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‘Large Igneous Provinces (LIPs)’: Definition, recommended terminology, and a hierarchical classification

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Abstract

This article is an appeal for the adoption of a correct and appropriate terminology with respect to the so-called *Large Igneous Provinces* (LIPs). The term LIP has been widely applied to large basaltic provinces such as the Deccan Traps, and the term *Silicic Large Igneous Province* (SLIP) to volcanic provinces of dominantly felsic composition, such as the Whitsunday Province. However, neither term (LIP, SLIP) has been applied to the large granitic batholiths of the world (e.g., Andes) to which both terms are perfectly applicable. LIP has also not been applied to broad areas of contemporaneous basalt magmatism (e.g., Indochina, Mongolia) and sizeable layered mafic intrusions (e.g., Bushveld) which in many significant respects may also be considered to represent ‘Large Igneous Provinces’. Here, I suggest that the term LIP is used in its broadest sense and that it should designate igneous provinces with outcrop areas ≥ 50,000 km^2. I propose a simple hierarchical classification of LIPs that is independent of composition, tectonic setting, or emplacement mechanism. I suggest that provinces such as the Deccan and Whitsunday provinces should be called *Large Volcanic Provinces* (LVPs), whereas large intrusive provinces (mafic–ultramafic intrusions, dyke/sill swarms, granitic batholiths) should be called *Large Plutonic Provinces* (LPPs). LVPs and LPPs thus together cover all LIPs, which can be felsic, mafic, or ultramafic, of sub-alkalic or alkalic affinity, and emplaced in continental or oceanic settings. LVPs are subdivided here into four groups: (i) the dominantly/wholly mafic *Large Basaltic Provinces* (LBPs) (e.g., Deccan, Ontong Java); (ii) the dominantly felsic *Large Rhyolitic Provinces* (LRPs) (e.g., Whitsunday, Sierra Madre Occidental); (iii) the dominantly andesitic *Large Andesitic Provinces* (LAPs) (e.g., Andes, Indonesia, Cascades), and (iv) the bimodal *Large Basaltic–Rhyolitic Provinces* (LBRPs) (e.g., Snake River–High Lava Plains). The intrusive equivalents of LRPs are the *Large Granitic Provinces* (LGPs) (e.g., the Andean batholiths), although an equivalent term for intrusive equivalents of LBPs is not necessary or warranted. The accuracy and usefulness of the terms *flood basalt, plateau basalt*, and *trap* are also examined. The largest LBP, LVP, and LIP is, of course, the bulk of the ocean floor. It is contended that the proposed LIP nomenclature and classification will lead to more accurate and precise terminology and hence better understanding of the wide variety of Large Igneous Provinces.

Keywords: Large igneous province; magmatism; volcanism; classification; nomenclature

1. Introduction

The French philosopher Abbé de Condillac is reported to have said that “we cannot improve the language of any science without at the same time improving the science itself; neither can we, on the other hand, improve a science, without improving the language or nomenclature which belongs to it”. I argue here that the phrase ‘Large Igneous Province’ (LIP) is currently used inappropriately, and suggest that several

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terminological sub-categories of LIP, coined here, allow a more precise phenomenological approach to the subject. This contribution is thus an appeal for the use of accurate and precise terminology in the field of large-scale volcanism and magmatism.

2. What is a Large Igneous Province (LIP)?

The term *Large Igneous Province* (LIP) implies a substantial province of igneous origin, use of the term 'large' clearly being both flexible and subjective. It would seem axiomatic that the term LIP should cover all large volcanic and intrusive igneous provinces, irrespective of emplacement mechanism or compositional affinity. However, the term LIP has been applied almost exclusively to *continental flood basalt* (CFB) provinces such as the Deccan, Siberian, and Columbia River basalt provinces, as well as basalt plateaus such as the Ontong Java in the oceans (e.g., Coffin and Eldholm, 1992; Ernst et al., 2005; Saunders, 2005). Though these provinces are unquestionably LIPs, the term LIP should also include large-volume felsic provinces such as the Sierra Madre Occidental in Mexico, given their areal (and usually also volumetric) dimensions. LIP should also include the huge granitic–granodioritic batholiths, such as those of Tibet–Himalaya, western North America, and the Andes. Large mafic layered intrusions, such as the Bushveld Intrusion, should also be consided LIPs. Indeed, continental rift zones such as the Rio Grande Rift and the Cameroon Line also represent LIPs, although none of these comprise eruptive forms of the 'flood basalt' type.

