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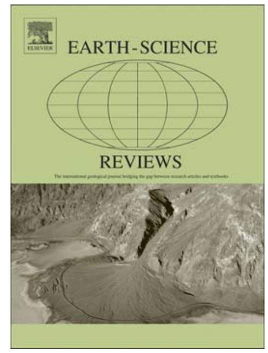

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Revised Definition of Large Igneous Province (LIP)

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Abstract

Substantial progress has been made on understanding several aspects of Large Igneous Provinces (LIPs) since their first formal categorization by Coffin & Eldholm (1994), and provides an opportunity to add to and revise the LIP database, identify the key characteristics that distinguish LIP events from other melting events of the upper mantle, and to reassess and revise how we define LIP. A precise definition is important to correctly recognize those LIP events with regional to global effects, and to aid in refining petrogenetic models of the origin of LIPs. In addition to areal extent, volume, duration, emplacement rates (or evidence for a transient high-emplacement rate pulse or pulses), and intraplate setting are fundamental to the definition of LIP. We revise the definition of LIP as follows: "*Large Igneous Provinces are mainly mafic magmatic provinces (having generally subordinate silicic and ultramafic components, whereas some are dominantly silicic) with areal extents >0.1 Mkm^2, igneous volumes >0.1Mkm^3 and maximum lifespans of ~50 Myrs that are emplaced in an intraplate setting and characterised by igneous pulse(s) of short duration (~1-5 Myrs), during which a large proportion (>75%) of the total igneous volume has been emplaced.*" In this revision, seamounts, seamount groups, submarine ridges and anomalous seafloor crust are no longer defined as LIPs. Although these are spatially-related features post-dating a LIP event, they are constructed by long-lived melting anomalies in the mantle at lower emplacement rates, and contrast with the more transient, high magma emplacement rate characteristics of the LIP event. Many LIPs emplaced in both continental and oceanic realms, are split and rifted apart by new ridge spreading centres, which reinforce the link with mid-ocean ridges as a post-LIP event. Three new types of igneous provinces are now included in the LIP inventory, to accommodate the recognition of a greater diversity of igneous compositions, and preserved expressions of LIP events since the Archean: 1) giant continental dyke swarms, sills and mafic-ultramafic intrusive provinces; 2) Silicic LIPs; and 3) tholeiite-komatiite associations, which may be Archean examples of LIPs. Establishing

the full extent of LIPs requires well-constrained plate reconstructions, and at present, plate reconstructions for the Precambrian are poorly known.

Keywords: Large Igneous Province; Definition; Flood basalt; Rhyolite; Komatiite; Dyke swarm

1. Introduction

The term "Large Igneous Province" (LIP) was initially proposed by Coffin & Eldholm (1994) to represent a variety of mafic igneous provinces with areal extents >0.1 Mkm^2 that represented "massive crustal emplacements of predominantly mafic (Mg- and Fe-rich) extrusive and intrusive rock, and originated via processes other than 'normal' seafloor spreading." The initial database upon which the term LIP was defined, relied almost exclusively on the relatively well-preserved Mesozoic and Cenozoic record that comprised continental flood basalt provinces, volcanic passive margins, and almost all of the oceanic volcanic features such as oceanic plateaus, submarine ridges, seamount groups and ocean basin flood basalts (Coffin & Eldholm, 1994, 2005). These types of provinces were distinguished into those that represent massive transient basaltic volcanism occurring over 0.1-1 Myrs (e.g., continental flood basalt provinces) and those representing persistent basaltic volcanism lasting 10-100 Myrs (e.g., seamount groups; Coffin & Eldholm, 2001). Since this first categorization of LIPs, substantial progress has been made in extending the LIP record back to the Paleozoic, Proterozoic and Archean (Ernst & Buchan, 1997; 2001, 2003; Tomlinson & Condie, 2001; Arndt et al., 2001; Isley & Abbott, 2002). For many ancient LIPs, where much or all the volcanic components of the LIP have been lost to erosion, definition has been based on the areal extent and volume of intrusive rock (e.g., giant continental dyke swarms, sills, layered intrusions), which is the exposed plumbing system to the province. In addition, it has also been recognized that LIPs can include massive crustal emplacements of predominantly silicic (>65 wt% SiO_2) extrusive and intrusive rocks that have originated via processes other than 'normal' seafloor spreading or subduction (Silicic LIPs of Bryan et al., 2002). Consequently, the increasing realization that LIPs are more varied in character, age and composition than first defined has prompted others to revise and broaden the original definition of LIP (Sheth, 2006).

2. Necessity for a Revised Definition

Correct identification of LIP events is critical for identifying, among other aspects: 1) major or catastrophic mantle events through Earth history (e.g., arrival of a core-mantle boundary-derived plume, mantle overturn or delamination), 2) major episodes of new crustal addition from the upper mantle, 3) episodes of continental breakup and supercontinent cycles, 4) those events that will have significantly impacted on the biosphere and atmosphere leading to climate shifts and mass extinctions, and 5) the formation of major mineral provinces (e.g., Ni-Cu-PGE deposits, and in the Silicic LIPs, epithermal Au-Ag bonanza deposits). It is therefore important to develop a definition and classification for LIPs that will direct us toward their origin and recognize those with regional to global effects. A variety of models have been proposed to explain the origin of LIPs (see summaries in Saunders, 2005; Ernst et al., 2005), including mantle plumes emanating from the core-mantle boundary (e.g., Richards et al., 1989; Campbell & Griffiths, 1990; Campbell, 2005; Dobretsov, 2005), impact-induced decompression melting (e.g., Jones et al., 2002; Coffin & Ingle, 2004); lithospheric delamination (Elkins-Tanton & Hager, 2000; Elkins-Tanton, 2005); decompression melting during rifting (White & McKenzie, 1989); Edge-driven convection (King & Anderson, 1998); melting of fertile mantle without excess heat (Anderson, 2005); stress-induced lithospheric fracturing and drainage of a relatively slowly accumulated sublithospheric basaltic magma reservoir (Silver et al., 2006); back-arc rifting (e.g., Rivers & Corrigan, 2000); or overriding of a spreading ridge by a continent (Gower & Krogh, 2002). Because the initial LIP definition has included such a wide variety of igneous provinces formed from both transient (high-rate) and persistent (low-rate) melting anomalies in the upper mantle, some of which may be spatially and temporally related, it has been difficult to develop a unifying model to explain the origin of LIPs.

In the original definition of Coffin & Eldholm (1994), areal extent (of predominantly mafic igneous rocks) was stressed as the important criteria in defining a LIP. As a consequence, this has meant that any mafic-dominant igneous terrane of either continuous exposure or an area defined by discontinuous exposure or occurrence (e.g., seamount groups) can potentially be defined as a LIP (see also Sheth, 2006). There are many volcanic provinces that meet this simple area criterion, but should not be defined as a LIP. One example that demonstrates this point is the Tertiary intraplate basalt volcanic province of eastern Australia, which forms a broken belt

>4400 km along the eastern highlands adjacent to the rifted margin (Johnson, 1989). Although the province has an areal extent >0.1 Mkm^2, is dominantly basaltic with intraplate compositions, and characterised by long lava flows typical of those in continental flood basalt provinces (Stephenson et al., 1998), the extrusive volume is only ~20,000 km^3 that has been emplaced over the last 80 Myrs. Volume, duration and emplacement rates are therefore important characteristics that need to be assigned to a revised definition of LIP.

3. Revised LIP Definition

Our understanding of LIPs has progressed significantly over the last decade that further criteria can be added to, and improve the definition of LIP. Our contribution to a revised LIP definition (Fig. 1) has been stimulated by the new proposed classification scheme of Sheth (2006). Like Sheth (2006), we also consider LIP to be a broad category and must encompass a number of igneous provinces not previously considered by Coffin & Eldholm (1994; 2005). LIPs can be defined or characterised by several other attributes, in addition to area: 1) age (e.g., Archean, Proterozoic, Phanerozoic), 2) volumetric size (e.g., Bleeker & Ernst, 2006), 3) crustal setting (continental vs oceanic); 4) tectonic setting; 5) duration or rapidity of magma emplacement; 6)
if primarily intrusive or extrusive (Sheth, 2006); and 7) composition (e.g., Mafic and Silicic LIPs of Bryan & Ernst, 2006).

Our revised definition emphasizes four attributes in addition to those of the Coffin & Eldholm (1994) definition: volume, duration and pulsed character of the igneous events, and tectonic setting. In addition, it is emphasized that substantial volumes of silicic magmatism are often an integral part of continental LIPs, and that a few LIPs are mainly silicic (Bryan et al., 2002):

"Large Igneous Provinces are mainly mafic magmatic provinces (having generally subordinate silicic and ultramafic components, whereas some are dominantly silicic) with areal extents >0.1 Mkm^2, igneous volumes >0.1Mkm^3 and maximum lifespans of ~50 Myrs that are emplaced in an intraplate setting and characterised by igneous pulse(s) of short duration (~1-5 Myrs), during which a large proportion (>75%) of the total igneous volume has been emplaced."

Below, we discuss the significance of each of these attributes to the definition of LIP.

3.1 Area

LIPs occupy large areas of the Earth's surface. As an extreme case, the Ontong-Java Plateau encompasses ~2 Mkm^2, which is approximately one-third of the coterminous United States (Coffin & Eldholm, 1994) or equivalent to the area of western Europe (Fitton et al., 2004). LIPs were initially defined as having areal extents >0.1 Mkm^2, which is the minimum areal extent for the smallest LIP, the Columbia River flood basalt province that forms a large plateau of ~0.164 Mkm^2 (Coffin & Eldholm, 1994; Hooper, 1997). Studies on the areal extents of the exposed plumbing systems and intrusive provinces to LIPs are also consistent with this (e.g., Yale & Carpenter, 1998; Marzoli et al., 1999; Ernst et al., 2005). Major regional continental dyke swarms for example, are >300 km in length (Ernst & Buchan 1997) and typically have areal extents of >90,000 km^2; this approaches the minimum areal extent considered for the continental flood basalt provinces. A review of several classic Mesozoic-Cenozoic LIPs concluded that the areal dimension of LIPs was ~1 Mkm^2 (see summary in Courtillot & Renne, 2003). Similarly, many oceanic plateaus cover areas >1 Mkm^2 (Kerr, 2005). The Silicic LIPs have dimensions well in excess of 0.1M km^2 (all are >0.5 Mkm^2; Bryan et al., 2002). We therefore conclude that in contrast to Sheth (2006), who revised downwards the minimum areal extent of LIPs to 0.05 Mkm^2, the original size definition be retained such that LIPs must have areal extents of >0.1Mkm^2.

3.2 Volume

Igneous volume is a critical attribute of LIPs as they are anomalous events emplacing tremendous volumes of magma throughout the crustal profile and at the Earth's surface. However, volume can be difficult to constrain where erosion has been substantial, the true thickness of the province is unconstrained or is highly variable across its areal extent, or where the province is defined mainly on intrusive rocks (e.g., giant continental dyke swarms and related mafic-ultramafic intrusive provinces such as the late Mesoproterozoic Warakurna LIP; Wingate et al., 2004).

LIPs vary in terms of the proportional volumes of volcanic and intrusive rock preserved, which reflects the degree of exhumation and age of the LIP, and potentially, lithospheric conditions at the time of LIP emplacement that may have promoted eruption or magma underplating/intrusion. The extrusive and intrusive components of a LIP are fundamentally related; for example giant continental dyke swarms are part of the intrusive architecture of a continental flood basalt province. For these reasons, we have not followed the approach of Sheth (2006) in subdividing LIPs into primarily volcanic or plutonic types.

It must be emphasized that published extrusive volume estimates for LIPs often include a subvolcanic intrusive component because dykes, sills and other subvolcanic intrusions are an integral part of, and can occur at shallow stratigraphic levels in the province (e.g., Huab sills of the Paraná-Etendeka LIP, Duncan et al., 1989; Karoo, Marsh et al., 1997). Distinguishing extrusive versus (subvolcanic) intrusive volumes can therefore be very difficult. Volume estimation is most problematic for the oldest (Precambrian) and often more deeply eroded LIPs. For the youngest provinces where erosion has been limited, the erupted volume can relatively easily be constrained, but the intrusive component is difficult to assess.

A further complication in volume estimations of LIPs is that in addition to the volumes of extrusive rocks and exposed subvolcanic intrusions, LIPs have a larger underplated magma volume emplaced at mid to lower crustal depths (e.g., White et al., 1987; Mohr, 1992). This underplated magma is commonly detected through geophysical studies as:

1) a high velocity lower crust (HVLC) often occurring along volcanic rifted margins in a zone of stretched continental crust between the unextended craton and normal oceanic crust (e.g., Eldholm & Grue, 1994; Kelemen & Holbrook, 1995; Menzies et al., 2002; Trumbull et al., 2002); and

2) abundant and extensive horizontal seismic reflectors which are interpreted as mantle-derived basaltic sills (e.g., Klemperer, 1989; Ross & Eaton, 1997; Mandler & Clowes, 1998; Planke et al., 1999).

The underplated igneous volume can be up to ten times larger than the associated extrusive volume. For example, the volume of the extrusive components of the Ontong Java oceanic plateau is estimated at 6 Mkm^3, whereas the volume of the combined extrusive and intrusive components is 44.4 Mkm^3 (Courtillot & Renne, 2003). For the North Atlantic Igneous Province, Roberts et al. (1984) estimated the total volume of Palaeocene to early Eocene basalt to be 2

Mkm^3, whereas White et al. (1987) and White & McKenzie (1989) suggested a total volume of up to 10 Mkm^3, and Eldholm & Grue (1994) estimated a total crustal volume of 6.6 Mkm^3.

Despite the complementary and larger volume of underplated basaltic magma, most volume estimates for LIPs are for the extrusive component. Preserved thicknesses of extrusive rocks for many Mesozoic-Cenozoic LIPs range from ~500 m to >3 km (e.g., Baker et al., 1996; Marsh et al., 1997; Bryan et al., 2002; Jerram & Widdowson, 2005), and the thickness of any individual section is typically $1 km. Many LIPs thus have areal extents and eruptive and/or subvolcanic intrusive volumes well in excess of 1 Mkm^2 and 1 Mkm^3, respectively (Courtillot & Renne, 2003).

We therefore conclude that LIPs should have a minimum extrusive/subvolcanic intrusive volume exceeding 0.1 Mkm^3, and that detailed thickness and volume estimates should be given in addition to areal extents of provinces. Care is required in estimating and comparing volumes for LIPs, and clarification should be given if an estimate includes extrusive and subvolcanic (upper crustal) intrusive volumes and/or middle and lower crustal components revealed by geophysical methods (see also Courtillot & Renne, 2003; Bleeker & Ernst 2006).

3.3 Duration of magmatism

Although LIPs represent massive volumes of igneous rock emplaced over huge areas, given sufficient time and space, all plate boundary processes generating magma (ie. mid-ocean ridges, subduction zones, continental rifts) will also produce igneous rock of LIP-scale dimensions. As pointed out by Sheth (2006), the 50,000 km-long worldwide network of mid-ocean ridges, with an average half-spreading rate of 5 cm/yr, creates 5 Mkm^2 of oceanic lithosphere of ~7 km thickness in just 1 million years. However, magma emplacement rates for LIPs have been estimated at ~10 to >100% greater than mid-ocean ridge emplacement rates (Coffin & Eldholm, 1994). A defining characteristic of LIPs therefore, is that large volumes of magma are emplaced over a geologically short and finite period and in a focused area.

Age resolution of LIPs is strongly dependent on the quality of the age data, sample quality and degree of weathering/alteration, the resolution of the dating techniques, and data availability (see

Hofmann et al., 2000; Courtillot & Renne, 2003; Heaman & LeCheminant 1993). Not all LIPs have been studied to the same level of detail, and age data in terms of reliability, technique and quantity are extremely variable. At most, LIPs appear to have an overall age duration of up to ~50 Myrs (Ernst & Buchan, 2001; Fig.2). The Mesozoic-Cenozoic continental flood basalt provinces appear to have the shortest durations with volcanic activity continuing for 10-15 Myrs (Courtillot & Renne, 2003; Jerram & Widdowson, 2005; Table 1). In many cases, thick sections of the flood basalt volcanic pile may have been emplaced in periods #1 Myrs (e.g., Hofmann et al., 2000; Larsen & Tegner, 2006). Layered intrusions such as the 9 km thick Bushveld complex may also have been emplaced rapidly (~75 Kyrs, Cawthorn & Walraven, 1998). The oceanic plateaus have been argued to have a rapid emplacement (e.g., 2-3 Myrs, Kerr, 2005) but such short durations are really only applicable to the formation of the top few hundred metres of these plateaus sampled at ODP drill sites. Importantly, the most recent ODP results for the Kerguelen and Ontong Java plateaus indicate a minimum 25 Myr span of volcanic activity, but which is likely to be pulsatory (Frey et al., 2003; Tejada et al., 1996; 2002). Consequently, those LIP events with lifespans >15 Myrs have been multiple-pulsed events (Fig. 2B).

