a possible genetic connection with a mantle plume, but that the relatively younger (~101–109 Ma) alkaline carbonatite complexes and lamprophyre of the Shillong Plateau are likely to have their derivation from distinct magma batches generated through the depleted asthenosphere and lithosphere with negligible contribution from the Kerguelen mantle plume. The latter, however, possibly provided additional heat necessary to melt the source

regions (Olierook *et al.*, 2017; Srivastava *et al.*, 2019d; Srivastava, 2020).

The other Phanerozoic LIP recorded from the Indian Shield is the well-known Cretaceous-Tertiary (Paleogene) Deccan LIP. A considerable amount of works on this LIP has been done in recent years. However, here we report only those publications which have direct connection with the Deccan LIP; this is because a report on the Deccan Volcanic Province is separately presented in this volume (Kumar *et al.*, 2020). Sprain *et al.* (2019) studied the Deccan Trap volcanism to understand the late Cretaceous environmental impacts and its contribution to the Cretaceous-Tertiary (Paleogene) boundary (KTB/KPB) ecosystem crisis. On the basis of high-precision $\text{Ar}^{40}/\text{Ar}^{39}$ age data, they preclude the prior interpretation of three discrete large pulses and instead conclude that >90% of the Deccan eruptions in <1 million years, with ~75% emplaced post-KPB. Their model improved our understanding on the Deccan volcanic fluxes with observed climate changes and to understand the specific role Deccan volcanism in the KPB mass extinction; similar to the results obtained earlier by Schoene *et al.* (2015) i.e. the Deccan Traps contributed to the Cretaceous environmental change and its role in the marine and terrestrial mass extinctions. It is further strengthened by new U-Pb zircon geochronology (Schoene *et al.*, 2019). They established four high-volume Deccan eruptive periods in which major eruptions were before and after the K-Pg extinction that supports both catastrophic events as drivers of environmental worsening.

The Sr and Nd isotopic signature of volcanic basalts of the Deccan LIP suggest its derivation from a heterogeneous mantle source, probably mixing of more than one distinct isotopic reservoirs and some degree of crustal assimilation (Manu Prasanth *et al.*, 2019). They further stated that the main phase of Deccan LIP could be linked with global warming, ocean acidification, climate effects, and mass extinction.

The Geological Society London has recently published a Special Issue on the Tectonics of the Deccan Large Igneous Province (Mukherjee *et al.*, 2017). Articles in this Special Issue deal with different aspects, but mostly on structural geology, related to the Deccan volcanism (Rajaram *et al.*, 2017; Maurya

Fig. 6: Paleogeographic reconstruction at 1.77 Ga (Figure taken from Shankar *et al.*, 2018)

et al., 2017, Misra and Mukherjee, 2017; Babar *et al.*, 2017). Kale *et al.* (2017) provided an overview on the relationship between geomorphology and Deccan plateau uplift. Ju *et al.* (2017) have used mafic dyke swarms associated with the Deccan LIP and showed that they follow trends of several rift zones in peninsular India, which are thought to have existed since Archean, to discuss effects of mechanical layering and regional tension on dyke emplacement within the Narmada rift zone. They emphasized that the distribution of maximum principal tensile stresses was altered by mechanical layering and/or regional tension, which has led to variations in potential dyke propagation pathways. Three sets of dykes, mostly feeder dykes associated with Deccan LIP, are identified; these are (i) 65.6 Ma, (ii) 65 Ma, and (iii) 64–63 Ma, which have been studied for their structural analyses (Misra and Mukherjee, 2017). Pathak *et al.* (2017), on the basis of Virtual Geomagnetic Pole (VGP), obtained by palaeomagnetic measurements of 37 lava flows from the eastern Deccan Volcanic Province, and concluded that the eastern and western Deccan Traps were erupted for a shorter period close to the Cretaceous–Palaeogene boundary (KPB).

Buchan and Ernst (2019) presented very exciting results on the different mafic dykes of the Deccan LIP and classified them as (i) radiating dykes and (ii) circumferential dykes; some other dykes, whose trends are not matching to radiating or circumferential swarms, are also reported. The radiating dyke swarm particularly belongs to the Narmada-Tapi, the West Coast, and the Saurashtra (Kathiawar) region sub-swarms. They further stated that the dykes that are perpendicular to these sub-swarms of the radiating system are part of a giant circumferential dyke swarm with an outer diameter of >600 km and an arc of ~220° and they locate the centre of this circumferential swarm near the focus of the radiating swarm in the Gulf of Cambay, which falls along the Réunion mantle plume track (see Fig. 8). Precise radiometric dating of mafic dykes belonging to both of these swarms is recommended for better understanding (Buchan and Ernst, 2019).

