Gondwana Large Igneous Provinces (LIPs): distribution, diversity and significance

SARAJIT SENSARMA[1]*, BRYAN C. STOREY[2] & VIVEK P. MALVIYA[3]

[1]*Centre of Advanced Study in Geology, University of Lucknow, Lucknow, Uttar Pradesh 226007, India*

[2]*Gateway Antarctica, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand*

[3]*24E Mayur Residency Extension, Faridi Nagar, Lucknow, Uttar Pradesh 226016, India*

**Correspondence: sensarma2009@gmail.com*

Abstract: Gondwana, comprising >64% of the present-day continental mass, is home to 33% of Large Igneous Provinces (LIPs) and is key to unravelling the lithosphere–atmosphere system and related tectonics that mediated global climate shifts and sediment production conducive for life on Earth. Increased recognition of bimodal LIPs in Gondwana with significant, sometimes subequal, proportions of synchronous silicic volcanic rocks, mostly rhyolites to high silica rhyolites (±associated granitoids) to mafic volcanic rocks is a major frontier, not considered in mantle plume or plate process hypotheses. On a $\delta^{18}O$ v. initial $^{87}Sr/^{86}Sr$ plot for silicic rocks in Gondwana LIPs there is a remarkable spread between continental crust and mantle values, signifying variable contributions of crust and mantle in their origins. Caldera-forming silicic LIP events were as large as their mafic counterparts, and erupted for a longer duration (>20 myr). Several Gondwana LIPs erupted near the active continental margins, in addition to within-continents; rifting, however, continued even after LIP emplacements in several cases or was aborted and did not open into ocean by coeval compression. Gondwana LIPs had devastating consequences in global climate shifts and are major global sediment sources influencing upper continental crust compositions. In this Special Publication, papers cover diverse topics on magma emplacements, petrology and geochemistry, source characteristics, flood basalt–carbonatite linkage, tectonics, and the geochronology of LIPs now distributed in different Gondwana continents.

The continents that were stitched together in late Neoproterozoic–early Cambrian times formed the continent Gondwana, which combined with Laurentia in the Carboniferous to form Pangea and progressively fragmented in the Mesozoic. For much of that time, Gondwana was the largest continent on Earth, covering more than 100 million km^2 in area (Fig. 1). Gondwana constituted the present-day continents of South America, Africa, most of Australia and Antarctica, the Indian subcontinent and Madagascar, and parts of Arabia. A Zealandia continent, 94% of which is now submerged under ocean water, was also part of Gondwana (Mortimer *et al.* 2017*a*). All these remnants of Gondwana, including Zealandia, constitute more than 64% of the present-day continental mass (Torsvik & Cocks 2013). The supercontinent Gondwana survived for more than 300 myr until several parts of it separated and drifted away. It is conceivable that the records of major and significant geological events that are central to understanding the origin and evolution of continents through entire geological time are likely to be preserved in the present-day Gondwana continents. Major igneous events that took place over geological time in Gondwana are therefore intrinsic to the understanding of the Earth's lithosphere–atmosphere system that finally shaped Earth's surface processes conducive for life on this planet.

Our understanding of Gondwana evolution is much improved in the last three decades of research. We have realized that one of the important aspects, as evidenced from the reconstruction of continents with kinematic continuity using the GPlates software, could be that the bulk of Gondwana and its constituent cratons may have been relatively weakly affected by Phanerozoic tectonics (Torsvik & Cocks 2013). We have also understood that associated regional-scale intrusive (e.g. dyke swarms) rocks represent a powerful tool in reconstructing the original size and extent of Large Igneous Provinces (LIPs) in order to assess their enormity, and to better understand crust–mantle systems and related

From: Sensarma, S. & Storey, B. C. (eds) 2018. *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**, 1–16.
First published online November 27, 2017, https://doi.org/10.1144/SP463.11

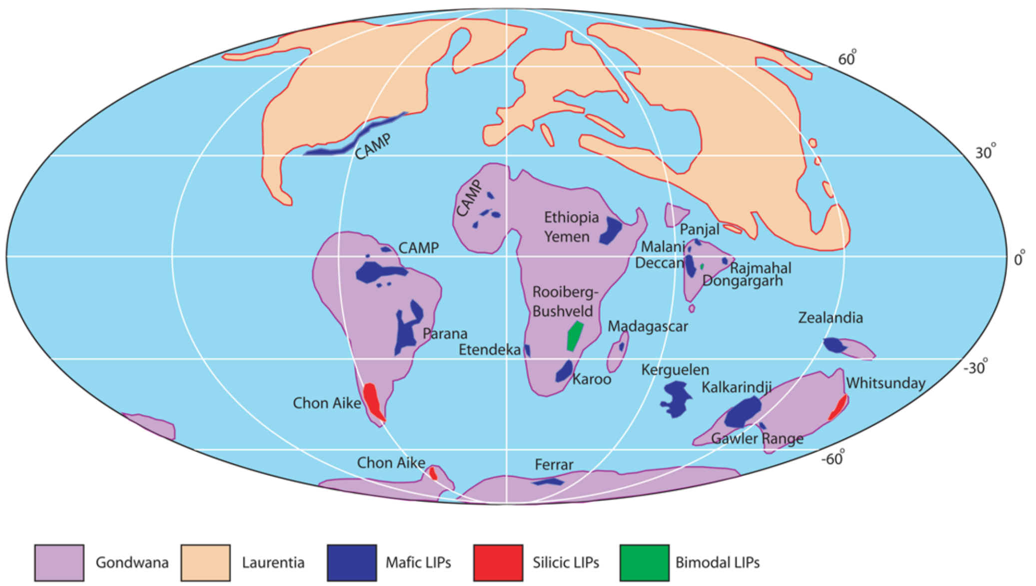

Fig. 1. Distribution of major Gondwana LIPs on a map after Gondwana break-up (*c.* 50.2 Ma). Already known bimodal LIPs are shown separately. The figure is modified after Coffin & Eldholm (1994), Bryan *et al.* (2002) and Paleomap Project, https://www.britannica.com/science (2001, C. R. Scotese, PALEOMAP Project).

tectonics. In many cases, remnants of single LIPs are now exposed in spatially separated continents. Despite our best efforts, however, understanding on their size, duration, frequency and link to continental break-up processes remains incomplete. The role of Gondwana LIPs in global climate and environmental shifts, and large-scale sediment production that influence even present-day upper continental crustal compositions are also of great interest.

This introductory paper to this Special Publication puts forward some perspectives as to how Gondwana large igneous events and related tectonics are important in understanding crust–mantle processes and their role in meditating global climate changes and sediment production over time. We also present an overview of the volume in the context of our understanding of Gondwana LIPs, highlighting the key points discussed in the included papers. For the benefit, in particular, of students and upcoming researchers, a note on possible issues concerning Gondwana LIP events that confront us at this time is briefly discussed at the end of this article.

Size and distribution of Gondwana LIPs

Large Igneous Provinces (LIPs) represent the largest volcanic events on Earth. The volcanic rocks in LIPs may cover huge areas of variable extent from as large as >100 000 km^2 (Bryan & Ernst 2007) to at least >50 000 km^2 (Sheth 2007). Gondwana is home to many of the largest LIPs globally. On the basis of a LIP inventory given in Ernst (2014), and different LIP webpages (largeigneousprovinces.org; mantleplume.org), the tentative size and distributions of the Gondwana LIPs are listed in Table 1. The compilation suggests that Gondwana LIPs cover nearly 58% of the surface area occupied by all LIPs on the present-day Earth (Gondwana and Laurentia LIPs put together). Amongst the LIPs, approximately 33% now occur in the Gondwana continents only.

Kalkarindji LIP (Australia), the oldest Phanerozoic LIP (*c.* 512–509 Ma), covers >2000 000 km^2 at present (Jourdan *et al.* 2014). The Paraná–Etendeka province (138–129 Ma), one of the largest LIPs ever erupted on Earth, covers presently at least 2 000 000 km^2 area (Ernst 2014), remnants of which are now exposed in Brazil, Paraguay and Africa across the Atlantic. The Afar province in Yemen–Ethiopia–Sudan–Egypt–Saudi Arabia at present covers an area as large as 2 000 000 km^2. The Panjal Traps (*c.* 290 Ma), presumably linked to the LIPs in the Himalayan magmatic province (HMP) emplaced during *c.* 290–270 Ma, is estimated to cover >2 000 000 km^2 in northern India–Pakistan–Tibet–Nepal. Another huge Gondwana LIP includes the Cretaceous (66–61 Ma) Deccan LIP (India) covering 600 000 km^2; on inclusion of part of the Madagascar province and the Seychelles, believed to be a detached remnant of the Deccan, the size of the

Deccan LIP may go up to >850 000 km^2. Other notable LIPs in Gondwana are the 188–178 Ma Karoo–Ferrar (nearly 150 000 km^2) in South Africa and Antarctica. With the Chon Aike province in Patagonia, recently recognized to be linked to the Karoo–Ferrar event (Pankhurst *et al.* 1998; Storey *et al.* 2013), the original size of the Karoo–Ferrar would obviously be larger than presently estimated. The 132–95 Ma Whitsunday province in eastern Australia covers nearly 200 000 km^2 (Bryan *et al.* 2000, 2012). Zealandia hosts volcanic rocks with an estimated volume of 4.9 million km^3 (Luyendyk 1995; Mortimer *et al.* 2017*a*). The total area covered by 116–95 Ma Rajmahal-Sylhet LIP (India) is *c.* 250 000 km^2 (Baksi 1995).