3.4 Pulsed nature of magmatism

In addition to constraining the duration of LIP magmatism, a telling feature of the variety of radiometric and paleomagnetic studies over the last 15 years, particularly of the Mesozoic-Cenozoic continental flood basalt provinces, is evidence for a transient or pulsed nature to magmatism lasting as little as ~0.5-1 Myrs where there was repeated eruption and rapid emplacement of large volume magma batches (e.g., Marzoli et al., 1999; Courtillot & Renne, 2003). Both the volume of magma erupted during individual eruptions and the total volume of magma emplaced during the main eruptive pulse(s) of LIPs (>1 Mkm^3) are exceptional in Earth history (Self et al., 2005). These features have focused many studies on: 1) the environmental impact of LIP events on climatic deterioration, and as catalysts for faunal and floral collapse and extinction (e.g., Wignall, 2001; 2005; Courtillot & Renne, 2003; Erba et al., 2004); and 2) mechanisms of large volume and rapid melt generation in, and extraction from, the upper mantle (e.g., White & McKenzie, 1989; Richards et al., 1989; Campbell & Griffiths, 1990).

Systematic dating combined with detailed stratigraphic and volcanological studies have revealed a far more complex igneous history for LIPs than previously considered. Eruption rates are extremely variable over the whole duration of a LIP, and even for the shorter duration continental flood basalt provinces. Several geochronologic studies have identified pulse(s) or peak(s) in magmatic output where the bulk of the extruded magma volume was emplaced over a period of ~1-5 Myrs (e.g., Saunders et al., 1997; Courtillot & Renne, 2003; Frey et al., 2003; Jerram & Widdowson, 2005). Evidence for a single short pulse and rapid emplacement of a large volume of magma is well-expressed in the Columbia River Flood Basalt Province, the youngest and smallest LIP. Although basaltic eruptions occurred between 17 and 6 Ma, >90% of the total volume (~0.234 Mkm^3) was erupted between 16.6 and 15.3 Ma (Camp et al., 2003; Hooper et al., in press). Two distinct pulses are observable in some continental LIPs (Fig. 2B) that can correspond to pre-rift and syn-rift magmatic events. In the North Atlantic Igneous Province, the first pulse from 62 to 58 Ma corresponded to the emplacement of the terrestrial continental flood basalt sequences, whereas the bulk of the volcanic sequences along the continental shelves forming the 'seaward-dipping reflector series' were emplaced during a second syn-rift pulse at

56-52 Ma (Saunders et al., 1997; Jerram & Widdowson, 2005). Zones of high-velocity lower crust are also thought to be produced during rifting associated with continental breakup (Menzies et al., 2002). The hiatus between pulses is variable, but can be a few to tens of million of years. The relative extrusive volumes of pulses can be varied, and the volume of the second pulse may exceed the first (Campbell, 1998; Courtillot et al., 1999). Nevertheless, the igneous volumes emplaced during these pulses represents a substantial proportion (>75%) of the total LIP igneous volume.

In detail, comparative studies have indicated that several continental flood basalt provinces were characterised by at least three eruptive phases that vary from 0.1 to >5 Myrs: 1) an initial phase of relatively low-volume transitional-alkaline basaltic eruptions; 2) the main phase of flood volcanism where the bulk of the volcanic stratigraphy is emplaced rapidly by repeated large volume eruptions of tholeiitic basalt magma and in some cases, silicic magma; and 3) a waning and more protracted phase of volcanism where the volume of eruptions rapidly decreases and may become more widely distributed or focused when rifting is occurring (Jerram & Widdowson, 2005; Bryan et al., 2002). Discrete peaks in magmatic output are also being recognized for the Kerguelen and Ontong Java plateaus from recent ODP results (e.g., Frey et al., 2003). For the Silicic LIPs, systematic dating combined with stratigraphic studies have as yet not been carried out in sufficient detail in all cases to establish a well-defined pulsed character to magmatism. However, from the available data, a pulsed character to the magmatic activity in these provinces is indicated. In the 188-153 Ma Chon Aike province of South America-Antarctica, U/Pb zircon and $^{40}Ar/^{39}Ar$ dating has identified three main pulses of silicic volcanic activity each of 5-10 Myrs duration when ~0.05 to >0.1 Mkm^3 of rhyolite magma was emplaced (Pankhurst et al., 1998; 2000). For the Whitsunday Silicic LIP, although age data indicate a main period of activity from ~120-105 Ma, pulses in volcanism occurred at ~118-113 Ma and ~110-105 Ma (Ewart et al., 1992; figure 3 of Bryan et al., 1997). In the mid-Tertiary Sierra Madre Occidental province of Mexico, recent work has shown the bulk of the volume of the rhyolite ignimbrites was emplaced in two pulses each of ~4 Myrs duration and the ~1-3 Myr age ranges for many exposed ignimbrite sections >1 km thick also emphasize a rapid emplacement (Ferrari et al., 2002; 2006).

In summary, LIPs should be finite igneous events of no longer than ~50 Myrs duration (Fig. 2A), and characterised by a magmatic pulse or pulses of <5 Myrs duration in which a large proportion (>75%) of the total igneous volume has been emplaced.

3.5 Intraplate setting

An integral part of the original definition of Coffin & Eldhom (1994) was that LIPs were formed by processes not observable at modern plate boundaries (i.e. mid-ocean ridges and subduction zones). Their current global distribution and through time, occurring on both continental and oceanic crust, as well as being located remote or proximal to, or at present and former plate boundaries, reinforces their independence from magma generating processes at subduction zones and mid-ocean ridges. Many LIPs were initially emplaced into the interiors of continents, immediately preceding continental breakup, or into areas undergoing extension, and are now sited along rifted continental margins. In some cases, complete rifting to form a new ocean basin did not follow a continental LIP event, with the Emeishan, Siberian Traps and Columbia River flood basalt provinces being the most prominent and recent examples. Nevertheless, not only are many LIPs emplaced remotely from then-active plate boundaries, importantly they are also emplaced into stable continental regions with a long history (often 100's Myrs) of no prior magmatism or contractional deformation (Table 1; Fig. 3). It is the abruptness and voluminous eruption in stable continental regions that make LIP events so distinctive and anomalous, and underpin the intraplate character of these events.

An important indication of an intraplate setting is the petrological, geochemical and isotopic distinctions of within-plate tholeiites of LIPs from plate margin magmatism (MORB and subduction-related basalts). The volume and rate of magma generation in LIP events have been related by many workers to hot mantle upwellings, and interpreting the geochemical characteristics of LIPs have been in terms of components from the asthenospheric mantle or plume, sub-continental lithospheric mantle and the depleted asthenospheric mantle (Carlson, 1991; Turner & Hawkesworth, 1995; Hofmann, 1997; Condie, 2003; Ewart et al., 2004a). Crustal contamination and source heterogeneity are major causes of intra- and inter-LIP variation, however, which in some cases can lead to apparent subduction-related signatures in flood basalts (e.g., Carlson, 1991; Hergt et al., 1991; Cox, 1992; Ewart et al., 1998a). Nevertheless, the least contaminated basalts and picrites in many continental LIPs have isotope and geochemical compositions similar to oceanic island basalts (ie. the high-Ti basaltic magma suites) that reinforce an intraplate tectonic setting to magmatism.

A few LIPs, however, have been emplaced along or near active plate boundaries. Some oceanic LIPs were emplaced initially at incipient plate boundaries, triple junctions or at new ridges, but are now mid-plate following ridge migrations (e.g., Shatsky Rise, Sager, 2005). Some LIPs have been emplaced along continental margins with a history of subduction-related magmatism and deformation immediately prior to and after the LIP event, and this is most evident for the Cenozoic LIPs of North America (Fig. 3). The Columbia River flood basalt province and Sierra Madre Occidental geographically overlap with subduction-related magmatism. Given this regional setting, it has been argued that magmatism and extension associated with the LIP event may be the result of back-arc spreading (e.g., Carlson & Hart, 1988; Smith, 1992). Furthermore, dominantly lithospheric geochemical signatures to the flood basalts and rhyolites make recognition of an intraplate signature difficult. However, the LIP events in plate margin settings

are distinctive from spatially associated plate margin-related magmatism in terms of their extent (both in terms of total area and extent in board from the plate margin), volume and rapidity of eruption, association with extension, and composition. For the Columbia River flood basalts, the large volumes of tholeiite magma and the geochemical similarities between the earliest flood basalt eruptions and oceanic island tholeiites contrast with the neighbouring subduction-related magmatism, and have been interpreted to indicate derivation from a mantle plume (e.g., Hooper, 1997).

3.6 Composition

Almost all LIPs are compositionally and volumetrically mafic-dominant (<56 wt% SiO_2), and usually viewed as comprising relatively homogenous successions where large volume (up to ~5000 km^3), phenocryst-poor tholeiitic basalt lavas are the main rock type. At the scale of individual eruptive units, flood basalt lavas generally show remarkable chemical and mineralogical homogeneity, even across many hundreds of kilometres (Hooper, 1997). However, at the provincial scale, significant compositional variations exist within LIPs, and this compositional variation occurs both spatially and temporally during a LIP event. Much of the broader compositional variation is due to the presence of silicic and ultramafic igneous rocks, which represent important components to most LIPs, and the ultramafic rocks have particular economic significance for Ni-Cu-PGE mineralisation (e.g., Naldrett, 1997; Pirajno, 2000). Small-volume undersaturated magmatism (e.g., lamprophyres, carbonatites, kimberlites) may also occur during the earliest stages of a LIP event, but which is otherwise predominated by transitional-alkaline and olivine-rich to picritic lavas (Jerram & Widdowson, 2005; Riley et al. 2003; Agashev et al., 2004).

Most, if not all LIPs emplaced into continental regions are compositionally bimodal with chemical groupings at 45-56 wt% and 65-75 wt% SiO_2 (e.g., the 31-22 Ma Afro-Arabian, 62-53 Ma NAIP; 138-127 Ma Paraná-Etendeka; 190-178 Ma Karoo; 825 Ma Gubei of South China; 2060 Ma Bushveld; 2500-2450 Ma Matachewan). Large-volume tholeiitic eruptions characterise the main pulse(s) of a LIP event, whereas silicic, often explosive volcanism may precede, occur throughout, or during the latter stages of the main pulse (Bryan et al., 2002). As demonstrated by the recent ODP results from the Kerguelen oceanic plateau (Frey et al., 2003), it should also not be assumed that silicic igneous rocks are absent from LIPs in oceanic settings. An important point is that the eruptive stratigraphies of LIPs are incompletely preserved yet many continental flood basalt provinces show an increasing proportion of silicic volcanism up-section (e.g., Ukstins Peate et al., 2005). Consequently, the proportion of silicic volcanic products may be underestimated (because of erosion), but also, their occurrence late in the evolution of a LIP may be an artefact of preservation (Bryan et al., 2002). Determining the true proportion of silicic to mafic igneous rock (and total volume) must also include the eroded portion and hidden intrusive component that in general, remain largely unknown.

The detailed geochemical studies undertaken over the last 15 years have recognized many (in some cases >10) different magma types in individual LIPs (e.g., Marsh et al., 2001; Saunders et al., 1997). These studies have established: 1) the occurrence of low- and high-Ti magma types, for both the mafic and associated silicic igneous rocks, distinguished on the basis of elevated Ti and other incompatible elements relative to other elements (e.g., Cox et al., 1967; Marsh et al., 2001); and 2) the generally marked provinciality in the distribution of the low- and high-Ti suites (e.g., Paraná-Etendeka, Karoo, Ferrar), but which can also be interbedded. The low-Ti character to the tholeiitic basaltic magma types has commonly been interpreted to reflect crustal contamination, either with the subcontinental lithospheric mantle and/or with the continental crust (e.g., Carlson, 1991; Peate, 1997; Ewart et al., 1998a; 2004a), or mantle melting conditions and potentially higher degrees of partial melting of the upper mantle at shallower depths (Arndt et al., 1993; Xu et al. 2001; 2004).

In contrast, the high-Ti mafic suites often show greater geochemical and isotopic similarity to OIB and are interpreted to comprise a significant and relatively uncontaminated asthenospheric mantle or plume component (e.g., Arndt et al., 1993; Zhao et al., 1994; Ewart et al., 1998a; 2004a). The presence of relatively low-volume, high-Mg picritic igneous rocks are also significant in LIPs. The refractory character of the picritic rocks indicates not only a high potential temperature and degree of melting in the underlying mantle, but are likely parental compositions to the large volume tholeiitic flood basalt lavas that have not undergone significant crystallisation or crustal interaction (Holm et al., 1993).

Although high-Mg rocks (>12% MgO picrites, komatiites and meimechites; Le Bas, 2000) are volumetrically less significant than basalts, they are important in interpreting the LIP record because their high degree of partial melting better preserves the mantle ratios of less incompatible elements such as Pr, Nd and Sm (e.g., Campbell, 2002). They are also important as the hosts for Ni-Cu-PGE ore deposits (e.g., Naldrett, 1997, Pirajno, 2000; Borisenko et al., 2006). High-Mg rock types that are present in Phanerozoic LIPs include picrites, ferropicrites, and rarely komatiites (Kerr et al., 1996; Gibson et al., 2000; Herzberg & O'Hara, 2002; Zhang et al., 2005). High-Mg rock types distinguished in the Archean are Al-depleted and Al-undepleted komatiites which reflect different depths of origin (e.g., Fan & Kerrich, 1997) and ferro-komatiites (Gibson et al., 2000). Debate exists, however, over whether the presence of the olivine-rich magmas and high-Mg olivine compositions do indicate higher mantle melting temperatures and temperature differences between upwelling (plume) and ambient mantle (e.g., de Wit and Ashwal, 1995; Thompson & Gibson, 2000; Green et al., 2001).

In contrast to most LIPs, the Silicic LIPs are compositionally and volumetrically dominated by silicic (>65 wt% SiO_2) igneous compositions, but often have a spectrum of extrusive and intrusive compositions from basalt to high-silica rhyolite (e.g., Ewart et al., 1992; Bryan et al.,
2000; Riley et al., 2001; Ferrari et al., 2006). As for other LIPs, the driving processes of large volume melt extraction from the upper mantle and large mantle-derived thermal and material fluxes into the crust (driving widespread partial melting) are also fundamental to the generation of the Silicic LIPs (e.g., Pankhurst & Rapela, 1995; Riley et al., 2001; Bryan et al., 2002). The difference between the Silicic LIPs and other continental mafic-dominated LIPs is thought to be due to different crustal settings: the Phanerozoic Silicic LIPs are restricted to continental margins where fertile, hydrous lower crustal materials were built up by Phanerozoic subduction, and large-scale crustal melting has been fundamental to the generation of the huge volumes of silicic magmas.

4. Revision to LIP types

Several different provinces were defined as LIPs by Coffin & Eldholm (1994), with the first four representing transient types of Coffin & Eldholm (2001):

- Continental flood basalt provinces
- Volcanic passive (or rifted) margins (including seaward-dipping reflectors)
- Oceanic plateaus
- Ocean basin flood basalts
- Submarine ridges
- Seamount groups

- Anomalous seafloor spreading crust

This initial inventory of LIP types was strongly influenced by Mesozoic to Recent examples, and by volcanic features on the seafloor, such that the present-day distribution of LIPs has been heavily biased towards oceanic examples (see figure 1 of Coffin & Eldholm, 1994). Excluding the volcanic passive margins, only 14 of the 97 LIPs listed by Coffin & Eldholm (1994) are known from the continents. Significant advances have been made to the geology of many regions over the last ten years, allowing the recognition of many more continental LIPs extending back in age to the Archean (see table 1 in Ernst & Buchan, 2001; Prokoph et al. 2004; Ernst et al., 2005).