Coffin and Eldholm (1992, 1993, 1994) were among the first to have adopted the term LIP in this restrictive sense, defining LIPs as "massive crustal emplacements of predominantly mafic (Mg and Fe rich) extrusive and intrusive rock which originate via processes other than 'normal' seafloor spreading… [and] include continental flood basalts, volcanic passive margins, oceanic plateaus, submarine ridges, seamount groups and ocean basin flood basalts." This cannot be accepted as a valid, comprehensive definition of LIPs, given its exclusion of many of the truly large igneous phenomena referred to above.

Bleeker and Ernst (2006), as well as Bryan and Ernst (2007), suggest 100,000 km^2 as the lower size (outcrop area) limit for LIPs. I suggest 50,000 km^2 as the lower limit, primarily because this allows many *non-flood basalt* compositional-genetic types of igneous provinces (e.g., the Mexican Volcanic Belt) to be considered LIPs (see below). Most LIPs indeed have much larger extent than the proposed 50,000 km^2. The Deccan Traps, for example, cover 0.5 million km^2 of western-central India today and have an estimated original extent of 1.5 million km^2 (Wadia, 1975). The Siberian Trap province is much more vast (Reichow et al., 2002), whereas comparatively smaller basalt provinces, such as the Emeishan (~ 250,000 km^2, He et al., 2003 –>) and the Columbia River (~ 215,000 km^2, Camp et al., 2003; Hooper et al., 2007) provinces also comfortably exceed the lower size threshold. Given the considerably greater uncertainties regarding magmatic volume (unless well defined by geophysical data, and considering the material removed by erosion in the older provinces), estimates of outcrop area are clearly the better descriptive parameter for comparing the relative sizes of LIPs.

I thus suggest that the term LIP be used in its broadest sense, and propose new necessary, more specific terms for the discrete LIP categories.

3. Large Volcanic Provinces (LVPs) and Large Plutonic Provinces (LPPs)

Just as there are large mafic volcanic provinces exemplified by the Deccan and the Columbia River CFBs, there are large felsic volcanic provinces dominated by highly evolved (broadly rhyolitic) lavas. Several such provinces (the so-called *silicic LIPs*) are described by Bryan et al. (2000, 2002) and include the early Cretaceous Whitsunday province of eastern Australia and the Sierra Madre Occidental of western Mexico. There are also large volcanic provinces dominated by andesite, and large volcanic provinces made up of near-equal volumes of basaltic and rhyolitic lavas. I propose that all such large volcanic provinces, irrespective of composition, can be termed *Large Volcanic Provinces* (LVPs).

I likewise suggest the term *Large Plutonic Provinces* (LPPs) (after Pluto, the Roman god of the underworld) for all intrusive-abyssal provinces meeting the above-described size requirements, irrespective of their compositional affinity, emplacement depth, and internal structure. This category would thus include mafic–ultramafic intrusions such as the Bushveld Complex, large granite–granodiorite provinces such as the Andean and Tibetan–Himalayan batholiths, and giant dyke swarms such as the Mackenzie dyke swarm of Canada (Ernst et al., 1995). Clearly, while all LVPs are LIPs, the converse is not always true.

4. Large Rhyolitic Provinces (LRPs) and Large Granitic Provinces (LGPs)

While the term 'silicic LIP', as used to describe rhyolite-dominated large volcanic provinces (Bryan et al., 2000, 2002), recognizes the fact that LIPs can be of felsic composition, this term should arguably include the large (mostly orogenic) granitic batholiths exposed today after erosinal and/or tectonic unroofing. Such batholiths may or may not have been the root zones of long-gone surface volcanoes and lava fields.