Precambrian LIPs, although still not adequately studied or known, are increasingly better identified and recognized in the Gondwana continents. The enormity of the Precambrian LIPs could be overwhelming as well (Ernst *et al.* 2013). The 2.19–2.10 Ga LIP event recognized in the West African Craton covers nearly 2000 000 km^2 at present, despite having been subjected to the prolonged action of secondary processes such as deformation, metamorphism, weathering and erosion. One of the major Precambrian LIPs is identified in the Yilgarn Craton in Australia. Despite prolonged weathering and erosion, several Precambrian LIPs located in Gondwana cover nearly 50 000–100 000 km^2: for example, the 1.9 Ga Great Dyke of the Zimbabwe Craton (Ernst 2014), the *c.* 2.5 Ga Dongargarh province (India: Sensarma 2007), the *c.* 2.06 Ma Rooiberg–Bushveld province (South Africa: Lenhardt & Eriksson 2012) and the *c.* 750 Ma Malani province (India: Sharma 2004) to name a few, implying that these provinces must have originally covered much larger areas. However, the effects of deformation and metamorphism, and other secondary processes make it difficult to identify and reconstruct matching details in the LIP remnants across continents. The lack of precise U–Pb ages in Precambrian LIPs further compounds the problem (Ernst *et al.* 2005, 2013).

The crust–mantle system of Gondwana LIPs and the tectonic context

The origin of LIPs is a first-order problem in Earth science. Neither the plume hypothesis nor plate tectonic processes adequately explain all observations in an integrated fashion for all LIPs. In some cases, none of the hypotheses is favoured. One of the emerging frontiers of LIP research today is recognition of the almost ubiquitous presence of significant amounts of silicic volcanic rocks, mostly rhyolites to high-silica rhyolites (and associated granitoids) in mafic LIPs. Indeed, in addition to mafic and silicic LIPs, bimodal LIPs do exist with substantial to subequal volumes of near-synchronous silicic and mafic rocks (Foulger 2007 and references therein). It is also known now that silicic LIP events could be as large as their mafic counterparts (Bryan & Ferrari 2013). Intrinsic to this compositional and petrological problem is the fact that the link between LIPs and continental break-up remains enigmatic. The break-up in many cases was aborted and did not culminate in the formation of an ocean because of coeval regional compression.

Increasing recognition of the substantial presence of silicic volcanic and associated plutonic rocks in continental mafic LIPs (e.g. Paraná–Etendeka (Harris & Milner 1997), Karoo–Ferrar–Chon Aike (Storey *et al.* 2013), Rajmahal (Ghose *et al.* 2016) and the Rooiberg–Bushveld province (Lenhardt & Eriksson 2012)) is a major advancement in contemporary LIP research. In the Karoo, the estimated volume of rhyolite is 35 000 km^3, which was emplaced after the main pulse (183–182 Ma) and is interstratified with basaltic lava (Cleverly *et al.* 1984). The Paraná–Etendeka province is dominantly mafic, but contains at least 20 000 km^3 of silicic volcanic rocks spread over 170 000 km^2 (Harris & Milner 1997). It is suggested that both mafic and silicic units in the Etendeka region may have originated from the same eruptive centres around the same time and are thus coeval (Milner *et al.* 1995). In the North Atlantic Igneous Province (NAIP) (62–54 Ma), a LIP not far from the Gondwana continent, substantial mafic–felsic rocks are present (Meade *et al.* 2014). In the Kalkarindji province, Jourdan *et al.* (2014) estimated the presence of a 15 000 km^{2}and 70 m-thick silicic volcanic breccia of explosive origin. New high-resolution U–Pb isotope dilution-thermal ionization mass spectrometry (ID-TIMS) geochronology on zircon and baddeleyite from both the *c.* 6000 km^3 layered silicic glassy hypabyssal intrusion, the Butcher Ridge Igneous Complex (BRIC), and from Ferrar mafic sills confirm that the BRIC magmatism occurred during the main phase of Ferrar LIP magmatism (184–182 Ma) (Nelson *et al.* 2015). It is also interesting to note that rhyolites to high-silica rhyolites in the LIPs, like Yemen–Ethiopian (500 km^3: Pankhurst *et al.* 2011), Dongargarh (8000 km^3: Sensarma *et al.* 2004; Sensarma 2007), the Sylhet Traps (Talukdar & Murthy 1971), Rooiberg–Bushveld (Lenhardt & Eriksson 2012) and Whitsunday (Bryan *et al.* 2000), are of high-temperature (800–1000°C) origin, compared to crust-derived normal magma temperatures (650–700°C).

Not only the compositional bimodality, but also the presence of substantial volumes of silicic volcanic rocks (plus silicic plutonic rocks), thus seem integral to several Gondwana mafic LIPs. The presence of a large volume of rheomorphic ignimbrites, ignimbrites, welded tuff, volcanic breccia/breccio-conglomerate and other primary pyroclastic deposits

Table 1. *Compilation of major Large Igneous Provinces (LIPs) in Gondwana with their respective area, age and duration*

SN	Name of LIP	Location	Covered area	Age (Ma)	Duration (Ma)	References
1	Afar Event	Yemen, Ethiopia, Djibouti, Saudi Arabia, Sudan, Egypt	2 000 000 km^2	31–29	3	Menzies *et al.* (1997); George *et al.* (1998); Hofmann *et al.* (1997)
2	NAVP (North Atlantic Volcanic Province) Event	UK and Greenland	1 300 000 km^2	62–58	4	Saunders *et al.* (1997)
3	Deccan Event	India and Seychelles	600 000 km^2, 1 800 000 km^2 (original area), 8 600 000 km^3	60.4–68	7.6	Eldholm & Coffin (2000)
4	Madagascar Event	Madagascar	260 000 km^2 (continental flood basalt portion only), 1 600 000 km^2, 4 400 000 km^3	90–84	6	Storey *et al.* (1997); Eldholm & Coffin (2000)
5	Kerguelen–Rajmahal Event	Indian Ocean, eastern India	6 000 000 km^3 (for South Kerguelen), 9 100 000 km^3 (for central Kerguelen–Brorken Ridge)	110–86	24	Mahoney *et al.* (1995); Kent *et al.* (1997); Eldholm & Coffin (2000); Frey *et al.* (2000)
6	Paraná–Etendeka Event	South America (Brazil, Paraguay), Africa (Namibia, Angola)	2 000 000 km^2, 1 800 000 km^2 (South America portion), 250 000 km^2 (African portion)	134–129, 138–135	9	Peate (1997)
7	Comei-Bunbury Event		*c.* 40 000 km^2	134–130	4	Zhu *et al.* (2009)
8	Karoo-Ferrar Event	Karoo (Africa), Ferrar (Antartica) provinces	Originally 5 000 000 km^3, originally (including underplating) 10 000 000 km^3, Karoo portion is 140 000 km^2, probably originally 1 000 000 km^2 and 2 500 000 km^3, Ferrar province is 500 000 km^3	183–179	16	Marsh *et al.* (1997); Storey & Kyle (1997); White (1997)
9	Chon Aike Event	Chon Aike silicic (South America) provinces	100 000 km^2	153–188	35	Pankhurst *et al.* (1998); Storey *et al.* (2013)
10	Whitsunday Event	Eastern Antartica	>500 000 km^2	132–95	37	Bryan *et al.* (2000, 2012)

11	CAMP (Central Atlantic Magmatic Province) Event	USA, South America, Africa	7 000 000 km^2, North America portion (400 000 km^2), South America portion (2 900 000 km^2), Africa portion (1 200 000 km^2)	204–191	13	May (1971); Courtney & White (1986); White & McKenzie (1989); Morgan *et al.* (1995); Burke (1996); Ernst & Buchan (1997); Marzoli *et al.* (1999)
12	Himalaya Neotethys Event (Panjal)	Northern India, Pakistan, Nepal, Tibet	*c.* 200 000 km^2	290–269	21	Garzanti *et al.* (1999)
13	Kalkarindji Flood Basalt	–	>2 000 000 km^2	508 ± 5–511.8 ± 1.9	4	Jourdan *et al.* (2014)
14	Malani Event	Aravali	*c.* 50 000 km^2	730–800 ± 50	20–80	Bhushan (2000); Sharma (2004)
15	Mundine Well Event	NW Australia (Pilbara, Yilgarn cratons)	180 000 km^2	758–752	6	http://www.largeigneousprovinces.org
16	Makuti Event	Zimbabwe, Zambia (Zambezi Belt)	–	880–740	6	http://www.largeigneousprovinces.org
17	Arabian–Nubian Shield Event	NE Africa and the Middle East (Arabian–Nubian Shield)	–	900–870	3	http://www.largeigneousprovinces.org
18	Lower Katangan Event(s)	Central Africa (Congo Craton)	140 000 km^2	1000–700	300	http://www.largeigneousprovinces.org
19	Mutare Event	Zimbabwe	20 000 km^2	1000–600	400	http://www.largeigneousprovinces.org
20	Gawler Range Event	Southern Australia (Gawler Craton)		1600–1500	100	http://www.largeigneousprovinces.org
21	Kolar Event	India	140 000 km^2	1800–1600	200	http://www.largeigneousprovinces.org
22	Bababudan Event	India (Western Dharwar Block)	30 000 km^2	3000–2500	500	http://www.largeigneousprovinces.org
23	Pietersburg–Giyani (O) Event	South Africa (north Kaapvaal Craton)	–	3500–3200	700	http://www.largeigneousprovinces.org
24	Rooiberg–Bushveld Event	Kaapvaal Craton	>200 000 km^2	2052 ± 48–2061 ± 2	37–55	Lenhardt & Eriksson (2012) and references therein
25	Dongargarh Event	Baster Craton		2506 + 4–2525 + 15; *c.* 2540–2467	*c.* 38–73	Sensarma (2007)

with/without rhyolitic lava flows in the silicic part of the LIP sequences (Chon–Aike–Karoo, Dongargarh, Whitsunday, Rajamahal, Etendeka and NAIP) and associated granitoids (crustal mush) may possibly suggest an association with large caldera structures. The largest silicic eruptions can sometimes be as large as flood basalt events as well (Bryan & Ferrari 2013).