High-Mg dolerite dykes (identified as micro-dolerites), exposed in the central part of the Deccan LIP, have been reported and studied for their geochemistry (Dongre *et al.*, 2018). The mineral chemistry of different constituent minerals and the

Fig. 7: Simplified plate tectonic reconstruction (modified from Zhu *et al.*, 2009; Singh *et al.*, 2019) of East Gondwanaland, showing major magmatic events during ~100-140 Ma which are supposed to be part of the Greater Kerguelen LIP. Location/events: AV, Abor volcanic; BB, Bunbury basalt; BL, Beaver Lake lamprophyres; CMP, Comei magmatic province; DVAP, Damodar Valley alkaline province; NPB, Naturaliste Plateau basalt; RB, Rajmahal basalts; SB, Sylhet basalts; SPAP, Shillong Plateau alkaline province (Figure taken from Srivastava, 2020)

high MgO nature of these picro-dolerite dykes are indicative of their genesis through plume magmatism, formed by high degrees of partial melting and also inferred that these are the source of alkali basalt flows, whereas tholeiitic dykes of the western and northern Deccan-related dyke swarms cannot represent the feeders for the alkali basalt flows (Dongre *et al.*, 2018).

Summary

The descriptions above clearly demonstrate a remarkable amount of work done on Large Igneous Provinces (LIPs) and their components for the Indian context in space and time since 2016. This will definitely be useful in understanding geodynamics of the Indian Shield and supercontinents through time and also identifying the avenue for new research. Some important observations are :

1. Broadly, the Indian Shield comprises twelve prominent LIP events during Precambrian and on the basis of new high-precision U-Pb data, a number of distinct magmatic events, mostly in form of mafic dyke swarms and continental flood basalts, are identified in the different Archean

cratons of the Indian Shield.

2. A 30° relative rotation in trend of mafic dyke swarms (older than 2.08 Ga) and other older geological features between northern and southern Dharwar cratons has been identified. This tectonic probably formed through either orthogonal extension of its eastern convex side or a zone of pervasive dextral shearing affecting its southern portion. This resultant change in dyke swarm patterns emplaced before 2.08 Ga swarm; radiating swarms converted to linear swarms.
3. In general, geochemical characteristics of the Paleoproterozoic mafic dykes suggest genesis through mantle melts and their emplacement in an intracratonic setting. However, the role of a previously modified metasomatized lithospheric mantle due to some ancient subduction event cannot be ignored.
4. An early Cretaceous Greater Kerguelen LIP event with a time span of ~35myrs (~100-135 Ma) is identified, which covers different magmatic events recorded in SE Tibet, NE India, Western Australia and Antarctica. The magmatic activities recorded in the Chhotanagpur Gneissic Complex the Shillong Plateau-Mikir Hills of the NE Indian Shield are part of the Greater Kerguelen LIP. This also includes Rajmahal-Sylhet-Bengal and Abor volcanics.
5. New geochronological data on the Deccan Trap volcanism helped to improve our understanding on how the Deccan volcanic fluxes link with observed climate changes and actually to understand the specific role of Deccan volcanism in the KPB mass extinction.
6. A giant circumferential dyke swarm with an outer diameter of >600 km and an arc of ~220° has been identified in the Deccan volcanic province. It is predicted that the centre of this circumferential swarm is situated near the focus of the radiating swarm in the Gulf of Cambay, which falls along the Réunion mantle plume track. However, further study, particularly geochronological and paleomagnetic, is recommended to come to any final conclusion.

Fig. 8: Circumferential and radiating dykes of the ca. 65 Ma Deccan LIP, India. Pink circles indicate the approximate outer and inner dimensions of the circumferential swarm. The centre of the circumferential swarm and the focus of the radiating swarm are similar and fall roughly on the Reunion plume track. S, Saurashtra (Kathiawar) region; GC, Gulf of Cambay. Figure taken from Buchan and Ernst, 2019

7. All of these important researches could be the basis for critical new tests for paleogeographic reconstructions of supercontinents and paleocontinents in Earth's history. The new paleomagnetic and geochronological data on the different LIPs of the Indian Shield have helped to identify ancient supercontinents.

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