Accordingly, I propose that Large Volcanic Provinces (LVPs) dominated by broadly rhyolitic rocks (i.e., the rhyolite–rhyodacite–dacite–trachyte compositional range, both sub-alkalic and alkalic lineages) be called *Large Rhyolitic Provinces* (LRPs). Besides the Whitsunday and the Sierra Madre Occidental provinces, the Neoproterozoic Malani province of northwestern India (Sharma, 2004, 2005) is a good example. On the other hand, Large Plutonic Provinces (LPPs) dominated by felsic magmas (granite–granodiorite–tonalite–trondhjemite) can be called *Large Granitic Provinces* (LGPs). The Archaean and Proterozoic charnockite (hypersthene–granite) massifs of southern India (Rajesh and Santosh, 2004) would be included in the LGP category. Note that, defined thus, both LRP and LGP are independent of origin and tectonic setting.

5. Large Basaltic Provinces (LBPs)

In this section, I propose that Large Volcanic Provinces (LVPs) of dominantly basaltic composition be referred to as *Large Basaltic Provinces* (LBPs), the term 'basaltic' implying the compositional range basaltic andesite–basalt–picrobasalt (and their alkalic equivalents). Basaltic andesites are included given that many so-called 'flood basalts' are in fact basaltic andesites. Examples include many Deccan lavas from the Western Ghats (e.g., Beane, 1988; see Sheth, 2005) and the Grande Ronde lavas of the Columbia River basalt province that constitute 85% of the volume of that province (Hooper, 1997).

It is to be noted that LBP refers not only to exclusively basaltic (mafic volcanic) provinces that lack felsic rocks (e.g. the Columbia River province; Hooper, 1997) but equally well to *dominantly* basaltic provinces with subordinate amounts of more evolved magmatic types such as rhyolite and trachyte. In fact, most *continental flood basalt* (CFB) provinces are of this type (see e.g., Macdougall, 1988 and references therein; Mahoney and Coffin, 1997 and references therein). Examples of LBPs would thus include the Columbia River, Deccan, Rajmahal, Madagascar, Siberian, Emeishan, Karoo, Parana–Etendeka, Yemen–Ethiopia, and the North Atlantic Tertiary provinces, among others. Oceanic flood basalt provinces, often referred to as *oceanic plateaus* (e.g., the Ontong Java, Iceland, and Kerguelen Plateaus), also constitute LBPs. Large oceanic island–seamount chains such as the Hawaii–Emperor and the Ninety East Ridge may also be considered to belong in the LBP category, as may other broad areas of diffuse basaltic volcanism on the continents and in the ocean basins. Examples are Indochina (Hoang and Flower, 1998; Flower et al., 1998), Mongolia (Barry et al., 2003), the circum-Mediterranean Cenozoic anorogenic province (Lustrino and Wilson, 2007) and the South Pacific Superswell (Janney et al., 2000). The term LBP is also independent of tectonic setting.

The largest LBP, LVP, and LIP is, of course, the bulk of the ocean floor. Although Coffin and Eldholm (1992, 1993, 1994) excluded basaltic piles formed by 'normal' seafloor spreading from their definition of LIPs, this exclusion, in light of the present discussion, is not warranted. Besides, "The central problem is satisfactorily defining normal" (Menard, 1969). And while the formation of oceanic crust is incremental and very long-lived, the magma production rate is comparatively very high. Along a 500-km-long ocean ridge segment spreading with a half-rate of 5 cm/yr, the creation of a 100 km transverse strip of new oceanic lithosphere (having an area of 50,000 km^2) takes only 1 million years. In other words, at such an average half-spreading rate, a 50,000-km-long global ocean ridge system creates 5 million km^2 of new oceanic lithosphere in just 1 million years. The average thickness of the modern oceanic crust is 7 ± 1 km (e.g., White et al., 1992), of which the basaltic part (pillow basalts and sheeted dykes) makes up ~ 2 km (Boudier and Nicolas, 1985; Nicolas, 1989). Thus, the lower size limit proposed here for an LIP, and the estimated areas and volumes of most LIPs, are quite small in relation to the magmatic output of the earth's ocean ridge system, or even large segments thereof, over comparable time scales.