The presence of large silicic rocks in so many Gondwana LIPs does not fit into the classic mantle plume model for large-volume mafic magma generation as the mantle plume model by itself does not produce significant volumes of silicic magma at any stage. Nor could the high-temperature (800–1000°C) large-volume silicic magmas be related to basaltic magma through fractionation. The presence of substantial silicic rocks within mafic LIPs is also not part of the models involving plate processes either. Obviously, the production of silicic rocks is linked to variable extents of crustal melting and interactions of crustal partial melts and mantle partial melts. A plausible scenario could be that the plume melting produces high-temperature magmas that impinge the crust to produce the crustal partial melts, and thereby promotes interactions of crustal and mantle partial melts. Of course, it is also possible that large volumes of mantle-derived primary basaltic magma are produced in an extensional tectonic setting independent of a mantle plume, which some workers ascribed to plume-induced rifting of the lithosphere (e.g. Samom *et al.* 2017).

Because continental crust is enriched in highly incompatible elements and thereby has a distinct radiogenic isotopic signature, incorporation of crustal components or interactions of crustal partial melts with the primary mantle-derived magma may lead to large-scale compositional heterogeneity in the final eruptive products that is now increasingly encountered in several Gondwana LIPs. For example, geochemical mass-balance calculations show that a basaltic komatiite melt may have dissolved about 20% silicic volcanics and erupted as a siliceous high-Mg basalt (SHMB) in the 2.5 Ga Dongargarh LIP (Sensarma *et al.* 2002). In the NAIP (62–54 Ma), widespread evidence of mixing and mingling of felsic (crustally derived) and mafic (mantle-derived) melts are manifested in textures, and in major, trace and high-resolution radiogenic (Sr-, Nd- and Pb-) isotope results (Meade *et al.* 2014), as also in the Panjal, to give rise to intermediate andesite rocks (Shellnutt 2017).

The low $\delta^{18}O$ value (<4–5‰) of rhyolites in some LIPs (e.g. Karoo: Miller & Harris 2007; and Dongargarh: Sensarma *et al.* 2004; Sensarma 2009) strongly argues for the involvement of hydrothermally altered crust in the generation of these rhyolites (Harris & Milner 1997; Colón *et al.* 2015). Nevertheless, the generation of LIP rhyolites call for various extents of crust–mantle interaction during emplacement of LIPs. The point is illustrated here by compiling and plotting $\delta^{18}O$ (whole rock/mineral separates as the case may be) v. initial $^{87}Sr/^{86}Sr$ of rhyolites from different Gondwana LIPs (Fig. 2). It is remarkable that rhyolites to high-silica rhyolites in Gondwana LIPs in practically all cases show a remarkable spread in-between continental crust ($\delta^{18}O$ *c.* 10–11‰) and mantle values (*c.* 5.5‰), or even 'mantle-like' values, and thus may plausibly have variable contributions of crust and mantle in their origin. Extremely high initial $^{87}Sr/^{86}Sr$ of rhyolites in some cases (e.g. Deccan) may be attributed to higher initial $^{87}Sr/^{86}Sr$ of the regional crust. Therefore, the composition (including isotopic) of the silicic component may adequately explain the trace element and isotopic variability in LIPs, and the presence of subducted crust in the plume source need not necessarily be invoked.

An interesting observation in many Gondwana mafic LIPs is the relative timing of the mafic and silicic phases; there is neither a consistent pattern to the eruption of silicic magmas, which may either precede (e.g. Ferrar, Panjal, Rajmahal, Rooiberg–Bushveld, Dongargarh), be contemporaneous with (e.g. Paraná–Etendeka) or post-date (Karoo–Lebombo) the peak of the basaltic flood volcanism.

Although the main phase of basalt erupted during a time period of *c.* 1–5 myr, occasionally extended to 1–10 myr in duration, there is significant departure too as longer time durations (30 myr for Karoo–Ferrar–Chon Aike, *c.* 24 myr for the Kerguelen–Rajmahal event, *c.* 70 myr for Dongargarh) is recorded in a couple of provinces (Fig. 3; also see Table 1). In fact, siliceous LIPs (e.g. 37 myr for Whitsunday, 20–80 myr for Malani) are known to have formed over a longer time period (40–60 myr: Bryan *et al.* 2000, 2013), However, more precise U–Pb single-zircon dating is required in several provinces to make the database robust.

The links between the emplacement of LIPs, rifting, and the process of the gradual break-up of continents and disintegration of Gondwana remain equally enigmatic (Storey 1995). There are several Mesozoic Gondwana LIPs (e.g. Deccan, Rajmahal, Karoo–Ferrar, Paraná and so on) that are plausibly linked to Gondwana rifting. However, in continental LIP provinces, whether the break-up was always concomitant to LIP emplacement and/or preceding it, or continued further in all cases even after LIP emplacement, is not adequately understood. This is important as Antarctica, even after it rifted from Gondwana, broke-up in the Mesozoic and moved to its present position in the South Pole, continued to rift further (Storey *et al.* 2013). Also, the rifting in many cases was aborted and did not finally break-up to open into an ocean because of coeval regional compression. Another important aspect is

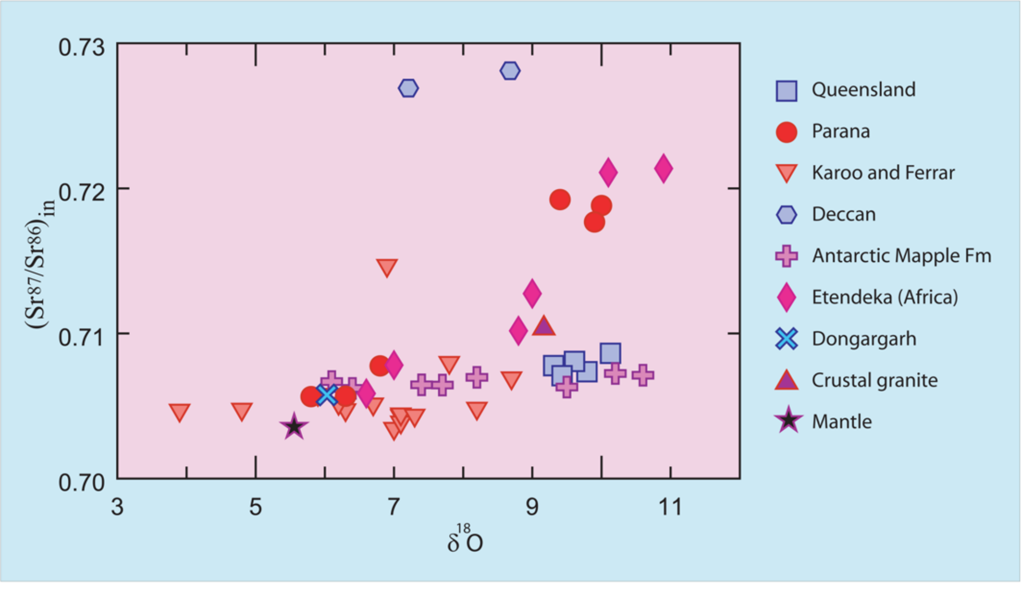

Fig. 2. $\delta^{18}O$ v. $(^{87}Sr/^{86}Sr)_{in}$ for silicic volcanic rocks (rhyolites, rhyodacites) occurring mostly in Gondwana mafic LIPs. The data spread between mantle and crustal values along a trend suggests contributions of both mantle and crust into the origin of silicic volcanic rocks in LIPs. Higher values in both oxygen- and Sr-isotopes in Paraná and Etendeka may suggest limited assimilation of supracrustals. $\delta^{18}O$ values are taken for mineral/whole-rock data as available in the literature. Data source: Queensland (Ewart 1982); Paraná (Harris *et al.* 2010); Karoo and Ferrar (Miller & Harris 2007); Deccan (Paul *et al.* 1977); Antarctic Mapple Formation (Riley *et al.* 2001); Etendeka (Harris *et al.* 2010); Dongargarh (Sensarma *et al.* 2004); crustal granite (Kempton & Harmon 1992); mantle (Rollinson 1993).

that many Gondwana LIPs (e.g. Chon Aike, Whitsunday) are close to once active plate boundaries and continental margins developed as part of plate processes. On the basis of lava geometry, the absence of domal uplift, a lack of large-volume eruption of high- to very-high-temperature (>1400°C) mantle partial melts (high Mg-rich basalts/picrites) and the enriched character of tholeiitic flood basalts, the Deccan Traps are also suggested to be intrinsically linked to plate processes by some researchers (e.g. Sheth 2005). The role of fluid in LIP genesis is also a matter of contemporary interest, particularly when nominally anhydrous minerals (e.g. olivine, pyroxene, plagioclase, garnet) could be a potential source of fluid during mantle melting even in within-plate settings. On the basis of the H_2O/Ce ratios of different mantle reservoirs, it is suggested that H_2O concentrations in plume sources may range from 300 to 1000 ppm (Hirschmann 2006 and references therein). It is argued that fluid released from mantle-plume induced subcontinent lithospheric metasomatism caused the latter (lithospheric mantle) to be enriched and fertile enough for the production of large volumes of flood basalts at shallower levels.