A number of the igneous province types of Coffin & Eldholm (1994) no longer fit the revised definition of LIP: submarine ridges, seamount groups and anomalous seafloor spreading crust. These provinces are often spatially associated, providing a spatial-temporal connection between

a LIP and an active hotspot (e.g., Paraná-Etendeka flood basalt province-Walvis Ridge-Tristan de Cunha). Submarine ridges and seamounts are often included in LIP studies because they can provide: 1) geochemical characteristics on the underlying asthenospheric hotspot or plume; and 2) a reference point on geochemical-isotopic variation diagrams of LIP compositions (Saunders et al., 1997). However, these submarine volcanic structures are post-LIP features forming in some cases 10's to100's Myrs after the main LIP pulse, but also over long intervals (10's to 100's Myrs). In the mantle plume hypothesis, submarine ridges and seamounts thus represent the 'trails' and 'tails' of plumes. Seamounts and seamount groups represent localised topographic features on the seafloor, and have a very different volcanic expression to other LIPs. Seamounts are centralised constructive (largely submarine) volcanoes, in contrast to the very extensive plateaus of the continental flood basalt and oceanic plateau provinces that are built up by repeated large-volume tabular and extensive basaltic lavas, sills and lesser silicic eruptive units (e.g., Jerram, 2002; Jerram & Widdowson, 2005). Although seamount groups may be areally extensive, the cumulative erupted volumes are significantly less than for the other LIPs, or have been emplaced over a much longer duration (>50 Myrs). For example, the Canary Islands were defined as a LIP by Coffin & Eldholm (1994), but have no temporal or spatial connection to a LIP event, are the result of persistent volcanism over the last 80 Ma, producing a cumulative volume of only ~0.12 Mkm^3 at averaged emplacement rates orders of magnitude less than for

LIPs (Coello et al., 1992; Schmincke, 1982; Geldmacher et al., 2001).

Many LIPs immediately precede continental breakup and the development of a new ocean basin and mid-ocean ridge spreading system. Subsequent rifting by new spreading centres soon after formation also characterises the oceanic LIPs (e.g., the reconstructed Ontong Java-Manihiki-Hikurangi oceanic plateaus, Taylor, 2006; Kerguelen-Broken Ridge plateaus, Frey et al., 2003; Agulhas - Maud Rise plateaus, Jokat et al., 2004). The Atlantic, Indian and Antarctic ocean ridge spreading systems can therefore be considered as the consequence of LIP events and not the LIP event itself (cf. Sheth, 2006).

We therefore recommend that seamounts/seamount groups, submarine ridges and anomalous seafloor crust no longer be considered as LIPs. A revised listing of LIP types is given in Figure 1 and the global distribution of Phanerozoic LIP events since 550 Ma is shown in Figure 4. LIPs can simply be subdivided into those occurring on the continents or in oceanic settings, and the important outcome of our revision is the recognition of several more types of continental LIPs than initially considered. Furthermore, although oceanic plateaus arguably represent the largest LIPs in terms of area and volume, certainly for the Mesozoic-Cenozoic, LIP events during this time have predominantly been a continental feature (Fig. 4), but with much of the post-LIP-related activity occurring in the ocean basins (see figure 1 of Anderson, 2005). Other authors have previously emphasized the peak in oceanic plateau formation during the Cretaceous (e.g., Larson, 1991; Kerr, 1998; 2005). It is also important to point out that the products of continental LIPs can be deposited in oceanic settings (e.g., Ukstins Peate et al., 2003), but their primary sites of eruption and accumulation are on the continents. In contrast, no oceanic LIP events during the Paleozoic are currently known (Fig. 4B).

The various provinces recognized and discussed by Coffin & Eldholm (1994) are updated and revised here (Figure 1) to include those major ancient LIPs in which the dyke swarms and mafic-ultramafic intrusive provinces are dominant. Separate groupings are also made for greenstone belts of tholeiitic and komatiitic rocks that may be Archean LIPs, and for the Silicic LIPs (Bryan et al., 2002). These subgroupings of LIPs also have temporal significance, as the character of LIPs shows some variation through time:

- Greenstone belts of the tholeiite-komatiite association in the Archean

- Proterozoic-Paleozoic LIPs occurring as eroded flood basalts or Silicic LIPs with exposed plumbing systems (dykes, sills, cauldrons, layered intrusions, batholiths), and
- Continental flood basalts, volcanic rifted margins, oceanic plateaus and Silicic LIPs in the Mesozoic and Cenozoic.

The characteristics of the new province types are summarised below.

4.1 Giant continental dyke swarms, sills & mafic-ultramafic intrusive provinces

The volcanic portion of older continental LIPs is largely removed by erosion and can be deformed during later continental collision. Therefore, in the early Mesozoic but especially in the Paleozoic and Proterozoic record, continental LIPs are typically recognized by their exposed plumbing system of giant dyke swarms, sill provinces, large layered intrusions, and remnants of flood basalts (Ernst & Buchan, 1997; 2001). Like their flood basalt equivalents, this class of LIPs has large areal extents and volumes, exhibit short duration pulses and occur in an intraplate setting.

Giant diabase/dolerite dyke swarms having lengths >300 km (Ernst & Buchan, 1997) are a particularly distinctive feature of ancient eroded LIPs. Dyke distribution tends to be either radial or linear. Radiating swarms can extend more than 2000-3000 km from a focal region, but generally only a portion of the radiating pattern (<90^{o}) is preserved because of continental fragmentation. Linear swarms can also extend more than 1000 km and are defined by lower dyke intensities over broad zones (>100 km) possibly associated with portions of broader radiating patterns, or high density dykes in narrow zones (<100 km) associated with rifts. Magnetic fabric studies have identified transitions from vertical to horizontal flow for a few giant dyke swarms such that the majority of magma flow along the strike length of dyke swarms >1000 km in length appears to be horizontal (Ernst & Baragar, 1992; Raposo & Ernesto, 1995). Where dyke swarms intersect pre-existing sedimentary basins, magma injection changes orientation, becoming sills within and near sedimentary basins (Ernst et al., 1995). Dykes belonging to giant dyke swarms have typical widths of 20-40 m, and maximum widths of 100-200 m. Ultramafic dykes associated with layered intrusions may be wider and up to 1000 m (e.g., the Great Dyke of Zimbabwe is up to 11 km at surface, but narrows at depth to about 1 km).

An impressive dyke swarm-dominated event is the 1270 Ma Mackenzie LIP, which extends over 2.7 Mkm^2 of the Canadian Shield (Buchan & Ernst, 2004; Baragar et al., 1996). The mid-Proterozoic Mackenzie magmatic event comprises three major components: the Mackenzie dykes which form a giant radiating dyke swarm that fans over 100 degrees across the northern margin of the Canadian shield; the Coppermine River flood basalts representing an erosional volcanic remnant exposed ~400 km south of the focal point to the dyke swarm, and the Muskox layered intrusion located at shallow depths beneath the southernmost exposure of the Coppermine River basalts (Baragar et al., 1996). Widespread U-Pb dating by LeCheminant & Heaman (1989) and Heaman & LeCheminant (1993) yielded ages of 1267-1272 Ma and established the essential contemporaneity of the preserved intrusive system throughout its enormous geographic extent. Likewise, the 1078-1070 Ma Warakurna LIP of central and Western Australia, comprising layered mafic-ultramafic intrusions, mafic to felsic volcanic rocks and dikes, and a 1000-km-long mafic sill province (Wingate et al., 2004) demonstrates the large lateral extent and short duration of large volumes of magma intruded during LIP events.

The 2060 Ma Bushveld intrusion of South Africa is the world's largest layered igneous intrusion, and is regarded as the intrusive equivalent of a flood basalt province, given its extensive volume and short duration (Hatton, 1995; Eales & Cawthorn, 1996; Cawthorn & Walraven, 1998; Kinnaird, 2005). It consists of a 9 km thick layered suite that was intruded beneath a volcanic carapace of which a 3 km thick volcanic/pyroclastic sequence is preserved (Kruger, 2004). The event can be extended for another 350 km to the west with the correlation of the Molopo Farms layered intrusion of Botswana (e.g., Reichardt, 1994; Kinnaird, 2005).

4.2 Silicic LIPs

Silicic igneous rocks are an integral part of all continental LIPs from the oldest Precambrian (e.g., Twist & French, 1983; Thorne & Trendall, 2001; Blake et al., 2004) to the youngest Cenozoic examples, and are particularly prevalent in the Mesozoic-Cenozoic continental flood basalt provinces and along volcanic rifted margins. In these LIPs, silicic volcanic and volcaniclastic rocks can form substantial parts of the eruptive stratigraphy and represent a significant contribution to the total magmatic output of a LIP (Bryan et al., 2002). It is underappreciated that the scale of some of the individual silicic units in LIPs is vast (e.g., in the

Paraná-Etendeka, the largest units cover areas >0.1 Mkm^2), being larger than the associated flood basalt lavas, such that they are ranked as amongst the largest volume terrestrial eruptive units so far recognized (Milner et al., 1995; Marsh et al., 2001; Ewart et al., 1998b, 2004b).

In addition to representing a significant igneous component in a dominantly mafic LIP, there are some silicic igneous provinces that meet the criteria of a LIP, but have low proportions of basalt expressed at the surface (Silicic LIPs). Importantly, some Silicic LIPs are spatially and temporally-related to other LIPs. For example, the Chon Aike Silicic LIP is linked with the Karoo-Ferrar flood basalt provinces (Pankhust et al., 1998; 2000). The Malani silicic igneous province (India) is coeval with mafic magmatism in the Seychelles, South China, Korea (Ogcheon), and Australia (Mundrie Well), although limited paleomagnetic data do not currently support a single grouping of all these igneous provinces (Li et al., 2006). However, the association of a silicic igneous province with a LIP may be obscured by continental rifting and fragmentation, and/or by poorly constrained plate reconstructions. The Chon Aike province of South America-Antarctica is a clear example of this where continental rifting and seafloor-spreading have isolated the Silicic LIP from its neighbouring and coeval continental flood basalt provinces (Karoo-Ferrar; Fig. 5A). It may be significant that the largest Silicic LIP (Whitsunday igneous province) and the largest known oceanic plateau and LIP (Ontong-Java-Manihiki-Hikurangi Plateau complex; Taylor, 2006) were emplaced at the same time ~120 Ma, with the latter occurring offshore from the fragmenting continent (Fig. 5B).

The Mesozoic-Cenozoic examples of Silicic LIPs are the best preserved, and their characteristics have been summarised in Bryan et al. (2002) and Skilling et al. (2006). Silicic LIPs have several unifying characteristics: 1) extrusive volumes are >0.25 Mkm^3 (up to ~3 Mkm^3); 2) the provinces comprise >80% by volume of dacite-rhyolite, with transitional calc-alkaline I-type to A-type signatures; 3) rhyolitic ignimbrite is the dominant volcanic lithology; 4) the duration of igneous activity is up to 40 Myrs, but during which a large proportion of the magma volume was erupted during shorter intervals or pulses (3-10 Myrs); and 5) crustal setting - Silicic LIPs are exclusively continental as they are produced by large-scale crustal anatexis, and many were a pre-rift magmatic event along volcanic rifted margins. The Whitsunday igneous province is the largest of the world's Silicic LIPs where the eruptive output (>2.2 Mkm^3) and preserved areal extent of volcanism and its products (>3 Mkm^2) surpasses that of many other LIPs (Bryan et al., 1997;

2000). The Sierra Madre Occidental of Mexico is representative of the general Silicic LIP architecture, being an extensive, relatively flat-lying ignimbrite plateau covering an enormous area (>0.5 Mkm^2) to ~1 km thickness. More ancient examples occur as continental caldera systems and major batholiths (e.g., the 320-280 Ma Kennedy-Connors-Auburn province, northeast Australia; Bryan et al., 2003). Silicic LIPs are expected to have similarly extensive mid to upper crustal granitic batholith underpinnings and dyke swarms, and more mafic igneous underplate at lower crustal depths (Ferrari et al., 2006). Large thermal and mass inputs from the mantle on the scale of those required to produce the continental flood basalt provinces are likely in order to produce the Silicic LIPs (Bryan et al., 2002). The initiation of crustal partial melting and rhyolite magma generation in the Chon Aike Silicic LIP was in response to crustal heating and magmatic underplating related to emplacement of the Karoo-Ferrar continental flood basalt provinces (Riley et al., 2001), and is supported by the close temporal-spatial linkages between these LIPs (Fig. 5A).

4.3 Archean greenstone belts (tholeiite-komatiite associations)

The extrapolation of the LIP record into the Archean is more speculative. Several workers have compared Archean tholeiitic basalt sequences with modern flood basalt provinces (see summary in Arndt, 1999), and erosional remnants of typical Archean flood basalt provinces include the Fortescue sequence of the Pilbara craton in Australia and the Ventersdorp sequence of the Kaapvaal craton in southern Africa (Eriksson et al., 2002). However, most Archean volcanic rocks occur as deformed and fault-fragmented packages termed greenstone belts (de Wit & Ashwal, 1997, 1998). One class of greenstone belts contain mafic to silicic igneous rocks with calc-alkaline geochemical signatures and have been interpreted to be remnants of island arc and rifted island arc terranes that developed remotely from continents. However, the other major class of greenstone belts consists of tholeiite sequences that often contain komatiites, and these are the best candidates for being remnants of Archean LIPs.

With respect to the classification criteria distinguished herein (area, volume, duration, and setting), the LIP nature of tholeiite-komatiite greenstone belts remains somewhat equivocal. Deformation and faulting generally prevents the tracing of Archean tholeiite-komatiite greenstone belts over LIP-scale distances. An important exception occurs in the Rae craton of northern Canada where the ca. 2700 Ma Prince Albert, Woodburn Lake, and Mary River Groups define a linear belt, which extends for a distance of 1500 km (>0.2 Mkm^2), and may be linked with a mantle plume and/or a late Archean breakup margin (e.g. McHattie et al., 2004). Another example of an extensively preserved Archean LIP is the ~2.7 Ga Bulawayan Supergroup, which contains 4-6 km thick mafic-ultramafic-silicic volcanic sequences that extend for ~0.25 Mkm^2 across the Zimbabwe Craton (Prendergast, 2004). Other extensive (> 800 km strike length) submarine volcanic sequences containing tholeiites and komatiites occur in the Yilgarn Craton (Norseman-Wiluna Belt) and Canadian Superior Province (Abitibi Belt), and are also significant for being the largest and most intensely mineralized Late Archaean greenstone belts (Barley et al., 1998). Event volume is even more difficult to assess given the deformation in most greenstone belts. The full scale of tholeiitic-komatiitic greenstone belts, and how many are of LIP scale, is likely to only become clearer when robust late Archean reconstructions are achieved (Bleeker, 2003).

The tholeiite-komatiite sequences in Archean greenstone belts contain a variety of volcanic (massive to pillowed lavas, hyaloclastites) and subvolcanic intrusive (dykes, sills) facies. Individual lavas can be traced for kilometres, whereas lava packages have been traced for up to 100 kilometres along strike (Arndt, 1999; Prendergast, 2004). Many tholeiite-komatiite lava successions are the result of submarine eruption and emplacement, however, much of the mafic-ultramafic and associated silicic volcanism recorded by the 2.7 Ga Fortescue Group of the Pilbara Craton was subaerial (Arndt, 1999; Blake, 2001). The apparent lateral continuity of the mafic-ultramafic lavas, the general lack of interbedded sedimentary rocks and the massive character of the lava units have been collectively interpreted to indicate the rapid eruption of large volumes of magma analogous to the Mesozoic-Cenozoic flood basalt provinces.

A characteristic of many Archean greenstone belts is multiple pulses. For example, the Abitibi belt has pulses of tholeiitic-komatiitic magmatism at 2750-2735 Ma, 2725-2720 Ma, 2718-2710 Ma, and 2710-2703 Ma (Ayer et al., 2002). The Fortescue flood basalt of the Pilbara craton has pulses at ca. 2770, 2720, and 2690 Ma (Thorne & Trendall, 2001; Blake et al., 2004; Pirajno, 2004). Whether these represent multiple pulses of a single LIP or the juxtaposition of separate LIPs remains to be determined. The final parameter is intraplate setting. The dominant view is that the tholeiite-komatiite-bearing greenstone belts are not produced by subduction, and indeed some are thought to be obducted oceanic plateaus (e.g., Kent et al., 1996; Tomlinson & Condie, 2001). However, many Archean tholeiite-komatiite examples showing geochemical evidence for crustal contamination and contemporaneous emplacement with significant volumes of silicic igneous rocks (e.g., Yilgarn) were emplaced onto submerged continental platforms (Arndt, 1999), submerged highly extended continental crust, or into intracontinental rift basins (e.g., Pilbara, Kaapvaal). These examples with continental basement and associated silicic igneous rocks are more analogous to the Mesozoic-Cenozoic volcanic rifted margins and continental flood basalt provinces. In addition, greenstone belts with komatiites are probably not produced by normal spreading ridge processes because komatiites indicate source region temperatures higher than those associated with normal spreading ridges, and the crustally contaminated geochemical signatures indicate eruption in continental regions (Arndt, 1999). However, some controversy exists for both these points. There is some evidence for the production of komatiites by melting of wet mantle under subduction conditions (e.g., Parman & Grove 2005), and it is also possible that normal ridge production can produce komatiite magmas, particularly given a hotter Archean geotherm (de Wit & Ashwal, 1995).