6. Large Basaltic–Rhyolitic Provinces (LBRPs)

A LBRP may be considered to comprise approximately equal volumes of felsic (rhyolitic) and mafic (basaltic) lavas, with magmas of intermediate composition more or less absent. It is thus a bimodal LVP. While this category of LVP is relatively unusual and uncommon as compared to LBPs, examples include the Tertiary Snake River Plain–Oregon High Lava Plains province in the western U.S.A. (e.g., Jordan, 2005), and the Palaeoproterozoic (2.5–2.2 Ga) Dongargarh province in central India (Sensarma et al., 2004; Sensarma, 2007).

7. Large Andesitic Provinces (LAPs)

A further category may be defined, of LIP-size ($\geq$ 50,000 km^2) magmatic provinces of dominantly

Table 1
Proposed terminology and hierarchical classification of the Large Igneous Provinces (LIPs), with examples

Large Igneous Provinces (LIPs) Extrusive/intrusive provinces of any composition and tectonic setting with a minimum area of 50,000 km^2							
Extrusive (lavas: pyroclastics = 100:0 to 0:100, sub-alkalic: alkalic = 100:0 to 0:100) **Large Volcanic Provinces (LVPs)**					Intrusive **Large Plutonic Provinces (LPPs)**		
Dominantly or wholly felsic: **Large Rhyolitic Provinces (LRPs)**	Dominantly or wholly andesitic: **Large Andesitic Provinces (LAPs)**	Dominantly or wholly mafic: **Large Basaltic Provinces (LBPs)**		Bimodal: **Large Basaltic–Rhyolitic Provinces (LBRPs)**	Dominantly or wholly felsic: **Large Granitic Provinces (LGPs)**	Dominantly or wholly mafic:	
Continental only	Usually continental	Both continental and oceanic		Continental only	Continental only	Both continental and oceanic	
'Silicic' LIPs: Whitsunday, Sierra Madre Occidental, Malani	*Island arcs:* Indonesia, Japan *Active continental margins:* Ecuadorian–Colombian Andes, Peruvian–Chilean Andes, Cascades, Mexico *Continental collision zones:* Anatolia–Iran	*Continental flood basalts:* Deccan, Rajmahal, Madagascar, Karoo, Ferrar, Siberia, Emeishan, Columbia River, Parana–Etendeka, Yemen–Ethiopia, North Atlantic Tertiary, Central Atlantic (CAMP) *Diffuse provinces:* Indochina, Mongolia	The ocean floor *Oceanic plateaus:* Ontong Java, Iceland, Kerguelen, Shatsky Rise, Manihiki, Caribbean *Oceanic island–seamount chains:* Hawaii–Emperor, Ninety East *Diffuse provinces:* South Pacific Superswell	Snake River Plain–Oregon High Lava Plains, Dongargarh, Ethiopia (in part)	*Orogenic/Anorogenic granitic batholiths:* Tibet–Himalaya, Patagonia, Peru–Chile Coastal Batholith, Coast Range Batholith NW USA *Charnockite massifs:* Southern India	*Layered mafic intrusions:* Bushveld *Giant dykes warms:* Mackenzie, Red Sea, CAMP *Anorthosite massifs* (size permitting)	Deeper portions of oceanic plateaus

andesitic character. No specific tectonic setting is implied, though andesites of calc-alkaline affinity are generally associated with subduction zones (e.g., Gill, 1981; but see e.g., Morris et al., 2000; Sheth et al., 2002). This category includes large-volume andesitic belts along island arcs (e.g., Indonesia, Japan), active continental margins (e.g., the Ecuadorian–Colombian Andes, the Peruvian–Chilean Andes, the Cascades, the Mexican Volcanic Belt), and continental collision zones (e.g., Anatolia–Iran).