Effects of Gondwana LIPs on climate and sediment production

The present LIP inventory indicates that most of the LIP events occurred in Gondwana and adjacent regions. Consequently, a study of Gondwana LIP emplacement would be critical to understanding global climate changes and habitat. Many researchers suggest that LIP formation has severely influenced global climate, environmental changes and, perhaps, mass extinctions (Saunders 2005; Wignall 2001, 2005). LIP eruptions are temporally associated with climate/environmental changes that include rapid global warming and cooling, perturbations in p_{CO_2}, CH_4, SO_2 and halogens, sea-level changes, oceanic anoxia, calcification crises, mass extinctions, evolutionary radiations, and the release of gas hydrates (Storey *et al.* 2013 and references therein). The connection between the Karoo–Ferrar LIP eruptions and their effects on global climate, both on continents and in the marine realm, has been presented by Storey *et al.* (2013). Some workers consider that >11 km^3 of Deccan basalt eruptions in a short interval of 750 kyr were directly linked to an environmental shift by emitting poisonous

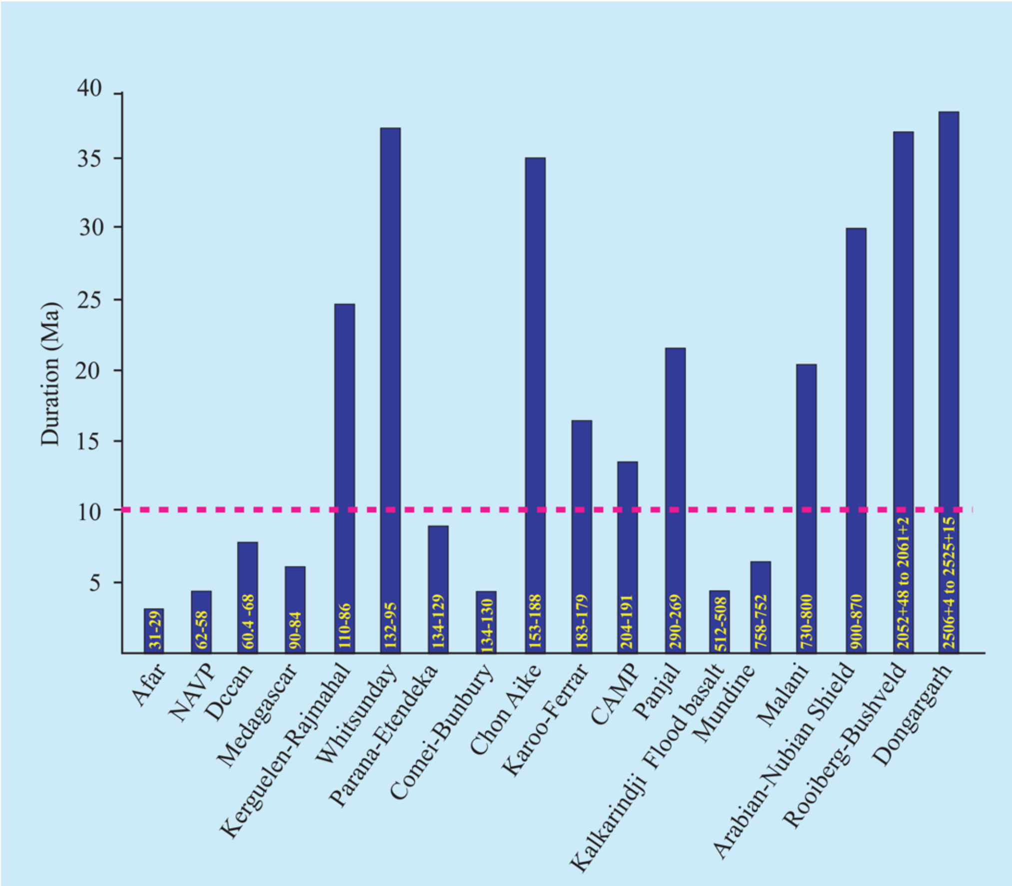

Fig. 3. The duration of LIP events in Gondwana and adjacent regions. Although the durations of several LIPs are within 1–10 myr, as expected in the mantle plume model, larger-duration (up to *c.* 40 myr) LIP events, including a few mafic LIPs, are there in Gondwana. For the data sources, see Table 1.

gases into the atmosphere with consequent adverse effects on the food chain in the very late Cretaceous, causing mass extinction of non-avial dinosaurs and ammonoids, and major biotic turnovers for invertebrates (corals, foraminiferas), reptiles and mammals (Schoene *et al.* 2015). Recent high-precision dating establishes the temporal synchronicity between the eruption of the Kalkarindji LIP (*c.* 512–509 Ma), a climatic shift and the early–middle Cambrian mass extinction in the beginning of the Phanerozoic Eon (Jourdan *et al.* 2014). On the other hand, some believe that LIP emplacement may have had a climatic impact, but did not necessarily directly cause mass extinction (Shellnutt *et al.* 2015). It may be equally possible that the biotic crisis may not be linked to the entire history of a LIP event. For example, the occurrence of repeated soft-sediment deformation structures (seismites), which are likely to be indicative of widespread seismicity, has been linked to end-Triassic mass extinction and the initial stages of the Central Atlantic Magmatic Province (CAMP) LIP emplacement (Lindström *et al.* 2015). Although the CAMP emplacement continued until the early Jurassic, there is no evidence of seismite up the section, while biotic recovery was on its way. This implies that the major igneous events on Gondwana are important links to understand the global climate and environmental changes, and associated biotic crisis. However, large caldera-forming events, as inferred from the large volume of high-temperature welded ignimbrites, welded tuff and other pyroclastic deposits within the LIP sequences, are known for their devastating consequences in global climate shifts.

The increased CO_2 emissions associated with Gondwana LIP emplacements must have caused enhanced CO_2 sequestering through increased silicate weathering and consequent sediment production.

In general, the upper continental crust (UCC) compositions closely approximate the intermediate granodioritic composition (SiO_2 55–66 wt%) believed to be forming typically at present-day convergent margins (Taylor & McLennan 1985). The weathering of rocks and erosion of sediments determine the mobility and distribution of chemical elements in different spheres of the Earth. The similarity in overall composition of global UCC and magmatic rocks of granodioritic compositions predominantly forming at the present-day convergent margins led to the suggestion that the subduction zone magmatic rocks are the principal or, perhaps, the sole global source for sediment production (see Taylor & McLennan 1985).

However, there are discrepancies to a factor of 2 or even ≥3 in the concentrations of certain trace elements such as Ni, Cr and Co in considering intermediate granodioritic rocks as the provenance (McLennan 2001). Continental flood basalt provinces (LIPs) are enriched in mafic/ultramafic igneous rocks and have a relatively high concentration of Cu, Co, Cr, etc. (Brügmann *et al.* 1987). In a recent study on the mineralogy and geochemistry of the river sediments in west-central India, Sharma *et al.* (2013) demonstrated that the discrepancy observed in the concentration of certain trace elements (e.g. Ni, Cr and Co) is better explained with the Deccan LIP as one of the sources (contributing more than 30%), in addition to the Archaean granitoids contributing the remaining (70%) to the bulk sediment compositions. Mafic LIPs, covering ≥50 000–100 000 km^2 in area, contain significant amounts of mafic rocks distributed across Gondwana, and therefore stand out as one of the major and potential global sediment sources. Also, it is suggested that at least 20% of Mg is lost from continents by chemical weathering (Mg being extremely mobile during weathering), which is one of the primary controls for finally leaving behind a Si-rich and Mg-poor continental mass, thereby decreasing crustal recycling by subduction (Lee *et al.* 2008), important for continental survival. So LIPs are important in better explaining the discrepancy in global UCC compositions and continent survival. Today *c.* 150 LIPs are known (Bryan & Ferrari 2013) and the inventory of LIPs is increasing. Hence, the identification and recognition of more LIPs of all ages in the geological record has wider implications.

Also, silicic LIPs constitute a significant part of the present-day UCC, and thus can act as a potential felsic end member, in addition to widespread granitoids, in calculating global UCC compositions. It is therefore pertinent to consider Gondwana LIPs, which cover a significant area on Earth's surface (see the earlier section on 'Size and distribution of Gondwana LIPs') as an important provenance in the models of UCC compositions and its chemical evolution. If the sediment inventory produced through Gondwana LIPs is better constrained in future, it is likely that the discrepancies observed in certain elemental abundances in UCC compositions, as mentioned above (McLennan 2001), could be better addressed and reconciled.

Overview of the volume

In the context of the ongoing studies on LIPs and their significance in better understanding Gondwana as a whole, the volume was conceived. Altogether 11 papers, including this one, have been included in the volume covering diverse topics on magma emplacements, petrology and geochemistry, source characteristics, flood basalt linkage to carbonatite magmatism, tectonics, and, to some extent, on geochronology of LIPs now distributed in different Gondwana continents.

Svensen *et al.* (2017) in an elegant and very timely review offer an overall perspective on the LIPs in Gondwana, including updated plate reconstructions using the GPlates and GMAP software from the key intervals of LIP magmatism in the history of Gondwana. This paper integrates information from several LIPs, such as the Kalkarindji, CAMP, Karoo–Ferrar and the Paraná–Etendeka, that are believed to have erupted within the time frame of the Gondwana supercontinent existence and recognizes the plume–crust interactions in the origin of LIPs. Importantly, they include LIP sills to estimate the volume of magmatism associated with the specific LIP events; thus, revising estimates of magma volume by including subvolcanic (dyke and sill) components, in addition to the lava flows, emplaced in adjacent sedimentary basins. The key role played by subvolcanic parts of LIPs in mediating climate and mass extinctions is also discussed in the paper.