5. Fragmented LIPs

An important issue in identifying LIPs and determining their original attributes (area, volume, duration, magmatic pulses) is that many become fragmented, and that fragmentation can occur soon after the LIP event. Continental LIPs can be fragmented in two ways: 1) by plate-breakup processes in which components of the LIP end up on separate rifted continental blocks or cratons, and/or 2) by deep erosion in which the continuity of the flood basalts and volcanic cover sequences are lost, and units belonging to the exposed plumbing system of the LIP have a scattered distribution. The propagation of mid-ocean ridge spreading centres and ridge jumps can also fragment oceanic LIPs and separations between the various LIP fragments can be large, as evidenced for the Ontong Java-Manihiki and Hikurangi plateau fragments (Taylor, 2006). The importance of reconstructions is underlined by this interpretation, because if correct, it then establishes a single Ontong Java-Manihiki-Hikurangi LIP with an original size of >80 Mkm^2 (Fig. 5B).

Reconstructions for the Mesozoic and Cenozoic continental LIPs can be undertaken using constraints from the seafloor age distributions. For example, closing of the central Atlantic ocean allows reconstruction of the ~200 Ma CAMP LIP with components (mainly dykes and sills) in North America, South America, Europe, and Africa (Fig. 4A). As another example, the two pieces of the ~132 Ma LIP, the Paraná of South America and the Etendeka of southwest Africa are reconstructed by closure of the South Atlantic. In contrast, Phanerozoic reconstructions are less robust and few constraints exist for Proterozoic reconstructions (e.g., Buchan et al., 2001). Fortunately, progress in Precambrian reconstructions is being made using the classical paleomagnetic method (e.g., Wingate et al., 2002), and more recently with the LIP 'bar code' (Fig. 6) and 'dyke swarm piercing point' methods (Bleeker & Ernst, 2006).

An additional problem is deciding whether coeval magmatic units that are located on different cratons actually should be reconstructed into a single LIP or whether they represent simultaneous but separate LIP events. In the younger record, there are many examples of such LIP clusters (plume-clusters of Ernst & Buchan, 2002; superplume of Larson, 1991). For example, LIPs at ~130 Ma include the Paraná-Etendeka of South America-Africa breakup, the Trap dykes of southern Greenland, the Bunbury basalt of southwestern Australia, and the initial pulse of the High Arctic Large Igneous province. A second example of a LIP cluster is the essentially coeval 65 Ma Deccan and 62 Ma North Atlantic LIPs of India and Europe-Greenland, respectively.

The second type of LIP fragmentation is where intense and/or long-lived erosion has obscured the continuity of volcanic (± subvolcanic) rock. In these cases, paleomagnetic, geochemical and especially geochronological techniques are required to show that widely distributed dykes, sills, layered intrusions, batholiths and any erosional remnants of volcanic rocks were emplaced synchronously and have geochemical similarity are therefore, likely to belong to the same LIP event. The 1076 Ma Warakurna LIP of central and western Australia is an excellent example of how a very large and deeply eroded LIP event has been assembled through the collation of detailed radiometric and paleomagnetic age constraints and geochemical similarities (Wingate et al., 2004). Importantly, this continental LIP had not been fragmented by rifting processes, but has been significantly eroded.

Another point regards the shortage of oceanic LIPs in the pre-200 Ma record (Fig. 4B), which may indicate a poor preservation potential of oceanic LIPs during subduction, the difficulty of recognizing partially subducted, and accreted oceanic LIPs within orogenic belts formed during ocean closure, or that fewer past LIP events occurred in oceanic settings. Oceanic plateaus are more buoyant than oceanic crust, and therefore are expected to be more resistant to subduction, leading to accretion onto continental margins and preservation in the geologic record (Kerr, 2005). Collisional orogenesis and the jamming of subduction zones are predicted where large (>10^4 km^2) and >30 km thick oceanic plateaus arrive at subduction zones, as has been evident with the Ontong Java Plateau colliding with the Solomon islands arc (Cloos, 1993). Remnants of Late Paleozoic to Mesozoic accreted oceanic plateaus are now being recognised around the north Pacific margins (e.g., Sorachi, Japan; Piñon Formation, Ecuador; Cache Creek and Wrangellia, Canada). A related point is the apparent shortage of ancient volcanic rifted margins, with respect to the present day where up to 90% of the global rifted margins are volcanic (Menzies et al., 2002). These points have been considered by Coffin & Eldholm (2001) who noted that "more ophiolite fragments may be obducted sections of volcanic passive margins and oceanic plateaus than we now suppose".

6. Conclusions

Earth history has been punctuated by events during which large volumes of mafic and generally subordinate silicic and ultramafic magmas were generated and emplaced by processes distinct from those observable at modern plate boundaries. Large Igneous Provinces (LIPs) are the preserved expression of these anomalous magmatic events. However, few LIPs have been fully characterized in terms of their size, the variation in melt emplacement rate throughout the LIP event, the geochemical character and inferred distribution of mantle source areas, the plumbing system for emplacing and distributing magma in the crust, and links with ore deposits (Ernst et al., 2005). The revised definition emphasizes several key characteristics (volume, duration and pulsed character of the igneous events, tectonic setting and composition) that are hallmarks of these unusual magmatic events, and distinguish them from magma generating processes at plate boundaries. The revised definition therefore is aimed at directing future studies towards a better characterisation of LIPs. Although based on Earth examples, the revised definition should also provide the framework for characterising possible planetary LIPs thought to exist on Mars, Venus and the Moon (Head & Coffin, 1997).

As a consequence of the revised definition, a number of oceanic volcanic features are no longer considered as LIPs (seamount groups, submarine ridges, anomalous seafloor spreading crust), whereas three new province types are included: dyke swarms and mafic-ultramafic intrusive provinces that are the dominant and preserved expression of an ancient LIP event; greenstone belts of tholeiitic and komatiitic rocks that may be Archean LIPs; and Silicic LIPs emplaced along fertile continental margins where widespread partial melting and silicic magma eruption driven by large mantle-derived thermal and material fluxes into the crust prevented the more typical outpouring of large volumes of basaltic magma.

Additionally, a separate grouping (‘waiting room’) may be required for those smaller-scale igneous provinces that could have been a LIP or part of a LIP, but currently do not meet the revised dimension criteria due to a lack of data or size limitations as a consequence of erosion or burial and/or continental fragmentation. New LIPs will be identified as additional age data are obtained allowing correlation of what were previously considered unrelated igneous events in different and widely separated tectonic terranes, as has been shown over the last decade since the first formal inventory of LIP (e.g., the 1078-1070 Ma, Warakurna LIP; Wingate et al., 2004; and 2215 Ma Ungava LIP of the Superior craton, Buchan et al., 1998). An accurate definition is vital to assist with new LIP recognition, to avoid confusion over the use and meaning of the term Large Igneous Province, and to ensure the terminology keeps pace with the rapid advances in our understanding of LIP events. Most importantly, the revised definition is intended to provide an improved framework for petrogenetic models on the origin of LIPs, and an ability to better recognize those LIPs in the geologic record most likely to have had regional to global environmental and climatic effects.

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Figures

Figure 1. Revised classification of Large Igneous Provinces, based on the initial work of Coffin & Eldholm (1994), but incorporates recent advances in the recognition of ancient LIPs and the Silicic LIPs. Representative examples of the various types of LIPs are also given.

Figure 2. A) Histogram showing the duration of LIP (both continental and oceanic) events. Many LIP events have an overall time span of up to 15 Myrs during which is a shorter period or pulse of high-intensity magmatism (see text). B) Plot illustrating three key variables of LIP events: event age, LIP event time span, and number of pulses. Single-pulsed LIP events have overall durations of no more than 10-15 Myrs, whereas LIP events with durations >15 Myrs comprise multiple pulses. Single- and multiple-pulsed LIP events have occurred throughout Earth history. Data sources for LIP events: Ernst & Buchan (2001); see also Table 1. Only those LIP events which have sufficient and precise (e.g., U-Pb age dates for the Palaeozoic and Precambrian LIP examples) age data to characterise the LIP event have been plotted.

Figure 3. Time-space plot for Late Paleozoic to Cenozoic continental LIPs illustrating the age of the LIP event and the corresponding ages of the previous magmatic and tectonic events in the LIP basement (see also Table 1). Many LIPs were emplaced across Archean cratons and bounding mobile belts which have much younger histories of deformation and magmatism, and is shown here. Abbreviations: CAMP, Central Atlantic Magmatic Province; CRB, Columbia River Basalts; NAIP, Emei., Emeishan; North Atlantic Igneous Province; Mad., Madagascar; P-E, Paraná-Etendeka; SMO, Sierra Madre Occidental; ST, Siberian Traps; WA, Western Australia; Whit., Whitsunday. Data sources are given in a data repository.

Figure 4. Revised global distribution of Large Igneous Provinces. A) LIP events from 0-275 Ma,

updated and revised from the PLATES project database and map (Institute of Geophysics, University of Texas, Austin). Map excludes seamount groups, submarine ridges and anomalous seafloor spreading crust that have previously been considered LIPs by Coffin & Eldholm (1994, 2001, 2005). Interpreted remnants of oceanic plateaux accreted around the Pacific margins (Sorachi, Japan; Piñon Formation, Ecuador; Cache Creek, Canada) are not shown because of the lack of detailed information on their original areal extent, volume and duration. Annotated ages denote the onset of the main phase or first pulse of magmatism to the LIP event; note that some LIPs have precursor magmatism at lower intensity up to 10 Myrs prior. Abbreviations: CAMP, Central Atlantic Magmatic Province; HALIP, High Arctic Large Igneous Province; NAIP, North Atlantic Igneous Province; OJP, Ontong Java Plateau. B) LIP events from 275-550 Ma. The inferred extent of the LIP events is shown by the dashed line. The number of well-defined LIP events (in terms of area, volume, duration) is much diminished and no examples of accreted oceanic LIPs have been recorded for this period, which generally corresponds to Gondwanaland assembly. Unlike many of the Mesozoic-Cenozoic LIP events, most Palaeozoic LIP events have not been associated with continental breakup and the opening of new ocean basins.

Figure 5. Plate reconstruction maps showing the spatial relationships between coeval Silicic LIPs and mafic-dominated LIPs. A) Gondwanaland reconstruction at 200 Ma (Dalziel, 1992) showing the distribution of the Karoo and Ferrar continental flood basalt provinces and the Chon Aike Silicic LIP. Abbreviations: AP, Antarctic Peninsula; E, Ellsworth-Whitmore block; MBL, Marie Byrd Land; NZ, New Zealand; TI, Thurston Island. B) eastern Gondwanaland reconstruction for ~120 Ma showing the LIP cluster of the Whitsunday Silicic LIP, Louisiade ?oceanic plateau and the Ontong Java-Hikurangi-Manihiki reconstructed oceanic plateau (Taylor, 2006). Both the Whitsunday Silicic LIP and OJHMP formed rapidly at ~120 Ma. The structure, age and composition of the Louisiade Plateau is poorly understood, but has recently been suggested to have an igneous basement of similar age and structure to the Ontong Java Plateau (Cowley et al., 1998). However, plate reconstructions indicate it was adjacent to the eastern Gondwanaland margin during the Cretaceous and became separated following seafloor spreading in the Coral Sea Basin (Gaina et al., 1999). Regional-scale crustal lineaments, which have partitioned deformation and influenced rifting along the eastern Gondwanaland margin are also shown. Abbreviations: HP, Hikurangi Plateau; LHR, Lord Howe Rise; MP, Manihiki Plateau; NZ, New Zealand; OJP, Ontong Java Plateau; PNG, Papua New Guinea; SNR, southern Norfolk Ridge.

Reconstruction is based on Bryan et al. (1997); Gaina et al. (1998; 1999); Muller et al. (2006); Sutherland (1999) and Mortimer (2006). The palaeogeographic position of the OJP is based on Riisager et al. (2003).

Figure 6. Age spectrum (‘bar code’) of LIP events through time (updated from Ernst et al., 2005). The bar code includes well-defined LIP events that meet the new criteria of area, igneous volume and evidence for a pulsed magmatic output defined in this paper. Selected events are labeled at the starting age of the main pulse, and for multi-pulse LIPs, the arrow is placed at the oldest pulse. Not all LIP events are labeled for clarity. Associated supercontinents are listed along the left side. LIP abbreviations are: BLIP, Baltic Large Igneous Province; CAMP, Central Atlantic Magmatic Province; CSDG, Central Scandinavian Dolerite Group; HALIP, High Arctic Large Igneous Province; NAIP, North Atlantic Igneous Province; OJMHP, Ontong Java - Manihiki - Hikurangi Plateau; and SMO, Sierra Madre Occidental. Locations for LIP events are: NA, North America; SA, South America; EU, Europe; AF, Africa; AS, Asia; AU, Australia; AN, Antarctica; and PA, Pacific Ocean.

Tables

Table 1. Summary of characteristics of Latest Paleozoic to Cenozoic LIPs. Almost all the continental LIPs have been emplaced into regions with pre-existing large cratonic sedimentary basins. Additional data sources are given in the electronic data repository.

References

Agashev, A.M., Pokhilenko, N.P., Tolstov, A.V., Polyanichko, V.V., Mal'kovets, V.G., Sobolev, N.V., 2004. New age data on kimberlites from the Yakutian diamondiferous province. Doklady Earth Sciences 399, 1142-1145.

Anderson, D.L., 2005. Large igneous provinces, delamination, and fertile mantle. Elements 1, 271-275.

Arndt, N., Bruzak, G., Reischmann, T., 2001. The oldest continental and oceanic plateaus: geochemistry of basalts and komatiites of the Pilbara craton, Australia, In Ernst, RE, Buchan KL (Eds) Mantle Plumes: Their Identification Through Time. Geological Society of America Special Paper 352, 359-387.

Arndt, N.T., 1999. Why was flood volcanism on submerged continental platforms so common in the Precambrian? Precambrian Research 97, 155–164.

Arndt, N.T., Czamanske, G.K., Wooden, J.L., Fedorenko, V.A., 1993. Mantle and crustal contributions to continental flood volcanism. Tectonophysics 223, 39-52.

Ayer, J., Amelin,Y., Corfu, F., Kamo, S., Ketchum, J., Kwok, K., Trowell, N., 2002. Evolution of the southern Abitibi greenstone belt based on U-Pb geochronology; autochthonous volcanic construction followed by plutonism, regional deformation and sedimentation. Precambrian Research 115, 63-95.

Baker, J., Snee, L., Menzies, M., 1996. A brief Oligocene period of flood volcanism in Yemen: implications for the duration and rate of continental flood volcanism at the Afro-Arabian triple junction. Earth and Planetary Science Letters 138, 39-55.

Baragar, R.A., Ernst, R.E., Hulbert, L., Peterson, T., 1996. Longitudinal Petrochemical Variation in the Mackenzie Dyke Swarm, Northwestern Canadian Shield. Journal of Petrology 37, 317-359.

Barley, M.E., Krapez, B., Groves, D.I., Kerrich, R., 1998. The Late Archaean bonanza: metallogenic and environmental consequences of the interaction between mantle plumes, lithospheric tectonics and global cyclicity. Precambrian Research 91, 65-90.

Blake, T.S., 2001. Cyclic continental mafic tuff and flood basalt volcanism in the late Archaean Nullagine and Mount Jope Supersequences in the eastern Pilbara, Western Australia. Precambrian Research 107, 139–177.

Blake, T.S., Buick, R., Brown, S.J.A., Barley, M.E., 2004. Geochronology of a Late Archaean flood basalt province in the Pilbara Craton, Australia: constraints on basin evolution, volcanic and sedimentary accumulation, and continental drift rates. Precambrian Research 133, 143-173.

Bleeker, W., 2003. The later Archean record: a puzzle in ca. 35 pieces. Lithos 970, 99-134.