8. A hierarchical classification of Large Igneous Provinces

The foregoing discussion shows that the term LIP should be a broad one, and is insufficiently precise. With a view to more precise terminology, a hierarchical classification of LIPs is suggested here (Table 1) that incorporates the new terms for the discrete LIP subcategories. The explanation to the classification in Table 1 follows:

1. The terms in boldface, with the exception of *Large Igneous Province* (LIP) are newly proposed here. The terms in italics are either formal terms (e.g., *flood basalts*, *island arcs*) currently in vogue as applied to these provinces, or informal (e.g., *diffuse provinces*).
2. The classification proposed is independent of tectonic setting. No tectonic setting is excluded *a priori*, although most of the provinces described above can be assigned to intraplate (continental/oceanic) or rifted continental margin settings, while the LAP category is for the most part associated with subduction zones.
3. As indicated above for LBP (Section 5), a LAP may well include other rock types — the only criterion to be satisfied being magmas of dominantly andesitic composition extruded over an area ~ 50,000 km^2 or larger. The 1000-km-long, 50–60 km wide Mexican Volcanic Belt, dominated by andesitic volcanics, though containing significant amounts of OIB-like alkali basalts (e.g., Verma, 2002), is thus a LAP.
4. Large Basaltic Provinces (LBPs) will necessarily include, besides the lavas, any associated, exposed dyke swarms and intrusive complexes.
5. The category of dominantly mafic, intrusive, continental LIPs includes layered mafic intrusions and giant dyke swarms. Both types of features may or may not have been feeders to pre-exiting flood basalts since removed by erosion. The famed Skaergaard Intrusion is quite small in size (100 km^2) and an integral part of the East Greenland flood basalt province, and hence does not feature in Table 1. The Dufek and Forrestal Intrusions of Antarctica that cover ~ 6600 km^2 (Ferris et al., 2003) similarly belong to the Jurassic Ferrar flood basalt province. Globally, the Precambrian Bushveld Complex of South Africa (60,000 km^2, Winter, 2001) is the only body characterized as a LIP whose exposed area approaches or exceeds the proposed lower size limit for LIPs. Other well-known layered mafic intrusions (Duluth, Stillwater, Muscox, Kiglapait) are smaller but may still be considered as genetically equivalent.
6. Whereas 'Large Granitic Provinces (LGPs)' is considered an apt term for the broadly granitic batholiths, a corresponding short and single term for the dominantly mafic, intrusive, continental category (e.g., 'Large Gabbroic Provinces') does not seem possible. This is because many layered mafic intrusions have significant volumes of ultramafic rocks, and the associated giant dyke swarms (e.g., Ernst et al., 1995) are mostly dolerite.

9. 'Flood basalt', 'Plateau basalt', and 'Trap'

Continental and oceanic *flood basalt* provinces of the world – the *Large Basaltic Provinces* (LBPs) herein – have been extensively researched during the past two decades or so (e.g., articles in Macdougall, 1988; Mahoney and Coffin, 1997; Ernst and Buchan, 2001; Ebinger et al., 2002; Kerr et al., 2005; Foulger et al., 2005; Saunders, 2005; Foulger and Jurdy, 2007). The CFB provinces are individual volcanic constructs that are laterally extensive (several hundred kilometres) and thick (about a kilometre on average). They represent the eruption of enormous volumes of mantle-derived magma on the Earth's surface in relatively short time periods (one to few million years). Oceanic LBPs (e.g., Ontong Java) forming the so-called *oceanic plateaus* are, in several cases, vastly larger (references above).

In this section, merits of terms such as 'flood basalt' and 'continental flood basalt' (CFB) are evaluated. The New Penguin Dictionary of Geology (Kearey, 1996) has defined *flood basalt* as "an extrusion of low viscosity basaltic magma of very large volume". Sigurdsson (1999) defines flood basalts as "laterally extensive deposits of basaltic lava flows, resulting from outpouring of vast volumes of magmas during fissure eruptions" whereas Bardintzeff and McBirney (2001) similarly define flood basalt as "a voluminous, laterally extensive lava flow, normally erupted from a fissure".