The Ferrar LIP (Antarctica) has a linear outcrop pattern (length 3250 km) that is uncharacteristic for LIPs, although the extent that may be covered under thick ice cover is not clearly known. The Rajmahal province is also an north–south-trending elongate belt in eastern India (see Ghose *et al.* 2016). The mechanism of large volumes of magma emplacements in LIPs is of interest. The key lies in resolving the chronology of emplacements of different magmatic elements, such as lava and associated intrusive rocks, related to the same magmatic system. Subaerial lava flows can travel for more than 1000 km, depending on the eruption rate and topography. One of the suggested hypotheses in large magmatic systems is that crystal-free less-dense lava would be erupted earlier through a system of intrusions (called density-driven hypothesis). Obviously, eruption of the most evolved magma takes place first and subsequent magmas are increasingly richer in MgO content up the lava section. In the alternative 'cracked-lid' hypothesis, a sill-fed dyke network is overlain by lavas supplied by the randomly orientated underlying dyke field. **Elliot & Fleming (2017)** assess both the mechanism of magma emplacement in the Ferrar province by integrating the order of emplacement of the basaltic lava pile, and the intrusive (sill) rocks through field relationships and major element and selected trace element concentrations. They find that the geochemistry of lava and intrusive rocks is partially or marginally consistent, or sometimes drastically inconsistent, in different sections with the expectations of the 'density-driven' model. The cracked-lid sill-fed hypothesis implies that sills are intruded first and, progressively with time, magmas migrate upwards forming younger and stratigraphically higher sills, eventually breaking through to the surface as lava. Also, there should be some geochemical linkage between the lava flows and sills. The authors provide evidence and argue that none of the features of the magma emplacement hypothesis is favoured for the Ferrar LIP, and many factors such as density, lithostatic pressure, magma overpressure, composition and physical properties might have controlled the emplacement of magmas, and these depend on the timing and the place where the source was being tapped, whether as sills or lava flows.

Five major LIPs were emplaced at or near the Gondwana margin, including the Himalayan magmatic province (*c.* 290–270 Ma) which was emplaced along the Tethyan margin of Gondwana (Wang *et al.* 2014 and references therein), the Emishan LIP (China) and the Siberian Traps (*c.* 251 Ma). **Shellnutt (2017)**, in a succinct review of the Panjal Traps (*c.* 290 Ma), an important component of the Himalayan magmatic province, discusses the synchronous nature of basalts, that chemically range from continental tholeiite to ocean-floor basalt, and crustally derived silicic volcanic rocks (rhyolites and trachytes: $^{206}Pb/^{238}U$ zircon *in situ* age of 289 ± 3 Ma), that developed in a shallow lithospheric rift with significant mingling between crustal melts and mafic magmas. This implies that crust and mantle melting are linked to a common thermal perturbation, but not necessarily to a mantle plume. The silicic volcanic rocks are associated with silicic plutonic rocks, although the time bracket of the latter is not clearly known. One of the interesting aspects is that silicic eruption preceded the main basalt eruption in the Panjal. The Traps (India) have a thickness of <3000 m and cover an area of *c.* 100 000 km^2 that initially erupted within a continental rift setting and eventually transitioned into the opening of a nascent ocean basin that formed the Neotethys Ocean and the ribbon-like continent Cimmeria. The author also argues that the eruption of the Panjal Traps LIP during the Early Permian was not linked to the mid-Capitanian mass extinction or to post-Neotethys magmatism.

Phanerozoic Gondwana LIPs could be the windows to the mantle and its possible heterogeneity. **Vijaya Kumar *et al.* (2017)** provide a geochemical perspective using a global geochemical database taken from GEOROCK on the critical role of subcontinental lithospheric mantle with/without invoking a plume for the origin of three important LIPs: the Panjal Traps (*c.* 289 Ma), the Rajmahal (*c.* 117 Ma) and the Deccan Traps (*c.* 65 Ma). They show different degrees of melting; 5–20% of spinel peridotite for the Panjal, 10–20% for the Rajmahal and 1–20% for the Deccan Traps formed the primary basaltic to picritic basalts in the respective provinces. A spinel peridotite to a garnet-bearing source is suggested for the Panjal and Deccan basalts, respectively, with the Rajmahal pulse from some intermediate depth in-between these two. Their study emphasizes variable lithospheric mantle participation in the origin of these LIPs with no discernible input from normal mid-ocean ridge basalt (N-MORB)-type depleted mantle and continental crust. The estimated relative contributions of lithosphere and asthenosphere could be 67 and 33% for the Panjal, 52 and 48% in Rajmahal, and 28 and 72% for the Deccan, respectively. The apparent lack of alkaline rocks and carbonatite in the Panjal, in contrast to the Deccan and Rajmahal, basalts is ascribed to lithospheric thickness and fertility. Contrary to the assertion of **Shellnutt (2017)** that carbonatites occurring in the Koga and Jambil areas (NW Pakistan) nearly 300 km west of the Panjal Traps have a possible linkage to the Panjal basalts, this paper suggests that these carbonatites are of mantle-derived melts formed beneath a thick continental lithosphere far away from a rift, whereas the Panjal basalts are characteristically rift-related and formed underneath a thinned continental lithosphere; and, therefore, not linked. The authors suggested that the Indian subcontinental lithosphere fertility may have increased with decreasing age and is possibly related to Gondwana fragmentation. Alternatively, the subcontinental lithosphere mantle (SCLM) was variably enriched in different segments.

A snapshot of the sub-Deccan continental lithospheric mantle that participated in mantle melting during the Deccan Traps eruption is discussed by **Pandey *et al.* (2017)** from a mantle nodule, rarely fresh enough for study, caught up in *c.* 55 Ga lamprophre dyke within the Narmada Rift Zone in the Deccan province. The nodule (Ol + Opx + Grt), perhaps, bears the first conclusive evidence of modal mantle metasomatism in the Deccan, and has reacted with metasomatic fluid to give rise to an assemblage Ol + Cpx + Phol + Spl + Ap that equilibrated at a temperature of *c.* 1200°C and a pressure of *c.* 12 kb (*c.* 40 km depth). Olivine reported in the nodule is Fe-rich ($Fo_{85.34}$), more Fe-rich than off-craton ($Fo_{88–92}$) and on-craton ($Fo_{91–94}$) mantle xenoliths hitherto known, and may confirm it to be a xenolith of Fe-rich sub-Deccan lithospheric mantle from the garnet stability field. The Fo and Ni content is suggestive of a Fe-rich peridotite, rather than of a pyroxenitic source, and the presence of phlogopite and apatite provide compelling evidence of mantle metasomatism. This study clearly indicates a post-Deccan metasomatic layer that survived melting somewhat during the Deccan eruption because of the variable thickness of the underlying lithosphere; a situation encountered in several LIPs, including the Paraná–Etendeka.

Carbonatites are spatially associated with several LIPs, including those in Gondwana, but their temporal relationship is not well established, which may, indeed, provide insight into carbonatite genesis and its link with the LIPs. The possible genetic link of the *c.* 65 Ma main Deccan eruption event to the Ambar Dongar carbonatite ($^{40}Ar/^{39}Ar$ dating 65 ± 0.3 Ma: Ray & Pande 1999), the youngest Indian carbonatite occurrence, is thus of interest. One of the major difficulties in testing the LIP–carbonatite link is the nature of the mantle source for the primary carbonatite melt: that is, whether the parental carbonatite magma was generated from the SCLM or from deep mantle sources. **Chandra *et al.* (2017)** demonstrate through detailed mineralogical and geochemical compositions and geochemical modelling that the metasomatism of the SCLM below the Deccan was key to a possible petrogenetic link between the main Deccan eruption event and the Ambar Dongar carbonatite. A notable feature is that the Ambar Dongar carbonatite, both ferrocarbonatite and calciocarbonatite varieties, is extremely rich in REE (total REE 1025–31 117 ppm) with ferrocarbonatite richer in REE than calciocarbonatite. On the basis of trace element modelling, the authors proposed a model in which the contributions of CO_2-rich fluids and heat supplied by the Deccan plume metasomatized the SCLM (carbonated garnet lherzolite) at 100 km for the production of parental carbonated silicate magma that underwent liquid immiscibility at crustal depth for nephelinite and carbonatite production. However, the model could not explain the abundances of Rb, Ba, Th, U and the REE pattern adequately. Metasomatism of the SCLM below the Deccan Traps was possibly more common than envisaged.

Rifting and break-up of Gondwana led to the production of large-scale basalt magmatism, and the amalgamation of continents that eventually stitched together to form Gondwana is marked with a chain of granitoid plutons. Gondwana includes a >10 000 km-long chain of 530–500 Ma granitoid magmatism intruded during the assembly of continents along the northern margin (Veevers 2004). **Sadiq *et al.* (2017)** discussed the origin and complex hybridization process preserved in the 550 ± 15 Ma Nongpoh Granite in the Shillong Plateau in NE India that represents part of a large magmatic system where mafic injection during different stages of crystallization of granitoid magma and felsic–mafic magma interactions took place. Evidence of an earlier injection is manifested as mafic magmatic enclaves (MMEs) and syn-plutonic dykes representing the later phase. The 501 Ma chemical (U–Th–Pb) age of monazite in the MMEs represents similar tectonothermal events reported from other parts of India, SW Australia and Antarctica, and represents the global Neopalaeo-proterozoic–Cambrian Pan-African events during the amalgamation of Eastern Gondwana.