Bleeker, W., Ernst, R., 2006. Short-lived mantle generated magmatic events and their dyke swarms: The key unlocking Earth's paleogeographic record back to 2.6 Ga. In: Hanski, E., Mertanen, S., Rämö, T., Vuollo, J. (eds) Dyke Swarms - Time Markers of Crustal Evolution. A.A. Balkema Publishers, Rotterdam, 2006.

Borisenko, A.S., Sotnikov, V.I., Izokh, A.E., Polyakov, G.V., Obolensky, A.A., 2006. Permo-Triassic mineralization in Asia and its relation to plume magmatism. Russian Geology and Geophysics 47, 166-182.

Bryan, S.E., Ernst, R.E., 2006. Proposed Revision to Large Igneous Province Classification. http://www.mantleplumes.org/LIPClass2.html

Bryan, S.E., Constantine, A.E., Stephens, C.J., Ewart, A., Schön, R.W., Parianos, J., 1997. Early Cretaceous volcano-sedimentary successions along the eastern Australian continental margin: Implications for the break-up of eastern Gondwana. Earth and Planetary Science Letters 153, 85-102.

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., Holcombe, R.J., Fielding, C.R., 2003. Reply to: "The Yarrol terrane of the northern New England Fold Belt: Forearc or backarc?" Discussion by Murray, C.G., Blake, P.R., Hutton, L.J., Withnall, I.W., Hayward, M.A., Simpson, G.A., Fordham, B.G. Australian. Journal of Earth Sciences 50, 271-293.

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 Paper 362, 99-118.

Buchan, K.L., Ernst, R.E., 2004. Diabase dyke swarms and related units in Canada and adjacent regions. Geological Survey of Canada, "A" Series Map. 2004. Geological Survey of Canada, Ottawa, Canada, 39 p.

Buchan, K.L., Mortensen, J.K., Card, K.D., Percival, J.A., 1998. Paleomagnetism and U-Pb geochronology of diabase dyke swarms of Minto Block, Superior Province, Quebec, Canada. Canadian Journal of Earth Sciences 35, 1054-1069.

Buchan, K.L., Ernst, R.E., Hamilton, M.A., Mertanen, S., Pesonen, L.J., Elming, S.Å., 2001. Rodinia: the evidence from integrated paleomagnetism and U-Pb geochronology Precambrian Research 110, 9-32.

Camp, V.E., Ross, M.E., Hanson, W.E., 2003. Genesis of flood basalts and Basin and Range volcanic rocks from Steens Mountain to the Malheur River Gorge, Oregon. Geological Society of America Bulletin 115, 105–128.

Campbell, I.H., 1998. The mantle's chemical structure; insights from the melting products of mantle plumes. In: Jackson, I. (ed) The Earth's mantle; composition, structure, and evolution. Cambridge University Press, Cambridge, United Kingdom, pp. 259-310.

Campbell, I.H., 2002. Implications of Nb/ U, Th/ U and Sm/ Nd in plume magmas for the relationship between continental and oceanic crust formation and the development of the depleted mantle. Geochimica et Cosmochimica Acta 66, 1651-1661.

Campbell, I.H., 2005 Large igneous provinces and the mantle plume hypothesis. Elements 1, 265-269.

Campbell, I.H., Griffiths, R.W., 1990. Implications of mantle plume structure for the evolution of flood basalts. Earth and Planetary Science Letters 99, 79-93.

Carlson, R.W., 1991. Physical and chemical evidence on the cause and source characteristics of flood basalt volcanism. Australian Journal of Earth Sciences 38, 525-544.

Carlson, R.W., Hart, W.K., 1988. Flood basalt volcanism in the Pacific northwestern United States. In: Macdougall, J.D. (ed) Continental Flood Basalts. Kluwer Academic Publishers, Dordrecht, pp. 35-61.

Cloos, M., 1993. Lithospheric buoyancy and collisional orogenesis: subduction of oceanic plateaus, continental margins, island arcs, spreading ridges, and seamounts. Geological Society of America Bulletin 105, 715-737.

Cawthorn, R.G. Walraven, F., 1998. Emplacement and crystallization time for the Bushveld Complex. Journal of Petrology 39, 1669–1687.

Coello, J., Cantagrel, J.M., Hernán, F., Fuster, J.M., Ibarrola, E., Ancochea, E., Casquet, C., Jammond, C., Díaz de Terán, J.R., Cendrero, A., 1992. Evolution of the eastern volcanic ridge of the Canary Islands based on new K-Ar data. Journal of Volcanology and Geothermal Research 53, 251-274.

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

Coffin, M.F., Eldholm, O., 2001. Large Igneous Provinces: progenitors of some ophiolites?" In: Ernst, R.E., Buchan, K.L. (Eds) Mantle Plumes: Their Identification Through Time. Geological Society of America Special Paper 352, 59-70.

Coffin M.F., Eldholm, O., 2005. Large igneous provinces. In: Selley, R.C., Cocks, R., Plimer I.R. (Eds) Encyclopedia of Geology. Elsevier, Oxford, p. 315-323.

Coffin, M.F., Ingle, S., 2004. Impact origin for the greater Ontong Java Plateau? Earth and Planetary Science Letters 218, 123-134.

Condie, K.C., 2003. Incompatible element ratios in oceanic basalts and komatiites: tracking deep mantle sources and continental growth rates with time. Geochemistry, geophysics, geosystems 4(1), 1005, doi:10.1029/2002GC000333, 28 p.

Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events. Comptes Rendus Geoscience 335, 113-140.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P., Besse, J., 1999. On causal links between flood basalts and continental breakup. Earth and Planetary Science Letters 166, 177-195.

Cowley, S.., Mann, P., Gahagan, L., 1998. Tectonic history of the northern Louisiade Plateau based on deep penetration seismic reflection lines. Eos, Transactions, American Geophysical Union 79, 870.

Cox, K.G., 1992. Karoo igneous activity, and the early stages of the break-up of Gondwanaland. Geological Society of London Special Publication 68, 137-148.

Cox, K.G., MacDonald, R., Hornung, G., 1967. Geochemical and petrological provinces in the Karoo basalts of southern Africa. American Mineralogist 52, 1451-1474.

Dalziel, I.W.D., 1992. Antarctica a tale of two supercontinents? Annual Review of Earth and Planetary Sciences 20, 501-526.

de Wit, M.J., Ashwal, L.D., 1995. Greenstone belts: what are they? South African Journal of Geology 98, 505-520.

de Wit, M.J., Ashwal, L.D. (eds.) (1997) Greenstone Belts. Clarendon, UK, 809 p.

de Wit, M.J., Ashwal, L.D., 1998. On Archean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? Precambrian Research 91, 181-226.

Dobretsov, N.L., 2005. 250 Ma large igneous provinces of Asia: Siberian and Emeishan traps (plateau basalts) and associated granitoids. Russian Geology and Geophysics 46, 870-890.

Duncan, A.R., Newton, S.R., van den Berg, C., Reid, D.L., 1989. Geochemistry and petrology of dolerite sills in the Huab River Valley, Damaraland, north-western Namibia. Communications of the Geological Survey of Namibia 5, 5-17.

Eales, R.V., Cawthorn, R.G., 1996. The Bushveld Complex In: Cawthorn, R.G. (ed.) Layered Intrusions. Elsevier, Amsterdam, pp 181-229.

Eldholm, O.J., Grue, K., 1994. North Atlantic volcanic margins: dimensions and production rates. Journal of Geophysical Research 99, 2955-2968.

Elkins-Tanton, L.T., 2005. Continental magmatism caused by lithospheric delamination. In: Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L. (eds) Plates, Plumes and Paradigms. Geological Society of America Special Paper 388, 449-462.

Elkins-Tanton, L.T., Hager, B.H., 2000. Melt intrusion as a trigger for lithospheric foundering and the eruption of the Siberian flood basalt, Geophysical Research Letters 27, 3937-3940.

Erba, E., Bartolini, A., Larson, R.L., 2004. Valanginian Weissert oceanic anoxic event. Geology 32, 149-152.

Ernst, R.E., Baragar, W.R.A., 1992. Evidence from magnetic fabric for the flow pattern of magma in the Mackenzie giant radiating dyke swarm. Nature 356, 511-513.

Ernst, RE, 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., (eds) Large Igneous Provinces: Continental, Oceanic, and Planetary Volcanism. Geophysical Monograph Series, vol. 100. American Geophysical Union, pp. 297- 333.

Ernst, R.E., Buchan, K.L., 2001. Large mafic magmatic events through time and links to mantle-plume heads. In: Ernst, R.E., Buchan, K.L. (Eds) Mantle Plumes: Their Identification Through Time. Geological Society of America Special Paper 352, 483- 575.

Ernst, R.E., Buchan, K.L., 2002. Maximum size and distribution in time and space of mantle plumes: evidence from large igneous provinces Journal of Geodynamics 34, 309-342 [Erratum, 2002, 34, 711-714].

Ernst, R.E., Buchan, K.L., 2003. Recognizing mantle plumes in the geological record. Annual Review of Earth and Planetary Sciences 31, 469-523.

Ernst, R.E., Buchan, K.L., Campbell, I.H., 2005. Frontiers in Large Igneous Province research. Lithos 79, 271-297.

Ernst, R.E., Head, J.W., Parfitt, E., Grosfils, E., Wilson, L., 1995. Giant radiating dyke swarms on Earth and Venus. Earth Science Reviews 39, 1-58.

Eriksson, P.G., Condie, K.C., van der Westhuizen, W., van der Merwe, R., de Bruiyn, H., Nelson, D.R., Altermann, W., Catuneanu, O., Bumby, A.J., Lindsay, J., Cunningham, M.J., 2002. Late Archaean superplume events; a Kaapvaal-Pilbara perspective. Journal of Geodynamics 34, 207-247.

Ewart, A., Marsh, J.S., Milner, S.C., Duncan, A.R., Kamber, B.S., Armstrong, R.A., 2004a. Petrology and geochemistry of Early Cretaceous bimodal continental flood volcanism of the NW Etendeka, Namibia, Part 1: Introduction, mafic lavas and re-evaluation of mantle source components. Journal of Petrology 45, 59-105.

Ewart, A., Marsh J.S., Milner, S.C., Duncan, A.R., Kamber, B.S., Armstrong, R.A., 2004b. Petrology and geochemistry of Early Cretaceous biomodal continental flood volcanism of the NW Etendeka, Namibia; Part 2, Characteristics and petrogenesis of the high- Ti latite and high-Ti and low-Ti voluminous quartz latite eruptives. Journal of Petrology 45, 107-138.

Ewart, A., Milner, S.C., Armstrong, R.A., Duncan, A.R., 1998a. Etendeka Volcanism of the Goboboseb Mountains and Messum Igneous Complex, Namibia. Part I: Geochemical evidence of Early Cretaceous Tristan plume melts and the role of crustal contamination in the Paraná-Etendeka CFB. Journal of Petrology 39, 191-225.

Ewart, A., Milner, S.C., Armstrong, R.A., Duncan, A.R., 1998b. Etendeka Volcanism of the Goboboseb Mountains and Messum Igneous Complex, Namibia. Part II: Voluminous quartz latite volcanism of the Awahab magma system. Journal of Petrology 39, 227-253.

Ewart A., Schön, R.W., Chappell, B.W., 1992. The Cretaceous volcanic-plutonic province of the central Queensland (Australia) coast – a rift related "calc-alkaline" province. Transactions of the Royal Society of Edinburgh, Earth Sciences 83, 327-345.

Fan, J., Kerrich, R., 1997. Geochemical characteristics of aluminum depleted and undepleted komatiites and HREE-enriched low-Ti tholeiites, western Abitibi greenstone belt; a heterogeneous mantle plume-convergent margin environment. Geochimica et Cosmochimica Acta 61, 4723-4744.

Ferrari, L., Lopez-Martinez,.M., Rosas-Elguera, J., 2002. Ignimbrite flare-up and deformation in the southern Sierra Madre Occidental, western Mexico; implications for the late subduction history of the Farallon Plate. Tectonics 21, 1-23.

Ferrari L., Moreno M.V., Bryan, S.E., 2006. Magmatism and tectonics of the Sierra Madre Occidental and its relation with the evolution of the western margin of North America. Geological Society of America Special Paper (in press).

Fitton, J.G., Mahoney, J.J., Wallace, P.J., Saunders, A.D., 2004. Leg 192 synthesis: origin and evolution of the Ontong Java plateau. Proceedings of the Ocean Drilling Program, Scientific Results Volume 192, 1-18.

Foulger, G., 2006. The 'Plate' model for the genesis of melting anomalies. In: Foulger, G., Jurdy, D. (eds) The Origins of Melting Anomalies: Plumes, Plates, and Planetary Processes. Geological Society of America Special Paper (submitted).

Frey, F.A., Coffin, M.F., Wallace, P.J,, Weis, D., 2003. Leg 183 synthesis: Kerguelen Plateau–Broken Ridge - a large igneous province. In Frey, F.A., Coffin, M.F., Wallace, P.J., Quilty, P.G. (Eds), Proceedings of the ODP, Scientific Results 183, 1–48.

Gaina, C., Müller, R.D., Royer, J.-Y., Stock, J., Hardebeck, J. Symonds, P., 1998. The tectonic history of the Tasman Sea: a puzzle with 13 pieces: Journal of Geophysical Research 103, 12413-12433.

Gaina C., Müller, R.D., Royer, J.Y., Symonds, P., 1999. Evolution of the Louisiade triple junction. Journal of Geophysical Research 104, 12,927-12,940.

Geldmacher, J., Hoernle, K., van den Bogaard, P., Zanki, G., Garbe-Schonberg, D., 2001. Earlier history of the $70-Ma-old Canary hotspot based on the temporal and geochemical evolution of the Selvagen Archipelago and neighbouring seamounts in the eastern North Atlantic. Journal of Volcanology and Geothermal Research 111, 55-87.

Gibson, S.A., Thompson, R.N., Dickin, A.P., 2000. Ferropicrites; geochemical evidence for Fe-rich streaks in upwelling mantle plumes. Earth and Planetary Science Letters 174, 355-374.

Gower, C.F., Krogh, T.E., 2002. A U-Pb geochronological review of the Proterozoic history of the eastern Grenville province. Canadian Journal of Earth Sciences 39, 795-829.

Green, D.H., Falloon, T.J., Eggins, S.M., Yaxley, G.M., 2001. Primary magmas and mantle temperatures. European Journal of Mineralogy 13, 437-451.

Hatton, C.J., 1995. Mantle plume origin for the Bushveld and Ventersdorp magmatic provinces, Journal of African Earth Sciences 21, 571–577.

Head J.W., Coffin, M.F., 1997. Large igneous provinces: a planetary perspective. In: Mahoney, J.J., Coffin, M.F., (eds) Large Igneous Provinces: Continental, Oceanic and Planetary Flood Volcanism. Geophysical Monograph, vol. 100. American Geophysical Union, Washington, pp. 411– 438.

Heaman, L.M., LeCheminant, AN., 1993. Paragenesis and U-Pb systematics of baddeleyite (ZrO_2). Chemical Geology 110, 95-126.

Hergt, J.M., Peate, D.W., Hawkesworth, C.J., 1991. The petrogenesis of Mesozoic Gondwana low-Ti flood basalts. Earth and Planetary Science Letters 105, 134-148.

Herzberg, C., O'Hara, M.J., 2002. Plume-associated ultramafic magmas of Phanerozoic age. Journal of Petrology 43, 1857-1883.

Hofmann, A.W., 1997. Mantle geochemistry: the message from oceanic volcanism. Nature 385, 219-229.

Hofmann, C., Feraud, G., Courtillot, V., 2000. $^{40}Ar/^{39}Ar$ dating of mineral separates and whole rocks from the Western Ghats lava pile: further constraints on duration and age of the Deccan traps, Earth and Planetary Science Letters 180, 13-27.

Holm, P.M., Gill, R.C.O., Pedersen, A.K., Larsen, J.G., Hald, N., Nielsen, T.F.D., Thirlwall, M.F., 1993. The Tertiary picrites of West Greenland: contributions from 'Icelandic' and other sources. Earth and Planetary Science Letters 115, 227-244.

Hooper, P.R., 1997. The Columbia River Flood Basalt Province: Current status. In: Mahoney, J.J., Coffin, M.F., (eds) Large igneous provinces. American Geophysical Union, Geophysical Monograph 100, Washington DC, pp.1-27.

Hooper, P.R., Camp, V.E.,. Reidel, S.P., Ross, M.E., (in press) The Columbia River Basalts and their relationship to the Yellowstone hotspot and Basin and Range extension. In: Foulger, G.R.,, Jurdy, J.M., (eds) Plumes, Plates, and Planetary Processes. Geological Society of America Special Paper.