Many individual lava flows in provinces like the Deccan and Columbia River exceed 100 m in thickness, extending laterally for more than ca. 100 km, with volumes exceeding 1000 km^3 (Bondre et al., 2004a,b; Sheth, 2006). The Columbia River basalt province was one of the first in the world to be studied in detail by modern methods. Shaw and Swanson (1970) presented a model of turbulent, rapid emplacement for these large lava flows. Based on features such as glassy selvages in the basalts at great distances (100 km) from the source vents, they correctly inferred that cooling of these lavas had been relatively insignificant, which they interpreted as implying very rapid emplacement over periods of days to weeks. Self et al. (1997), on the other hand, have argued that the implied lack of heat loss in Columbia River basalts does not imply rapid, turbulent emplacement. Based on observations of modern Hawaiian lavas (much smaller in size than individual flood basalt flows) (Hon et al., 1994) and of "medium-size" lava flows in Iceland, Self et al. (1997) and Thordarson and Self (1998) have argued that the extrusion of huge individual Columbia River basalt flows could have occurred over longer time periods (months to years) if their consolidation was inhibited by the effects of internal growth by inflation and surface insulation from the atmosphere during lava transport. This would have enabled transport over several hundreds of kilometres with almost negligible cooling and solidification. According to Self et al. (1997), individual lava flows in the flood basalt provinces, orders of magnitude larger than Hawaiian flows, might also have formed through inflation, over months to years.

Nonetheless, early proponents of rapid CFB emplacement, such as Shaw and Swanson (1970), probably did *not* envisage these lavas flowing for 100's of kilometres like torrential rivers in flood, without significant cooling. The first use of the term 'flood basalt' is not known, but the word *flood* probably was meant to imply inundation rather than torrential flow. Fluvial floods fill and inundate low-lying topography; the basaltic 'floods' render originally uneven topography into more or less flat topography. The term is therefore a valid descriptor of large-volume lava flows of high fluidity that produce essentially flat landscapes by inundating and filling pre-existing topography.

Long before the recognition of oceanic plateau basalts, early workers (e.g., Washington, 1922; Tyrrell, 1929) mostly described CFBs as *plateau basalts*, although Tyrrell (op. cit., p. 138) also refers to the great 'basalt floods' of the Deccan, Siberia and Iceland. As noted by such pioneers, all such CFB provinces comprise elevated, dissected plateaus of flat-lying lava flows: the Deccan, Columbia River, Parana, Siberian, Karoo, and the Yemen–Ethiopian CFBs are all excellent examples. The term 'plateau basalt' is an unsatisfactory term, however. Although it conveys a good mental picture of their *present-day* geomorphology, the plateau topography of CFBs, in contrast with their oceanic counterparts, is not constructional. A CFB province, when formed, might have consisted of a broad, gentle shield, its present-day topography displaying the effects of substantial post-eruption uplift and dissection (e.g., Sheth, 2007). In the above examples, the term *plateau basalt* is derived from the topography which is typically generated by processes not directly related to the volcanism. On the other hand, the topographic configuration of oceanic plateaus such as the Ontong Java Plateau is largely, if not wholly, constructional. Therefore, *flood basalt* is preferred as a descriptive term over *plateau basalt*.

The word *trap* has been widely used for the Deccan, Siberian, and other CFBs, though rarely if at all for the Columbia River CFB. (It is used by miners as well for any dark-coloured dyke intruding a coal seam or other rocks.) Sigurdsson (1999, p. 113) ascribes the first use of the word *trap* for basalt to Emanuel Swedenborg, the term derived from the Old Norse word *trappa*, a step in a stair. However, the step-like topography of many CFBs is also a product of post-eruption erosion and geomorphic processes. The term may be continued as an informal term. On the basis of the above discussion, therefore, it is suggested that the most appropriate terms to describe these large-volume basalt provinces on the continents and in the oceans are *flood basalt province* and *Large Basaltic Province* (LBP).

10. Conclusions

There is little or no justification for the continued use of the term *Large Igneous Province* (LIP) to mean flood basalt provinces alone. LIP is a broad term and should cover all igneous provinces, irrespective of petrogenesis or compositional affinity, exposed over a suggested minimum area of 50,000 km^2. New formal terms for several discrete LIP categories based on rock composition and extrusive or intrusive emplacement are proposed here. A new, tabulated hierarchical classification of LIPs that incorprates these new terms is also offered. An accurate and precise nomenclature system is important, and surely there are more than one ways to classify LIPs (see Bryan and Ernst, 2007 for a different scheme). The simple, comprehensive classification proposed here is intended to facilitate more accurate and effective communication among scientists working on the Large Igneous Provinces.

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