Whether rifting and break-up continued after the main break-up of Gondwana in the Mesozoic is of great interest. We have two papers in the volume addressing this question, although the datasets, methodologies adopted and line of treatment in these papers are different. **Mortimer *et al.* (2017*b*)** discuss new Ar/Ar and limited U–Pb ages and geochemistry (both trace element and Nd isotopic analyses) of widespread volcanism on the northern part of the Zealandia continent by using dredged samples obtained in different cruises and integrated with their earlier findings on the southern Zealandia in an attempt to give a more updated picture of magmatism across the whole Zealandia continent. This study showed that the lavas erupted both in northern and southern Zealandia are underlain by continental rather than oceanic crust, and record Late Cretaceous–Eocene intracontinental rifting both during and after continental break-up. Interestingly, Zealandia intraplate volcanic rocks share generally similar age ranges and composition with those of West Antarctica and Australia that were together before the break-up.

In the case of the Deccan Traps LIP, pre- and syn-magmatic rifting is widely reported. However, the question of whether rifting continued even after Deccan magmatism is not adequately studied or understood. The issue of possible post-magmatic rifting in the Deccan is dealt with by **Mitra *et al.* (2017)** by geochemical modelling of weathering of abundant tholeiitic basalt, as well as less common alkali basalt occurring in the far west of India (Kutch region) at elevated but variable atmospheric p_{CO_2} (p_{CO_2}: $10^{-2.5}$ and less), a condition that presumably prevailed in the end Cretaceous–early Paleocene time at about syn- to post-Deccan basalt emplacement. REACT, a module included in the software packages Geochemists' Workbench 10.0.4, is used to model thermodynamic equilibrium reaction paths for the weathering of basalt. The authors consider both open- and closed-system weathering in order to simulate basalt weathering with/without rainwater interactions characteristic of tropical climatic conditions that existed during or after Deccan eruption. More intense weathering of basalts to form kaolinite at the base of rift basins, and less weathering leading to formation of smectite in the rift flanks, is argued to have been controlled by rift-generated topography, and not mediated by variations in atmospheric p_{CO_2}. Post-magmatic tectonics, rather than climate, thereby controlled the weathering of basalts at the terminal to post-Deccan time.

A major challenge lies in identifying remnants of LIPs, particularly of Precambrian age, that occur now in spatial isolation in different continents or within the same landmass. In an attempt to reconstruct a Palaeoproterozoic LIP event of plume origin in the northern India Shield, **Samon *et al.* (2017)** discuss new geochemical and Sm–Nd isotopic constraints from a huge 2104 ± 23 Ma mafic sill that extended for more than 120 m in depth emplaced in an the Gwalior Basin in north central India. They integrate the results with other major synchronous mafic provinces in the northern Indian Shield that were part of the same LIP. The authors suggest that the record of intracratonic basin formation due to lithospheric stretching, plume-induced rift magmatism, large gabbro/doleritic sills and dykes emplacements between 2.5 and 2.1 Ga are part of a LIP event, and are associated with the break-up of the Kenorland supercontinent, the parts of which later amalgamated and became part of Gondwana.

The future

Based on the results of publications in this volume, we suggest that understanding the formation and age of the silicic plutonic rocks associated with silicic volcanic rocks in LIPs is a major frontier. The study of stratigraphic constraints supported by precise age dating with robust methods (e.g. U–Pb single-zircon data) and volume estimation of LIPs pose a great challenge in reconstructing the LIP events better. The definite linkage between LIP emplacement and biotic crisis need to be better established. More petrological constraints and the study of source characteristics are obviously required to reassess and refine the existing models of LIP genesis. One of the associated challenges before us is also to assess the possibility of a large eruption and associated risk. It is estimated that volcanism of the size of a LIP may happen once in 100 000 years. So there might be adequate signals and geological events, including earthquakes and other surficial processes, over a sufficient time period (years or decades) to provide a reasonable warning. Better resolution of seismic images might help in determining the amount of the eruptible magma and estimating the possibility of a large eruption. However, there are always large uncertainties in predicting such large eruptions. In order to lessen uncertainties in predicting LIP size eruptions, we need to know much more about the past LIPs, their ages and duration, what their true size was, and what types of deposits they produced. LIPs associated with continental margin settings in some cases pose a challenge to unravel whether LIP emplacement is always a within-plate phenomenon. Needless to say, the future study on post-magmatic rifting in LIP provinces and its implication for the underlying crust–mantle system in Gondwana will certainly add to our understanding of LIP tectonics.

Concluding remarks

Gondwana, comprising >64% of the present-day continental mass, is home to 33% of large igneous provinces (LIPs). The study of Gondwana LIPs is therefore critical to understanding the Earth's lithosphere–atmosphere system that finally shaped Earth's surface processes, thereby creating conditions conducive for life on this planet. Gondwana is home to many of the largest LIPs, each covering 200 000–2 000 000 km^2. The Precambrian LIPs in Gondwana are numerous and their size could also be overwhelming, although difficult to estimate because of the effects of deformation, metamorphism, and prolonged weathering and erosion. One of the major recent frontiers is the ubiquitous presence of significant to subequal amounts of synchronous silicic volcanic rocks in mafic LIPs, thereby suggesting a more common presence of bimodal LIPs than believed earlier. It is also now known that silicic LIP events could be as large as their mafic counterparts. Also, the origin of large silicic rocks in so many of the Gondwana LIPs by crust–mantle interactions is not part of the classic plume or plate tectonic model as it does not consider significant volumes of silicic magma production at any stage. Several Gondwana LIPs are truly linked to Gondwana rifting meditated directly or indirectly to mantle plume activity. However, whether the Gondwana break-up was syn- or pre-LIP emplacement, or continued even after LIP emplacement, is not adequately understood. Many LIPs, particularly silicic LIPs (SLIPs) and bimodal LIPs are also of longer duration (>20 myr), again not in tune with expectations of plume model (up to 10 myr). The few LIPs associated with a continental margin setting pose the question of whether LIP emplacement is strictly a within-plate phenomenon.

This would like to thank the organizers of the SCAR ISAES conference held in Goa in India in 2015 for facilitating the LIP session on which the papers within this volume are based. Detailed and critical reviews by Saibal Gupta and Phil Leat are gratefully acknowledged. S.S. thanks UGC (New Delhi) and University of Lucknow for support.

References

Baksi, A.K. 1995. Petrogenesis and timing of volcanism in the Rajmahal flood basalt province, northeast India. *Chemical Geology*, **121**, 73–90.

Bhushan, S.K. 2000. MalaniRhyolies: a review. *Gondwana Research*, **3**, 65–77.

Brügmann, G.E., Arndt, N.T., Hofmann, A.W. & Tobschall, H.J. 1987. Noble metal abundances in komatiite suites from Alexo, Ontario and Gorgona Island, Colombia. *Geochimica et Cosmochimica Acta*, **51**, 2159–2169.

Bryan, S.E. & Ernst, R. 2007. Revised definition of Large Igneous Provinces (LIPs). *Earth-Science Reviews*, **86**, 175–202.

Bryan, S.E. & Ferrari, L. 2013. Large igneous provinces and silicic large igneous provinces: progress in our understanding over the last 25 years. *Geological Society of America Bulletin*, **125**, 1053–1078.

Bryan, S.E., Ewart, A., Stephens, C.J., Parianos, J. & Downes, P.J. 2000. The Whitsunday Volcanic Province, Central Queensland, Australia: lithological and stratigraphic investigations of a silicic-dominated large igneous province. *Journal of Volcanology and Geothermal Research*, **99**, 55–78.

Bryan, S.E., Riley, T.R., Jerram, D.A., Leat, P.T. & Stephens, C.J. 2002. Silicic volcanism: an under-valued component of large igneous provinces and volcanic rifted margins. *In*: Menzies, M.A., Klemperer, S.L., Ebinger, C.J. & Baker, J. (eds) *Magmatic Rifted Margins*. Geological Society of America, Special Papers, **362**, 99–120.

Bryan, S.E., Cook, A.G., Allen, C.M., Siegel, C., Purdy, D.J., Greentree, J.S. & Uysal, I.T. 2012. Early-mid Cretaceous tectonic evolution of eastern Gondwana: from silicic LIP magmatism to continental rupture. *Episodes*, **35**, 142–152.

Bryan, S.E., Orozco-Esquivel, T., Ferrari, L. & López-Martínez, M. 2013. Pulling apart the Mid to Late Cenozoic magmatic record of the Gulf of California: is there a Comondú Arc? *In*: Gomez-Tuena, A., Straub, S.M. & Zellmer, G.F. (eds) *Orogenic Andesites and Crustal Growth*. Geological Society, London, Engineering Geology Special Publications, **385**, 389–407, https://doi.org/10.1144/SP385.8

Burke, K. 1996. The African plate. *South African Journal of Geology*, **99**, 341–409.

Chandra, J., Paul, D., Viladkar, S.G. & Sensarma, S. 2017. Origin of the Amba Dongar carbonatite complex, India and its possible linkage with the Deccan Large Igneous Province. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 10, 2017, https://doi.org/10.1144/SP463.3

Cleverly, R.W., Betton, P.J., Bristow, J.W. & Erlank, A.J. 1984. Geochemistry and petrogenesis of the Lebombo rhyolites. *In*: Erlank, A.J. (ed.) *Petrogenesis of the Volcanic Rocks of the Karoo Province*. Geological Society of South Africa, Special Publications, **13**, 171–194.

Coffin, M.F. & Eldholm, O. 1994. Large igneous provinces: crustal structure, dimensions, and external consequences. *Reviews of Geophysics*, **32**, 1–36.