Isley, A.E., Abbott, D.H., 2002. Implications of the temporal distribution of high-Mg magmas for mantle plume volcanism through time. Journal of Geology 110, 141-158.

Jerram, D.A., 2002. Volcanology and facies architecture of flood basalts. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J., Baker, J., (eds) Magmatic Rifted Margins. Geological Society of America Special Paper 362, 119-132.

Jerram, D.A., Widdowson, M., 2005. The anatomy of Continental Flood Basalt Provinces: geological constraints on the process and products of flood volcanism. Lithos 79, 385-405.

Johnson, R.W., (ed.), 1989. Intraplate Volcanism in Eastern Australia and New Zealand. Cambridge University Press, Sydney, pp. 1-408.

Jokat, W., Ritzmann, O., Reichert, C., Hinz, K., 2004. Deep crustal structure of the continental margin off the Explora Escarpment and in the Lazarev Sea, East Antarctica. Marine Geophysical Researches 25, 283–304.

Jones, A.P., Price, G.D., Price, N.J., De Carli, P.S., Clegg, R., 2002. Impact induced melting and the development of large igneous provinces. Earth and Planetary Science Letters 202, 551-561.

Kelemen, P.B., Holbrook, W.S., 1995. Origin of thick, high-velocity igneous crust along the U.S. east coast margin. Journal of Geophysical Research 100, 10077-10094.

Kent, R.W., Hardarson, B.S., Saunders, A.D., Storey, M., 1996. Plateaux ancient and modern; geochemical and sedimentological perspectives on Archaean oceanic magmatism. Lithos 37, 129-142.

Kerr, A.C., 1998. Oceanic plateau formation: A cause of mass extinction and black shale deposition around the Cenomanian-Turonian boundary. Journal of the Geological Society of London 155, 619-626.

Kerr, A.C., 2005. Oceanic Plateaus: the kiss of death. Elements 1, 289-292.

Kerr, A.C., Marriner, G.F., Arndt, N.T., Tarney, J., Nivia, A., Saunders, A.D., Duncan, R.A., 1996. The petrogenesis of Gorgona komatiites, picrites and basalts: new field, petrographic and geochemical constraints. Lithos 37, 245-260.

King, S.D., Anderson, D.L., 1998. Edge-Driven Convection. Earth and Planetary Science Letters 160, 289-296.

Kinnaird, J.A., 2005. The Bushveld Large Igneous Province. www.largeigneousprovinces.org/LOM.html [May 2005].

Klemperer, S.L., 1989. Deep seismic reflection profiling and the growth of the continental crust. Tectonophysics 161, 233-244.

Kruger, F.J., 2004. Filling the Bushveld Complex magma chamber: lateral expansion, roof and floor interaction, magmatic unconformities, and the formation of giant chromitite, PGE and Ti-V-magnetite deposits. EGRI circular, University of the Witwatersrand, 34 p.

Larsen, R.B., Tegner, C., 2006. Pressure conditions for the solidification of the Skaergaard intrusion: Eruption of East Greenland flood basalts in less than 300,000 years. In: IAVCEI 2006 International Conference on Continental Volcanism, Abstracts and Programs, May14-18, 2006

Guangzhou, China, p. 137.

Larson, R.L., 1991. Latest pulse of Earth: Evidence for a mid-Cretaceous superplume. Geology 19, 547-550.

Le Bas, M.J., 2000. IUGS Reclassification of the High-Mg and Picritic Volcanic Rocks. Journal of Petrology 41, 1467-1470.

LeCheminant, AN., Heaman, L.M., 1989. Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening. Earth and Planetary Science Letters 96, 38-48.

Li, Z.X., Bogdanova, S.V., Collins, A.S., Davidson, A., De Waele, B., Ernst, R.E., Fitzsimons, I.C.W., Fuck, R.A., Gladkochub. D.P., Jacobs, J., Karlstrom, K.E., Lu, S., Natapov, L.M., Pease, V., Pisarevsky, S.A., Thrane, K., Vernikovsky, V., 2006. Assembly, configuration, and break-up history of Rodinia: a synthesis. Precambrian Geology, special issue (submitted).

MacHattie, T., Heaman, L., Creaser, R., Skulski, T., Sandeman, H., 2004. Remnants of an Archean Large Igneous Province: Evidence from the komatiite-bearing greenstone belts of the northern Rae domain, Nunavut, Canada. www.largeigneousprovinces.org/LOM.html [July 2004].

Mandler, H.A.F., Clowes, R.M., 1998. The HSI bright reflector: further evidence for extensive magmatism in the Precambrian of western Canada. Tectonophysics 288, 71-81.

Marsh, J.S., Ewart, A., Milner, S.C., Duncan, A.R., Miller, R.McG., 2001. The Etendeka igneous province; magma types and their stratigraphic distribution with implications for the evolution of the Parana-Etendeka flood basalt province. Bulletin of Volcanology 62, 464-486.

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 Volcanism. Geophysical Monograph Series, vol. 100. American Geophysical Union, pp. 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.

Menzies, M.A., Klemperer, S.L., Ebinger, C.J., Baker, J., 2002. Characteristics of volcanic rifted margins. Geological Society of America Special Paper 362, 1-14.

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.

Mohr, P., 1992. Nature of crust beneath magmatically active continental rifts. Tectonophysics 213, 269-284.

Mortimer, N., 2006. Zealandia. AESC2006 Conference abstracts, Melbourne, Australia.

Muller, R.D., Gaina, C., Sdrolias, M., 2006. In search of the best model: uncertainties in Mesozoic to present day plate kinematics and implications for global analysis. Geophysical Research Abstracts 8, 5310.

Naldrett, A.J., 1997. Key factors in the genesis of Noril'sk, Sudbury, Jinchuan, Voisey's Bay and other world-class Ni-Cu-PGE deposits: implications for exploration. Australian Journal of Earth Sciences 44, 283-315.

Pankhurst, R.J., Rapela, C.R., 1995. Production of Jurassic rhyolite by anatexis of the lower crust of Patagonia. Earth and Planetary Science Letters 134, 23-36.

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.

Pankhurst, R.J., Riley, T.R., Fanning, C.M., Kelley, S.P., 2000. Episodic silicic volcanism in Patagonia and the Antarctic Peninsula: chronology of magmatism associated with the break-up of Gondwana. Journal of Petrology 41, 605-625.

Parman, S.W., Grove, T.L., 2005. Komatiites in the plume debate In: Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L. (eds) Plates, plumes, and paradigms. Geological Society of America. Special Paper 388, 249-256.

Peate, D.W., 1997. The Paraná-Etendeka province. In: Mahoney J.J., Coffin, M.F., (Eds) Large Igneous Provinces: Continental, Oceanic, and Planetary Volcanism. Geophysical Monograph Series, vol. 100. American Geophysical Union, pp. 217-245.

Pirajno, F. 2000. Ore Deposits and Mantle Plumes. Kluwer, Dordrecht, 556 p.

Pirajno, F. 2004. The Fortescue Group, Western Australia; An Archaean (2.7 Ga) Large Igneous Province. www.largeigneousprovinces.org/LOM.html [December 2004].

Planke, S., Alvestad, E., and Eldholm, O., 1999. Seismic characteristics of basaltic extrusive and intrusive rocks: The Leading Edge 19, 342–348.

Prendergast, M.D., 2004. The Bulawayan Supergroup: a late Archaean passive margin-related large igneous province in the Zimbabwe craton. Journal of the Geological Society, London 161, 431–445.

Prokoph, A., Ernst, R.E., Buchan, K.L., 2004. Time-series analysis of large igneous provinces: 3500 Ma to Present. Journal of Geology 112, 1-22.

Raposo, M.I.B., Ernesto, M., 1995. Anisotropy of magnetite susceptibility in the Ponta Grossa dykes warm (Brazil) and its relationship with magma flow direction. Physics of the Earth and Planetary Interiors 87, 183-196.

Reichardt, F.J., 1994. The Molopo Farms Complex, Botswana: history, stratigraphy, petrography, petrochemistry, and Ni-Cu-PGE mineralisation. Exploration and Mining Geology 3, 264-284.

Richards, M.A., Duncan, R.A., Courtillot, V.E., 1989. Flood basalts and hot-spot tracks; plume heads and tails. Science 246,103-107.

Riisager, P., Hall, S., Antretter, M., Zhao, X., 2003. Paleomagnetic paleolatitude of Early Cretaceous Ontong Java Plateau basalts: implications for Pacific apparent and true polar wander. Earth and Planetary Science Letters 208, 235-252.

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, 1043-1065.

Riley, T.R., Leat, P.T., Storey, B.C., Parkinson, I.J., Milar, I.L., 2003. Ultramafic lamprophyres of the Ferrar large igneous province: evidence for a HIMU mantle component. Lithos 66, 63-76.

Rivers, T., Corrigan, D., 2000. Convergent margin on southeastern Laurentia during the Mesoproterozoic: tectonic implications. Canadian Journal of Earth Sciences 37, 359-383.

Roberts, D.G., Schnitker, D., et al., 1984. Initial Reports, Deep Sea Drilling Project 81, 923 pp.

Ross, G.M., Eaton, D.W., 1997. Winagami reflection sequence: seismic evidence for postcollisional magmatism in the Proterozoic of western Canada. Geology 25, 199-202.

Sager, W.W., 2005. What built Shatsky Rise, a mantle plume or ridge tectonics? In: Foulger, G.R., Natland, J.H., Presnall, D.C., Anderson, D.L., (eds) Plates, plumes, and paradigms. Geological Society of America Special Paper 388, 721-733.

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 Monograph 100, Washington DC, pp.45-93.

Schmincke, H.-U., 1982. Volcanic and chemical evolution of the Canary Islands. In: von Rad, U., Hinz, K., Sarnthein, M., Siebold, E. (eds) Geology of the Northwest African Continental Margin. Springer-Verlag, Berlin, pp. 273-306.

Self, S., Thordarson, T., Widdowson, M., 2005. Gas Fluxes from Flood Basalt Eruptions. Elements 1, 283-287.

Sheth, H., 2006. Large Igneous Provinces (LIPs): Definition, recommended terminology, and a hierarchical classification. Journal of Volcanology & Geothermal Research (in press).

Silver, P.G., Behn, M.D., Kelley, K., Schmitz, M., Savage, B., 2006. Understanding cratonic flood basalts. Earth Planetary Science Letters 245, 190-201.

Skilling, I.P., White, J.D.L., Bryan, S.E., Ross, P.-S., Self, S., 2006. Physical Volcanology of Large Igneous Provinces: A Review. Journal of Volcanology and Geothermal Research (in press).

Smith, A.D., 1992. Back-arc convection model for Columbia River basalt genesis. Tectonophysics 207, 269-285.

Stephenson, P.J., Burch-Johnston, A.T., Stanton, D., Whitehead, P.W., 1998. Three long lava flows in North Queensland. Journal of Geophysical Research 103, 27,359-27,370.

Sutherland, R., 1999. Basement geology and tectonic development of the greater New Zealand region: an interpretation from regional magnetic data: Tectonophysics 308, 341-362.

Taylor, B., 2006. The single largest oceanic plateau: Ontong Java–Manihiki–Hikurangi. Earth and Planetary Science Letters 241, 372–380.

Tejada, M.L.G., Mahoney, J.J., Duncan, R.A., Hawkins, M.P., 1996. Age and geochemistry of basement and alkalic rocks of Malaita and Santa Isabel, Solomon Islands, southern margin of Ontong Java Plateau. Journal of Petrology 37, 361–394.

Tejada, M.L.G., Mahoney, J.J., Neal, C.R., Duncan, R.A., Petterson, M.G., 2002. Basement geochemistry and geochronology of Central Malaita, Solomon Islands, with implications for the origin and evolution of the Ontong Java Plateau. Journal of Petrology 43, 449–484.

Thompson, R.N., Gibson, S.A., 2000. Transient high temperatures in mantle plume heads inferred from magnesian olivines in Phanerozoic picrites. Nature 407, 502-506.

Thorne, A.M., Trendall, A.F., 2001. Geology of the Fortescue Group, Pilbara Craton, Western Australia. Geological Survey of Western Australia Bulletin 144, 249p.

Tomlinson, K.Y., Condie, K.C., 2001. Archean mantle plumes: evidence from greenstone belt geochemistry. In: Ernst, R.E., Buchan, K.L. (Eds) Mantle Plumes: Their Identification Through Time. Geological Society of America Special Paper 352, 341-357.

Trumbull, R.B., Sobolev, S.V., Bauer, K., 2002. Petrophysical modeling of high seismic velocity crust at the Namibian volcanic margin. In: Menzies, M.A., Klemperer, S.L., Ebinger, C.J., Baker, J. (eds) Volcanic Rifted Margins. Geological Society of America Special Paper 362, 221–230.

Turner, S., Hawkesworth, C., 1995. The nature of the sub-continental mantle; constraints from the major-element composition of continental flood basalts. Chemical Geology 120, 295-314.

Twist, D., French, B.M., 1983. Voluminous acid volcanism in the Bushveld Complex: a review of the Rooiberg Felsite. Bulletin of Volcanology 46, 225-242.

Ukstins Peate, I., Baker, J.A., Kent, A.J.R., Al-Kadasi, M., Al-Subbary, A., Ayalew, D., Menzies, M., 2003. Correlation of Indian Ocean tephra to individual Oligocene silicic eruptions from Afro-Arabian flood volcanism. Earth and Planetary Science Letters 211, 311-327.

Ukstins Peate, I., Baker, J.A., Al-Kadasi, M., Al-Subbary, A., Knight, K.B., Riisager, P., Thirlwall, M.F., Peate, D.W., Renne, P.R., Menzies, M.A., 2005. Volcanic stratigraphy of large-volume silicic pyroclastic eruptions during Oligocene Afro-Arabian flood volcanism in Yemen. Bulletin of. Volcanology 68, 135-156.

White, R.S., McKenzie, D.P., 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. Journal of Geophysical Research 94, 7685-7729.

White, R.S., Spence, G.D., Fowler, S.R., McKenzie, D.P., Westbrook, G.K., Bowen, A.N., 1987. Magmatism at rifted continental margins. Nature 330, 439-444.

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. Elements 1, 293-297.

Wingate, M.T.D., Pisarevsky, S.A., Evans, D.A.D., 2002. Rodinia connections between Australia and Laurentia: no SWEAT, no AUSWUS? Terra Nova 14, 121-128.

Wingate, M.T.D., Pirajno, F., Morris, P.A., 2004. Warakurna large igneous province: a new Mesoproterozoic large igneous province in west-central Australia. Geology 32, 105–108.

Xu, Y., Chung, S.L., Jahn, B.-M., Wu, G., 2001. Petrologic and geochemical constraints on the petrogenesis of Permian-Triassic Emeishan flood basalts in southwestern China. Lithos 58, 145-168.

Xu, Y., He, B., Chung, S.L., Menzies, M.A., Frey, F.A., 2004. Geologic, geochemical, and geophysical consequences of plume involvement in the Emeishan flood-basalt province. Geology 32, 917-920.

Yale, L.B., Carpenter, S.J., 1998. Large igneous provinces and giant dike swarms: proxies for supercontinent cyclicity and mantle convection. Earth and Planetary Science Letters 163, 109-122.

Zhang, Z., Mao, J., Wang, F., Hao, Y., Mahoney, J.J., 2005. Mantle plume activity and melting conditions; evidence from olivines in picritic-komatiitic rocks from the Emeishan large igneous province, southwestern China. Episodes 28, 171-176.

Zhao, J.-X., McCulloch, M.T., Korsch, R.J., 1994. Characterisation of a plume-related ~ 800 Ma magmatic event and its implications for basin formation in central-southern Australia. Earth and Planetary Science Letters 121, 349-367.

Table 1. Bryan & Ernst.