Colón, D.P., Bindeman, I.N., Ellis, B.S., Schmitt, A.K. & Fisher, C.M. 2015. Hydrothermal alteration and melting of the crust during the Columbia River Basalt–Snake River Plain transition and the origin of low-$\delta^{18}O$ rhyolites of the central Snake River Plain. *Lithos*, **224–225**, 310–323.

Courtney, R.C. & White, R.S. 1986. Anomalous heat flow and geoid across the Cape Verde Rise: evidence for dynamic support from a thermal plume in the mantle. *Geophysical Journal of the Royal Astronomical Society*, **87**, 815–867.

Eldholm, O. & Coffin, M.F. 2000. Large igneous provinces and plate tectonics. *In*: Richards, M., Gordon, R. & Van der Hilst, R. (eds) *The History and Dynamics of Global Plate Motions*. American Geophysical Union, Geophysical Monographs, **121**, 309–326.

Elliot, D.H. & Fleming, T.H. 2017. The Ferrar Large Igneous Province: field and geochemical constraints on supra-crustal (high-level) emplacement of the magmatic system. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 10, 2017, https://doi.org/10.1144/SP463.1

Ernst, R.E. 2014. *Large Igneous Provinces*. Cambridge University Press, Cambridge.

Ernst, R.E. & Buchan, K.L. 1997. Giant radiating dyke swarms: their use in identifying pre-Mesozoic large igneous provinces and mantle plumes. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 297–333.

Ernst, R.E., Buchan, K.L. & Campbell, I.H. 2005. Frontiers in large igneous province research. *Lithos*, **79**, 271–297.

Ernst, R.E., Bleeker, W., Soderlund, U. & Kerr, A.C. 2013. Large Igneous Provinces and super continent: towards completing the plate tectonic revolution. *Lithos*, **174**, 1–14.

Ewart, A. 1982. Petrogenesis of the tertiary anorogenic volcanic series of Southern Queensland, Australia, in the light of trace element geochemistry and O, Sr and Pb isotopes. *Journal of Petrology*, **23**, 344–382.

Foulger, G.R. 2007. The 'plate' model for the genesis of melting anomalies. *In*: Foulger, G.R. & Jurdy, D.M. (eds) *Plates, Plumes, and Planetary Processes*. Geological Society of America, Special Papers, **430**, 1–28, https://doi.org/10.1130/2007.2430(01)

Frey, F.A., Coffin, M.F. *et al.* 2000. Origin and evolution of a submarine large igneous province: the Kerguelen Plateau and Broken Ridge, southern Indian Ocean. *Earth and Planetary Science Letters*, **176**, 73–89.

Garzanti, E., Le Fort, P. & Sciunnach, D. 1999. First report of Lower Permian basalts in South Tibet: tholeiitic magmatism during break-up and incipient opening of Neotethys. *Journal of Asian Earth Sciences*, **17**, 533–546.

George, R., Rogers, N. & Kelley, S. 1998. Earliest magmatism in Ethiopia: evidence for two mantle plumes in one flood basalt province. *Geology*, **26**, 923–926.

Ghose, N.C., Chatterjee, N. & Windley, B.F. 2016. Subaqueous early eruptive phase of the late Aptian Rajmahal volcanism, India: Evidence from volcaniclastic rocks, bentonite, black shales, and oolite. *Geoscience*

Frontiers, **8**, 809–822, https://doi.org/10.1016/j.gsf.2016.06.007

Harris, C. & Milner, S. 1997. Crustal origin for the Paraná rhyolites: discussion of 'description and petrogenesis of the Paraná rhyolites, southern Brazil' by Garland *et al.* (1995). *Journal of Petrology*, **38**, 299–302.

Harris, C., Whittingham, A.M., Milner, S.C. & Armstrong, R.A. 2010. Oxygen isotope geochemistry of the silicic volcanic rocks of the Etendeka-Paraná Province: source constraints. *Geology*, **18**, 1119–1121.

Hirschmann, M.M. 2006. Water, melting, and the deep Earth H_2O cycle. *Annual Review of Earth and Planetary Sciences*, **34**, 629–653.

Hofmann, C., Courtillot, V., Féraud, G., Rochette, P., Virgu, G., Ketefo, E. & Pik, R. 1997. Timing of the Ethiopian flood basalt event and implications for plume birth and global change. *Nature*, **389**, 838–841.

Jourdan, F., Hodges, K. *et al.* 2014. High-precision dating of the Kalkarindji large igneous province, Australia, and synchrony with the Early–Middle Cambrian (Stage 4–5) extinction. *Geology*, **42**, 543–546.

Kempton, P.D. & Harmon, R.S. 1992. Oxygen isotope evidence for large-scale hybridization of the lower crust during magmatic underplating. *Geochimica et Cosmochimica Acta*, **56**, 963–970.

Kent, W., Saunders, A.D., Kempton, P.D. & Ghose, N.C. 1997. Rajmahal basalts, eastern India: Mantle sources and melt distribution at a volcanic rifted margin. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 145–182.

Lee, C.T.A., Morton, D.M., Little, M.G., Kistler, R., Horodyskyj, U.N., Leeman, W.P. & Agranier, A. 2008. Regulating continent growth and composition by chemical weathering. *Proceedings of the National Academy of Sciences of the United States of America*, **105**, 4981–4986.

Lenhardt, N. & Eriksson, P.G. 2012. Volcanism of the Palaeoproterozoic Bushveld Large Igneous Province: the Rooiberg Group, Kaapvaal Craton, South Africa. *Precambrian Research*, **214–215**, 82–94.

Lindström, S., Pedersen, G.K. *et al.* 2015. Intense and widespread seismicity during the end-Triassic mass extinction due to emplacement of a large igneous province. *Geology*, **43**, 387–390, https://doi.org/10.1130/G36444.1

Luyendyk, B.P. 1995. Hypothesis for Cretaceous rifting of east Gondwana caused by subducted slab capture. *Geology*, **23**, 373–376.

Mahoney, J.J., Jones, W.B., Frey, F.A., Salters, V.J.M., Pyle, D.G. & Davies, H.L. 1995. Geochemical characteristics of lavas from Broken Ridge, the Naturaliste Plateau and southernmost Kerguelen Plateau: Cretaceous plateau volcanism in the southeast Indian Ocean. *Chemical Geology*, **120**, 315–345.

Marsh, J.S., Hooper, P.R., Rehacek, J., Duncan, R.A. & Duncan, A.R. 1997. Stratigraphy and age of Karoo basalts of Lesotho and implications for correlations within the Karoo igneous province. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 247–272.

Marzoli, A., Renne, P.R., Piccirillo, E.M., Ernesto, M., Bellieni, G. & De Min, A. 1999. Extensive 200-million-year-old continental flood basalts of the central Atlantic Magmatic Province. *Science*, **284**, 616–618.

May, P.R. 1971. Pattern of Triassic–Jurassic diabase dikes around the North Atlantic in the context of predrift position of the continents. *Geological Society of America Bulletin*, **82**, 1285–1292.

McLennan, S.M. 2001. Relationships between the trace element composition of sedimentary rocks and upper continental crust. *Geochemistry, Geophysics, Geosystems*, **2**, 1021, https://doi.org/10.1029/2000GC0 00109

Meade, F.C., Troll, V.R., Ellam, R.M., Freda, C., Font, L., Donaldson, C.H. & Klonowska, I. 2014. Bimodal magmatism produced by progressively inhibited crustal assimilation. *Nature Communications*, **5**, 4199, https://doi.org/10.1038/ncomms5199

Menzies, M., Baker, J., Chazot, G. & Al'kadasi, M. 1997. Evolution of the Red Sea volcanic margin, western Yemen. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 29–43.

Miller Jodie, A. & Harris, C. 2007. Petrogenesis of the Swaziland and northern Natal rhyolites of the Lebombo rifted volcanic margin, South East Africa. *Journal of Petrology*, **48**, 185–218.

Milner, S.C., Duncan, A.R., Whittingham, A.M. & Ewart, A. 1995. Trans-Atlantic correlation of eruptive sequences and individual silicic volcanic units within the Paraná-Etendeka igneous province. *Journal of Volcanology and Geothermal Research*, **69**, 137–157.

Mitra, K., Mitra, S., Gupta, S., Bhattacharya, S., Chauhan, P. & Jain, N. 2017. Modelling basalt weathering at elevated CO_2 concentrations: implications for terminal to post-magmatic rifting in the Deccan Traps, Kachchh, India. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 17, 2017, https://doi.org/10.1144/SP463.8

Morgan, J.P., Morgan, W.J. & Price, E. 1995. Hotspot melting generates both hotspot volcanism and a hotspot swell? *Journal of Geophysical Research*, **100**, 8045–8062.

Mortimer, N., Campbell, H.J. *et al.* 2017*a*. Zealandia: Earth's hidden continent. *GSA Today*, **27**, 27–35, https://doi.org/10.1130/GSATG321A.1

Mortimer, N., Gans, P.B. *et al.* 2017*b*. Regional volcanism of northern Zealandia: post-Gondwana break-up magmatism on an extended, submerged continent. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online August 16, 2017, https://doi.org/10.1144/SP463.9

Nelson, D., Cottle, J., Barboni, M. & Schoene, B. 2015. Petrogenesis of the Butcher Ridge Igneous Complex, a unique layered glassy silicic intrusion within the Ferrar Large Igneous Province. Abstract 116 presented at the XII International Synposium on Antractic Earth Sciences, 13–17 July 2015, Goa, India.

Pandey, R., Rao, N.V.C., Pandit, D., Sahoo, S. & Dhote, P. 2017. Imprints of modal metasomatism in the post-Deccan subcontinental lithospheric mantle: petrological evidence from an ultramafic xenolith in an Eocene lamprophyre, NW India. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 5, 2017, https://doi.org/10.1144/SP463.6

Pankhurst, M.J., Schaefer, B.F. & Betts, P.G. 2011. Geodynamics of rapid voluminous felsic magmatism through time. *Lithos*, **123**, 92–101.