LIP	LIP type	Age of LIP (Ma)	Age of magmatic pulses (Ma)	Age of previous magmatic (M) or tectonic (T) event (Ma)	Emplacement of LIP into or across a pre-existing sedimentary and rift basin?
Columbia River	CFB	17-6	16.6-15.3	32-20 (M); 74-50 (T)	Partly into continental sedimentary basins (Pasco, John Day)
Afro-Arabia	CFB/VRM	31-14	31-29, 22	630-545 (M); >540 (T)	Yes, into fluvio-shallow marine intracontinental sag basin (Marib-Shabwa)
Sierra Madre Occidental	Silicic	38-20	32-28, 24-20	~120-38 (M); ~90-60(T)	No; rift basins/grabens are syn to-post-volcanic
North Atlantic	CFB/VRM	62-53	62-58, 56-53	300-280 (M), 365-305 (T)	Partly into relatively localised continental and lacustrine environments and shallow marine basins with incipient rift-related grabens (Nuussuaq, Jamesonland, Kangerlussuaq)
Deccan	CFB/VRM	67-60	66-65	760-730 (M); 550-500 (T)	Partly into continental fluvio-lacustrine basins (Kutch, Cambay, Narmada, Tapi, Saurashtra)
Madagascar	CFB/VRM	90-84	87-86	630-530 (M); >550 (T)	Yes, into continental sedimentary basins (Majunga, Morondava)
Caribbean-Colombian	OP	95-69	92-88, 76-72	~160-180 (M)	No, emplaced on to oceanic crust
Hess Rise	OP	~111-88	?	~125-115 (M)	No, emplaced on to oceanic crust and probably near a triple junction
Ontong-Java	OP	$125-119, ~90	~122, 90	~165-145 (M)	No, emplaced on to oceanic crust
Nauru Basin	OBFB	~130-110	?	~157-135 (M)	No, emplaced on to oceanic crust
Southwestern Australia-India-(Kerguelen)	VRM/OP	130-100	~120-110	535 (M), 615 (T)	Partly into continental sedimentary basins (Perth, Bengal)

High Arctic	CFB/GDS	130-80	~130, ~90	370-333 (M), ~370-345 (T)	Partly into Sverdrup and Barents Basins and coeval sedimentary sequences in Svalbard and Franz Josef Land
Whitsunday	Silicic/VRM	~132-95	~118-113; 110-105	229-350 (M), 230 (T)	Partly, resedimented volcaniclastics deposited into adjacent intracontinental sag and rift basins (Great Artesian, Otway-Gippsland-Bass basin systems); volcanics within Maryborough Basin; syn-volcanic rift basins on Lord Howe Rise (Central and western Rift provinces)
Magellan Rise	OP	135-100	?	~150-133 (M)	No, emplaced on to oceanic crust
Paraná-Etendeka	CFB/VRM	138-125	134-129, ~125	550-490 (M), 550-510 (T)	Yes, on to aeolian sand field of Paraná-Huab-Karoo continental basins
Shatsky Rise	OP	#147-124	146-144	~150-122 (M)	No, emplaced on to oceanic crust affected by jumps of spreading ridge and triple junction
Northwestern Australia	VRM/OP	~165-155	?160	~310-295 (T) 755 (M)	Partly in Mesozoic rift-related basins of the Westralian Superbasin
Ferrar	CFB/VRM	185-175	183-180	530-484 (M), 515-505 (T)	Yes, deposition in a volcano-tectonic rift basin system (Transantarctic)
Karoo	CFB	190-178	183-182	530-510 (M), 560-515 (T)	Yes, in a continental sedimentary basin (Karoo)
Chon Aike	Silicic	188-153	188-178, 172-162, 157-153	275-220 (M); ~300-270 (T)	Partly, into continental sedimentary basins & grabens (San Jorge, Magallanes, Malvinas)
CAMP	CFB/VRM	205-191	202-200	330-260 (M); 327-270 (T)	Partly, in to continental sedimentary rift basins (Newark, Argana, Hartford, Culpeper, Deep River, Danville/Dan River, South Georgia, Carson, Essaouria, Fundy, Farmville, Gettysburg, Georges Bank, Jeanne d'Arc, Mohican, Nantucket, Norfolk, Orpheus, Pomperaug, Taylorsville)

Siberian Traps	CFB	254-248	251-249	640-600 (M), 370-340 (T)	Yes, in to continental sedimentary basins (West Siberian, Tunguska, Kuznetsk)
Emeishan	CFB	261-251	259-257	825-820 (M); 1300-1000 (T)	Yes, on to active shallow marine carbonate reef platform

Data Repository of Bryan SE & Ernst RE.
Revised Definition of Large Igneous Provinces (LIPs)

Additional data sources (and references therein) for Table 1.

Columbia River

Hooper, P.R., Camp, V.E., Reidel, S.P., Ross, M.E., 2007. The Origin of the Columbia River Flood Basalt Province: Plume versus Nonplume Models. Geological Society of America Special Paper 430, in press.

Reidel, S.P., Bush, J., Garwood, D., Kauffman, J., Martin, B.S., 2005. The tectonic evolution of the northern Columbia River flood-basalt province. Abstracts with Programs - Geological Society of America 37, 126.

Snyder, W.S., Dickinson, W.R., Silberman, M.L., 1976. Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States. Earth and Planetary Science Letters 32, 91-106.

Smith, G.A., 1988. Neogene synvoclanic and syntectonic sedimentation in central Washington. Geological Society of America Bulletin 100, 1479-1492.

Ward, P.L., 1995. Subduction cycles under western North America during the Mesozoic and Cenozoic eras. In: Miller, D.M., Busby C. (eds), Jurassic Magmatism and Tectonics of the North American Cordillera. Geological Society of America Special Paper, 299, 1-45.

Afro-Arabia

Davison, I., Al-Kadasi, M., Al-Khirbash, S., Al-Subbary, A.K., Baker, J., Blakey, S., Bosence, D., Dart, C., Heaton, R., McClay, K., Menzies, M., Nichols, G., Owen, L., Yelland, A., 1994. Geological evolution of the southeastern Red Sea Rift margin, Republic of Yemen. Geological Society of America Bulletin 106, 1474–1493.

Johnson, P.R., 2005. Post-amalgamation basins of the NE Arabian shield and implications for Neoproterozoic III tectonism in the northern East African orogen. Precambrian Research 123, 321–337.

Ukstins Peate, I., Larsen, M., Lesher, C.E., 2003. The transition from sedimentation to flood volcanism in the Kangerlussuaq Basin, East Greenland: basaltic pyroclastic volcanism during initial Palaeogene continental break-up. Journal of the Geological Society of London 160,
759-772.

Sierra Madre Occidental

Ward, P.L., 1995. Subduction cycles under western North America during the Mesozoic and Cenozoic eras. In: Miller, D.M., Busby C. (eds), Jurassic Magmatism and Tectonics of the North American Cordillera. Geological Society of America Special Paper, 299, 1-45.

North Atlantic

Heeremans, M., Faleide, J.I., and Larsen, B.T., 2004. Late Carboniferous – Permian of NW Europe: an introduction to a new regional map. In: Wilson, M., Neumann, E.-R., Davies, G.R., Timmerman, M.J., Heeremans, M., and Larsen, B.T. (eds.) Permo-Carboniferous Magmatism and Rifting in Europe. Geological Society, London, Special Publications 223, 75-88.

Woodcock, N., Strachan, R., 2000. Geological history of Britain and Ireland. Blackwell Science, Oxford, 423 p.

Deccan

Biswas, S.K., 1982. Rift basins in western margin of India and their hydrocarbon prospects with special reference to Kutch Basin. AAPG Bulletin 66, 1497-1513.

Rajan S , Tiwary A., Pandey D. 2005. The Deccan Volcanic Province: Thoughts about its genesis. http://www.mantleplumes.org/Deccan2.html

Rathore, S.S., Venkatesan, T.R., Srivastava, R.K., 1999. Rb-Sr isotope dating of Neoproterozoic (Malani Group) magmatism from south-west Rajasthan, India: evidence of younger Pan-African thermal event ^{40}Ar-^{39}Ar studies. Gondwana Research 2, 271-281.

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

Madagascar

Collins, A.S., Fitzsimons, I.C.W., Hulscher, B., Razakamanana, T. 2005. Structure of the eastern margin of the East African Orogen in central Madagascar. Precambrian Research 123, 111-133.

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. Geophysical Monograph 100, 95-122.

Caribbean-Colombian

Hoernle, K., Hauff, F., van den Bogaard, P., 2004. 70 m.y. history (139–69 Ma) for the Caribbean large igneous province: Geology 32, 697–700.

Hess Rise

Pringle, M.S., Dalrymple, G.B. 1993. Geochronological constraints on a possible hot spot origin for Hess Rise and the Wentworth seamount chain. In: Pringle, M.S., Sager, W.W., Sliter, W.V., Stein S. (eds) The Mesozoic Pacific: Geology, Tectonics, Volcanism. Geophysical Monograph 77, 263-277.

Vallier, T.L., Dean, W.E., Rea, D.K., Thiede, J. 1983. Geologic evolution of Hess Rise, central North Pacific Ocean. Geological Society of America Bulletin 94, 1289-1307. 47

Ontong-Java, Nauru Basin

Castillo, P.R., Carlson, R.W., Batiza, R., 1991. Origin of Nauru Basin igneous complex: Sr, Nd and Pb isotope and REE constraints. Earth and Planetary Science Letters 103, 200-213.

Mochizuki, K., Coffin, M.F., Eldholm, O., Taira A., 2005. Massive Early Cretaceous volcanic activity in the Nauru Basin related to emplacement of the Ontong Java Plateau, Geochemistry, Geophysics, Geosystems, 6, Q10003, doi:10.1029/2004GC000867, 19 p.

Southwestern Australia-India-(Kerguelen)

Myers, J.S., Shaw, R.D., Tyler, I.M., 1996. Tectonic evolution of Proterozoic Australia. Tectonics 15, 1431-1446.

High Arctic

Buchan K.L., Ernst R.E., 2006. The High Arctic Large Igneous Province (HALIP): Evidence for an Associated Giant Radiating Dyke Swarm. http://www.largeigneousprovinces.org/LOM.html [April 2006]

Buchan, K.L. Ernst, R. 2006. Giant dyke swarms and the reconstruction of the Canadian Arctic islands, Greenland, Svalbard and Franz Josef Land. In: Hanski, E., Mertanen, S., Rämö, T., and Vuollo, J. (eds.) Dyke Swarms: Time Markers of Crustal Evolution Taylor and Francis Group, London p. 27-48.

Maher, H.D., Jr., 2001. Manifestation of the Cretaceous High Arctic Large Igneous Province in Svalbard. Journal of Geology 109, 91-104.

Piepjohn, K., 2000. The Svalbardian-Ellesmerian deformation of the Old Red Sandstone and the pre-Devonian basement in NW Spitsbergen (Svalbard). Geological Society Special Publications 180, 585-601.

Trettin, H.P. (ed.) 1991 Geology of the Innuitian Orogen and Arctic Platform of Canada and Greenland. Geological Survey of Canada, Geology of Canada, no. 3, (also Geological Society of America, The Geology of North America v. E), 569 p.

Trettin, H.P., 1998. Pre-Carboniferous geology of the northern part of the Arctic Islands; Northern Heiberg fold belt, Clements Markham fold belt, and Pearya; northern Axel Heiberg and Ellesmere islands. Geological Survey of Canada Bulletin 425, 401 p.

Trettin, H.P., Parrish, R., Loveridge, W.D., 1987. U-Pb age determinations on Proterozoic to Devonian rocks from northern Ellesmere Island, Arctic Canada. Canadian Journal of Earth Sciences 24, 246-256.

Trettin, H.P., Parrish, R.R., Roddick, J.C., 1992. New U-Pb and ^{40}Ar-^{39}Ar age determinations from northern Ellesmere and Axel Heiberg islands, Northwest Territories and their tectonic significance. In: Radiogenic age and isotopic studies; Report 6. Geological Survey of Canada. Paper 92-02, 3-30.

Whitsunday

Fielding, C.R., Sliwa, R., Holcombe, R.J., Jones, A.T., 2001. A new palaeogeographic synthesis for the Bowen, Gunnedah and Sydney Basins of Eastern Australia. In: Hill, K.C., Bernecker, T. (eds) Eastern Australasian Basins Symposium, A Refocused Energy Perspective for the Future. Petroleum Exploration Society of Australia, Special Publication, p. 269-277.

Magellan Rise

Nakanishi, M., Winterer, E.L., 1998. Tectonic history of the Pacific-Farallon-Phoenix triple junction from Late Jurassic to Early Cretaceous; an abandoned Mesozoic spreading system in the Central Pacific Basin. Journal of Geophysical Research 103, 12,453-12,468.

Smith, A.D., 2003. A reappraisal of stress field and convective roll models for the origin and distribution of Cretaceous to Recent intraplate volcanism in the Pacific Basin. International Geology Review 45, 287-302.

Paraná-Etendeka

Goscombe, B., Gray, D., Hand, M., 2004. Variation in metamorphic style along the northern margin of the Damara Orogen, Namibia. Journal of Petrology 45, 1261-1295.

Shatsky Rise

Mahoney, J.J., Duncan R.A., Tejada, M.L.G., Sager, W.W., Bralower, T.J. 2005. Jurassic-Cretaceous boundary age and mid-ocean-ridge–type mantle source for Shatsky Rise. Geology, 33, 185–188.

Nakanishi, M., Sager, W.W., Klaus, A. (1999) Magnetic lineations within Shatsky Rise, Northwest Pacific Ocean; implications for hot spot-triple junction interaction and oceanic plateau formation. Journal of Geophysical Research 104, 7539-7556.

Sager, W.W., 2005. What built Shatsky Rise, a mantle plume or ridge tectonics? Geological Society of America Special Paper 388, 721-733.

Sager, W.W., Han-Hyun, C. 1993. Rapid formation of the Shatsky Rise oceanic plateau inferred from its magnetic anomaly. Nature 364, 610-613.

Sager, W.W., Kim, J., Klaus, A., Nakanishi, M., Khankishieva L.M.., 1999. Bathymetry of Shatsky Rise, Northwest Pacific Ocean; implications for ocean plateau development at a triple junction. Journal of Geophysical Research, B, Solid Earth and Planets 104, 7557-7576.

Northwestern Australia

Colwell, J.B., Symonds, P.A., Crawford, A.J., 1994. The nature of the Wallaby (Cuvier)

Plateau and other igneous provinces of the west Australian margin. AGSO Journal of Australian Geology and Geophysics 15, 137-156.

Exon N.F., Colwell, J.B. 1994. Geological history of the outer North West Shelf of Australia: a synthesis. AGSO Journal of Australian Geology and Geophysics 15, 177-190.

Hocking, R.M., Moors, H.T., Van De Graaff, W.J.E., 1987. Geology of the Carnarvon Basin Western Australia. Geological Survey of Western Australia Bulletin 133, 307 p.

von Rad, U., Exon N.F., 1982. Mesozoic-Cenozoic sedimentary and volcanic evolution of the starved passive continental margin off northwest Australia. American Association of Petroleum Geologists Geological Memoir 34, 253-281.

Wingate, M.T.D., Giddings, J.W., 2000. Age and palaeomagnetism of the Mundine Well dyke swarm, Western Australia: implications for an Australia–Laurentia connection at 755 Ma. Precambrian Research 100, 335–357.

Ferrar

Boger, S.D., Miller, J.McL., 2004. Terminal suturing of Gondwana and the onset of the Ross–Delamerian Orogeny: the cause and effect of an Early Cambrian reconfiguration of plate motions. Earth and Planetary Science Letters 219, 35-48.

Elliot, D.H., 2000. Stratigraphy of Jurassic pyroclastic rocks in the Transantarctic Mountains. Journal of African Earth Sciences 77, 77-89.

Lisker, F., Laeufer, A.L., Olesch, M., Rossetti, F., Schaefer, T. 2006. Transantarctic Basin; new insights from fission-track and structural data from the USARP Mountains and adjacent areas (northern Victoria Land, Antarctica). Basin Research 18, 497-520.

Karoo

Riley, T.R., Knight, K.B., 2001. Age of pre-break-up Gondwana magmatism: a review. Antarctic Science 13, 99-110.

Riley, T.R., Leat, P.T., Curtis, M.L., Millar, L.L., Fazel, A., 2005. Early-Middle Jurassic dolerite dykes from western Dronning Maud Land (Antarctica): identifying mantle sources in the Karoo large igneous province. Journal of Petrology 46, 1489-1524.

Chon Aike

Gust, D.A., Biddle, K.T., Phelps, D.W., Uliana, M.A., 1985. Associated Middle to Late Jurassic volcanism and extension in southern South America. Tectonophysics 116, 223-253.

von Gosen, W., 2002. Polyphase structural evolution in the northeastern segment of the North Patagonian Massif (southern Argentina). Journal of South American Earth Sciences 15, 591-623.

CAMP

Olsen, P.E., 1997. Stratigraphic record of the early Mesozoic breakup of Pangea in the Laurasia-Gondwana rift system. Annual Review of Earth and Planetary Sciences 25, 337-401.