Pankhurst, R.J., Leat, P.T., Sruoga, P., Rapela, C.W., Márquez, M., Storey, B.C. & Riley, T.R. 1998. The Chon Aike province of Patagonia and related rocks in West Antarctica: a silicic large igneous province. *Journal of Volcanology and Geothermal Research*, **81**, 113–136.

Paul, D.K., Potts, P.J., Rex, D.C. & Beckinsale, R.D. 1977. Geochemical and petrogenetic study of the Girnar igneous complex, Deccan volcanic province, India. *Geological Society of America Bulletin*, **88**, 227–234.

Peate, D.W. 1997. The Paraná-Etendeka Province. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 217–245.

Ray, J.S. & Pande, K. 1999. Carbonatite alkaline magmatism associated with continental flood basalts at stratigraphic boundaries: cause of mass extinctions. *Geophysical Research Letters*, **26**, 1917–1920.

Riley, T.R., Leat, P.T., Pankhurst, R.J. & Harris, C. 2001. Origins of large volume rhyolitic volcanism in the Antarctic Peninsula and Patagonia by crustal melting. *Journal of Petrology*, **42**, 1043–1106.

Rollinson, H.R. 1993. *Using Geochemical Data: Evaluation, Presentation, Interpretation*. Longman, Harlow, UK.

Sadiq, M., Umrao, R.K., Sharma, B.B., Chakraborti, S., Bhattacharyya, S. & Kundu, A. 2017. Mineralogy, geochemistry and geochronology of mafic magmatic enclaves and their significance in evolution of Nongpoh granitoids, Meghalaya, NE India. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 6, 2017, https://doi.org/10.1144/SP463.2

Samom, J.D., Ahmad, T. & Choudhary, A.K. 2017. Geochemical and Sm–Nd isotopic constraints on the petrogenesis and tectonic setting of the Proterozoic mafic magmatism of the Gwalior Basin, central India: the influence of Large Igneous Provinces on Proterozoic crustal evolution. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 10, 2017, https://doi.org/10.1144/SP463.10

Saunders, A.D. 2005. Large Igneous Provinces: origin and environmental consequences. *Elements*, **1**, 259–263.

Saunders, A.D., Fitton, J.G., Kerr, A.C., Norry, M.J. & Kent, R.W. 1997. The North Atlantic Igneous Province. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 45–93.

Schoene, B., Samperton, K.M., Eddy, M.P., Keller, G., Adatte, T., Bowring, S.A. & Gertsch, B. 2015. U–Pb geochronology of the Deccan Traps and relation to the end-Cretaceous mass extinction. *Science*, **347**, 182–184.

Sensarma, S. 2007. A bimodal large igneous province and the plume debate: the Paleoproterozoic Dongargarh Group, central India. *In*: Foulger, G.R. & Jurdy, D.M. (eds) *Plates, Plumes, and Planetary Processes*. Geological Society of America, Special Papers, **430**, **430**, 831–839.

Sensarma, S. 2009. Low-δ^{18}O rhyolites in the c. 2.5 Ga Dongargarh bimodal LIP, India: textural and chemical evidence for magma mixing and source characteristics. Paper presented at the Geological Society of America Penrose Conference on Low-δ18O Rhyolites and Crustal Melting: Growth and Redistribution of the Continental Crust, 9–13 September 2009, Twin Falls, Idaho, and Yellowstone National Park, Wyoming, USA.

Sensarma, S., Palme, H. & Mukhopadhyay, D. 2002. Crust–mantle interaction in the genesis of siliceous high magnesian basalts: evidence from the Early Proterozoic Dongargarh Supergroup, India. *Chemical Geology*, **187**, 21–37.

Sensarma, S., Hoernes, S. & Mukhopadhyay, D. 2004. Relative contributions of crust and mantle to the origin of the Bijli Rhyolite in a Palaeoproterozoic bimodal volcanic sequence (Dongargarh Group), central India. *Journal of Earth System Science*, **113**, 619–648.

Sharma, A., Sensarma, S., Kumar, K., Khanna, P.P. & Saini, N.K. 2013. Mineralogy and geochemistry of the Mahi River sediments in tectonically active western India: implications for Deccan large igneous province source, weathering and mobility of elements in a semi-arid climate. *Geochimica et Cosmochimica Acta*, **104**, 63–83.

Sharma, K.K. 2004. The Neoproterozoic Malani magmatism of the northwestern Indian shield: implications for crust-building processes. *Proceedings of the Indian Academy of Science (Earth Planetary Sciences)*, **113**, 795–807.

Shellnutt, J.G. 2017. The Panjal Traps. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 6, 2017, https://doi.org/10.1144/SP463.4

Shellnutt, J.G., Bhat, G.M., Wang, K.-L., Yeh, M.-W., Brookfield, M.E. & Jahn, B.-M. 2015. Multiple mantle sources of the early Permian Panjal Traps, Kashmir, India. *American Journal of Science*, **315**, 589–619.

Sheth, H.C. 2005. From Deccan to Réunion: no trace of a mantle plume. *In*: Foulger, G.R., Natland, J.H., Presnall, D.C. & Anderson, D.L. (eds) *Plates, Plumes, and Paradigms*. Geological Society of America, Special Papers, **388**, 477–501.

Sheth, H.C. 2007. Plume-related regional pre-volcanic uplift in the Deccan Traps: absence of evidence, evidence of absence: discussion. *In*: Foulger, G.R. & Jurdy, D.M. (eds) *Plates, Plumes, and Planetary Processes*. Geological Society of America, Special Papers, **430**, 803–813.

Storey, B.C. 1995. The role of mantle plumes in continental breakup: case histories from Gondwanaland. *Nature*, **377**, 301–308.

Storey, B.C. & Kyle, P.R. 1997. An active mantle mechanism for Gondwana breakup. *In*: Hatton, C.J. (ed.)

Special Issue on the Proceedings of the Plumes, Plates and Mineralisation '97 Symposium. South African Journal of Geology, **100**, 283–290.

Storey, B.C., Vaughan, A.P.M. & Riley, T.R. 2013. The link between large igneous provinces, continental break-up and environmental change: evidence reviewed from Antarctica. *Earth and Environmental Science Transactions of the Royal Society of Edinburgh*, **104**, 1–14.

Storey, M., Mahoney, J.J. & Saunders, A.D. 1997. Cretaceous basalts in Madagascar and the transition between plume and continental lithosphere mantle sources. *In*: Mahoney, J.J. & Coffin, M.F. (eds) *Large Igneous Provinces: Continental, Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 95–122.

Svensen, H.H., Torsvik, T.H. *et al.* 2017. Gondwana Large Igneous Provinces: plate reconstructions, volcanic basins and sill volumes. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online August 30, 2017, https://doi.org/10.1144/SP463.7

Talukdar, S.C. & Murthy, M.V.N. 1971. The Sylhet traps, their tectonic history, and their bearing on problems of Indian flood basalt provinces. *Bulletin Volcanologique*, **35**, 602–618.

Taylor, S.R. & McLennan, S.M. 1985. *The Continental Crust; Its Composition and Evolution. An Examination of the Geochemical Record Preserved in Sedimentary Rocks*. Blackwell, Oxford.

Torsvik, T.H. & Cocks, L.R.M. 2013. GR focus review: Gondwana from top to base in space and time. *Gondwana Research*, **24**, 999–1030.

Veevers, J.J. 2004. Gondwanaland from 650 to 500 Ma assembly through 320 Ma merger in Pangea to 185–100 Ma breakup: supercontinental tectonics via stratigraphy and radiometric dating. *Earth-Science Reviews*, **68**, 1–132.

Vijaya Kumar, K., Laxman, M.B. & Nagaraju, K. 2017. Mantle source heterogeneity in continental mafic Large Igneous Provinces: insights from the Panjal, Rajmahal and Deccan basalts, India. *In*: Sensarma, S. & Storey, B.C. (eds) *Large Igneous Provinces from Gondwana and Adjacent Regions*. Geological Society, London, Special Publications, **463**. First published online July 11, 2017, https://doi.org/10.1144/SP463.5

Wang, M., Li, C., Wu, Y.-W. & Xie, C.-M. 2014. Geochronology, geochemistry, Hf isotopic compositions and formation mechanism of radial mafic dykes in northern Tibet. *International Geology Review*, **56**, 187–205.

White, R.S. 1997. Mantle plume origin for the Karoo and Ventersdorp flood basalts, South Africa. *In*: Hatton, C.J. (ed.) *Special Issue on the Proceedings of the Plumes, Plates and Mineralisation '97 Symposium. South African Journal of Geology*, **100**, 271–282.

White, R.S. & McKenzie, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*, **94**, 7685–7729.

Wignall, P.B. 2001. Large igneous provinces and mass extinctions. *Earth-Science Reviews*, **53**, 1–33.

Wignall, P.B. 2005. The link between large igneous province eruptions and mass extinctions. *In*: Saunders, A.D. (ed.) *Large Igneous Provinces: Origin and Environmental Consequences*. *Elements*, **1**, (5), 293–297.

Zhu, D.C., Chung, S.L., Mo, X.X., Zhao, Z.D., Niu, Y., Song, B. & Yang, Y.H. 2009. The 132 Ma Comei-Bunbury large igneous province: remnants identified in present-day southeastern Tibet and southwestern Australia. *Geology*, **37**, 583–586, https://doi.org/10.1130/G30001A.1