Sinha, A.K., Zietz, I., 1982. Geophysical and geochemical evidence for a Hercynian magmatic arc, Maryland to Georgia. Geology 10, 593-596.

Warr, L.N., 2000. The Variscan Orogeny: The Welding of Pangaea. In: Woodcock, N., Strachan, R. (eds) Geological history of Britain and Ireland. Blackwell Science, Oxford, pp 271-296.

Siberian

Nikishin, A.M., Ziegler, P.A., Abbott, D., Brunet, M.-F., Cloetingh, S., 2002. Permo-Triassic intraplate magmatism and rifting in Eurasia: implications for mantle plumes and mantle dynamics. Tectonophysics 351, 3-39.

Reichow, M.K., Saunders, A.D., White, R.V., Pringle, M.S., Al-Mukhamedov, A.I., Medvedev, A.I., Kirda, N.P., 2002. $^{40}Ar/^{39}Ar$ dates from the West Siberian Basin; Siberian flood basalt province doubled. Science 296, 1846-1849.

Sharma, M., 1997. Siberian Traps. In: Mahoney J.J., Coffin, M.F., (Eds) Large Igneous Provinces: Continental, Oceanic, and Planetary Volcanism. Geophysical Monograph Series, vol. 100. American Geophysical Union, pp. 273-295.

Vernikovsky, V.A., Vernikovskaya, A.E., Kotov, A.B., Sal'nikova, E.B., Kovach, V.P., 2003. Neoproterozoic accretionary and collisional events on the western margin of the Siberian craton: new geological and geochronological evidence from the Yenisey Ridge. Tectonophysics 375, 147– 168.

Emeishan

He, B., Xu, Y.-G., Huang, X.-L., Luo, Z.-Y., Shi, Y.-R., Yang, Q.-J., Yu, S.-Y., 2007. Age and duration of the Emeishan flood volcanism, SW China: Geochemistry and SHRIMP zircon U–Pb dating of silicic ignimbrites, post-volcanic Xuanwei Formation and clay tuff at the Chaotian section, Earth and Planetary Science Letters

255, 306-323.

Li, Z.-X., Li, X.-H., Zhou, H., Kinny, P.D., 2002. Grenvillian continental collision in south China: New SHRIMP U-Pb zircon results and implications for the configuration of Rodinia. Geology 30, 163–166.

Li, Z.-X., Li, X.-H., Kinny, P.D., Wang, J., 1999. The breakup of Rodinia: did it start with a mantle plume beneath South China? Earth and Planetary Science Letters 173, 171–181.

Zhong, H., Zhu, W.-G., Song, X.-Y., He, D.-F., 2006. SHRIMP U-Pb zircon geochronology, geochemistry, and Nd-Sr study of contrasting granites in the Emeishan large igneous
province, SW China. In: IAVCEI 2006: International Conference on Continental Volcanism, Abstracts and Programs, May14-18, 2006 Guangzhou, China, p. 58.

Figure 1. Bryan & Ernst, ESR.

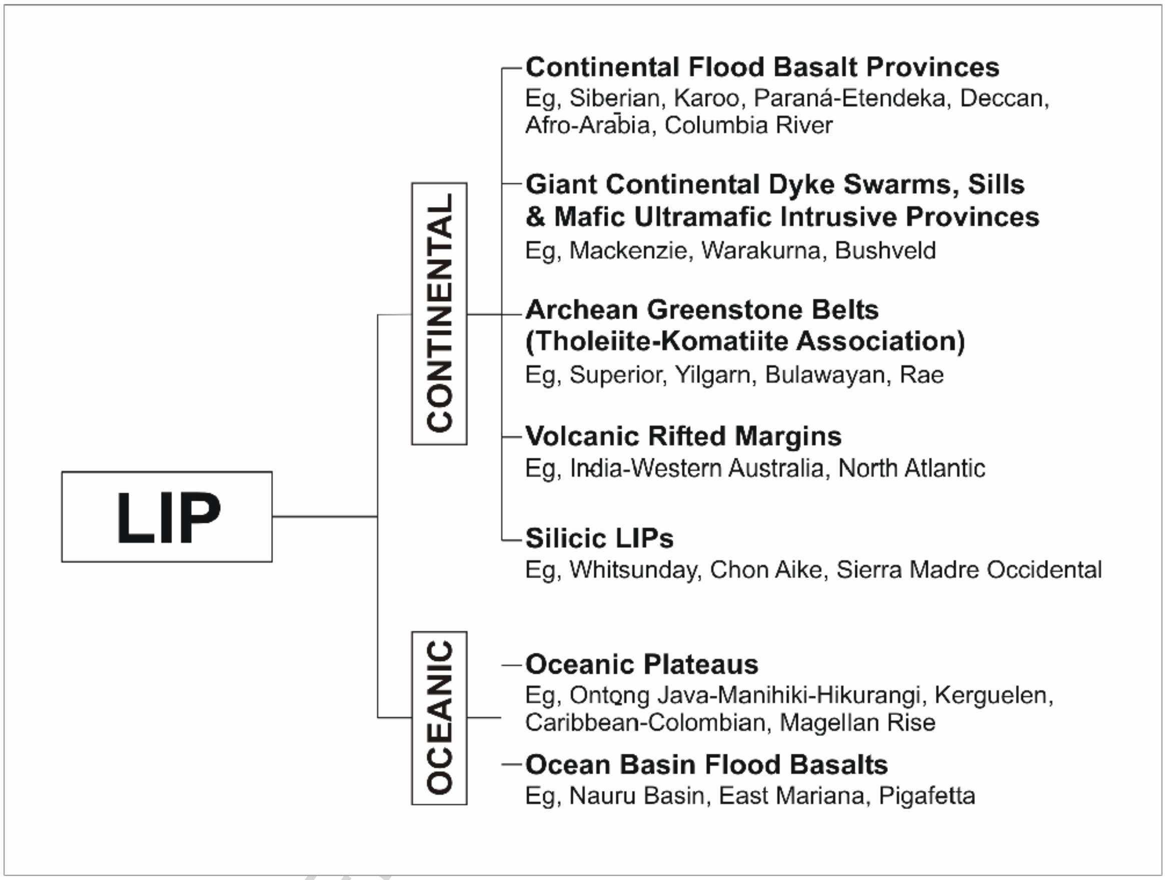
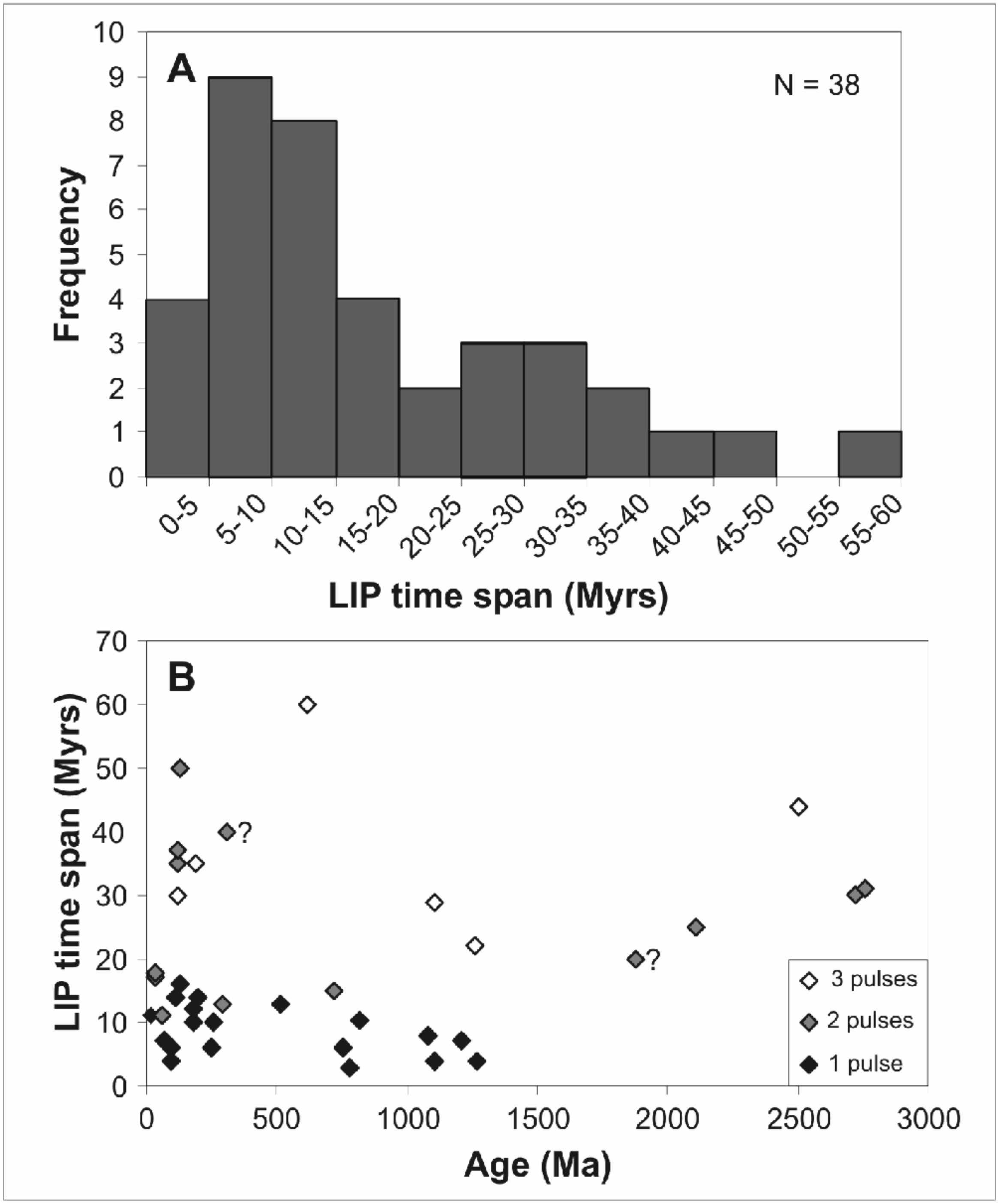


Figure 2. Bryan & Ernst



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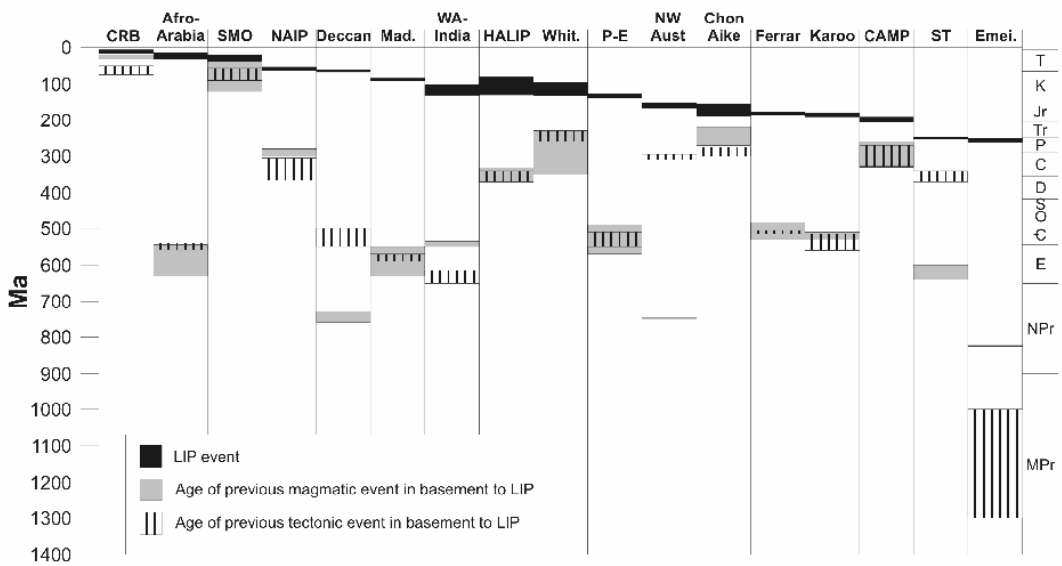

Figure 4A. Bryan & Ernst.

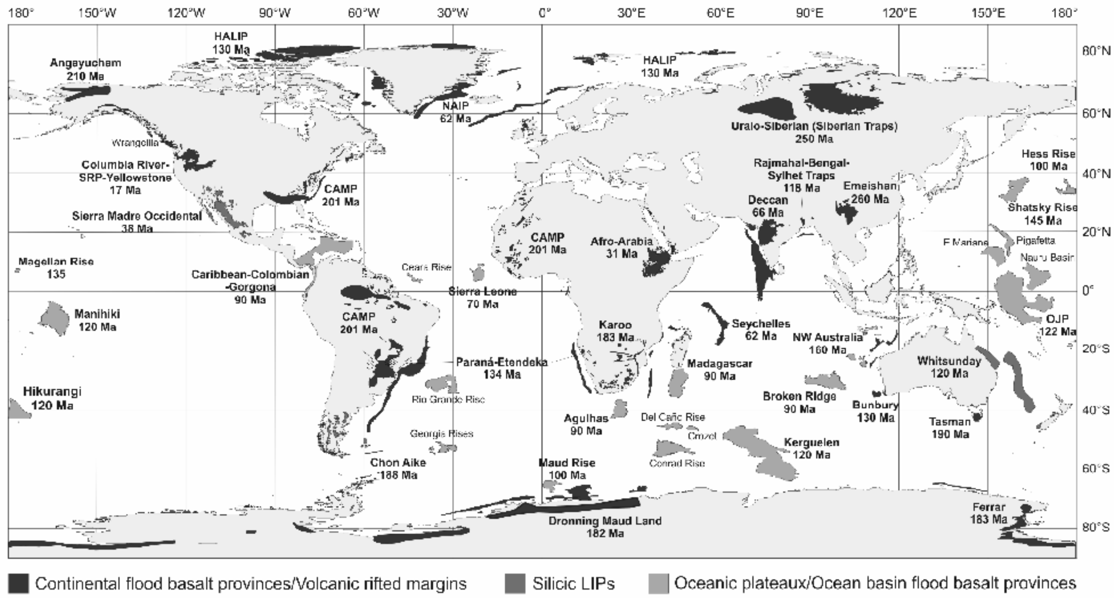

Figure 4B. Bryan & Ernst.

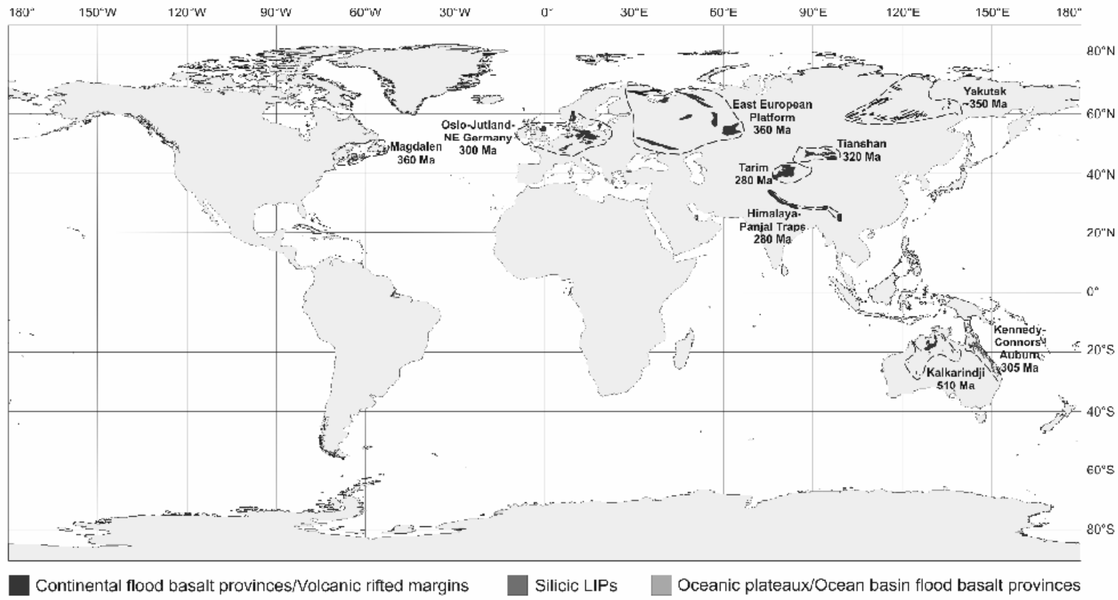

Figure 5. Bryan & Ernst.

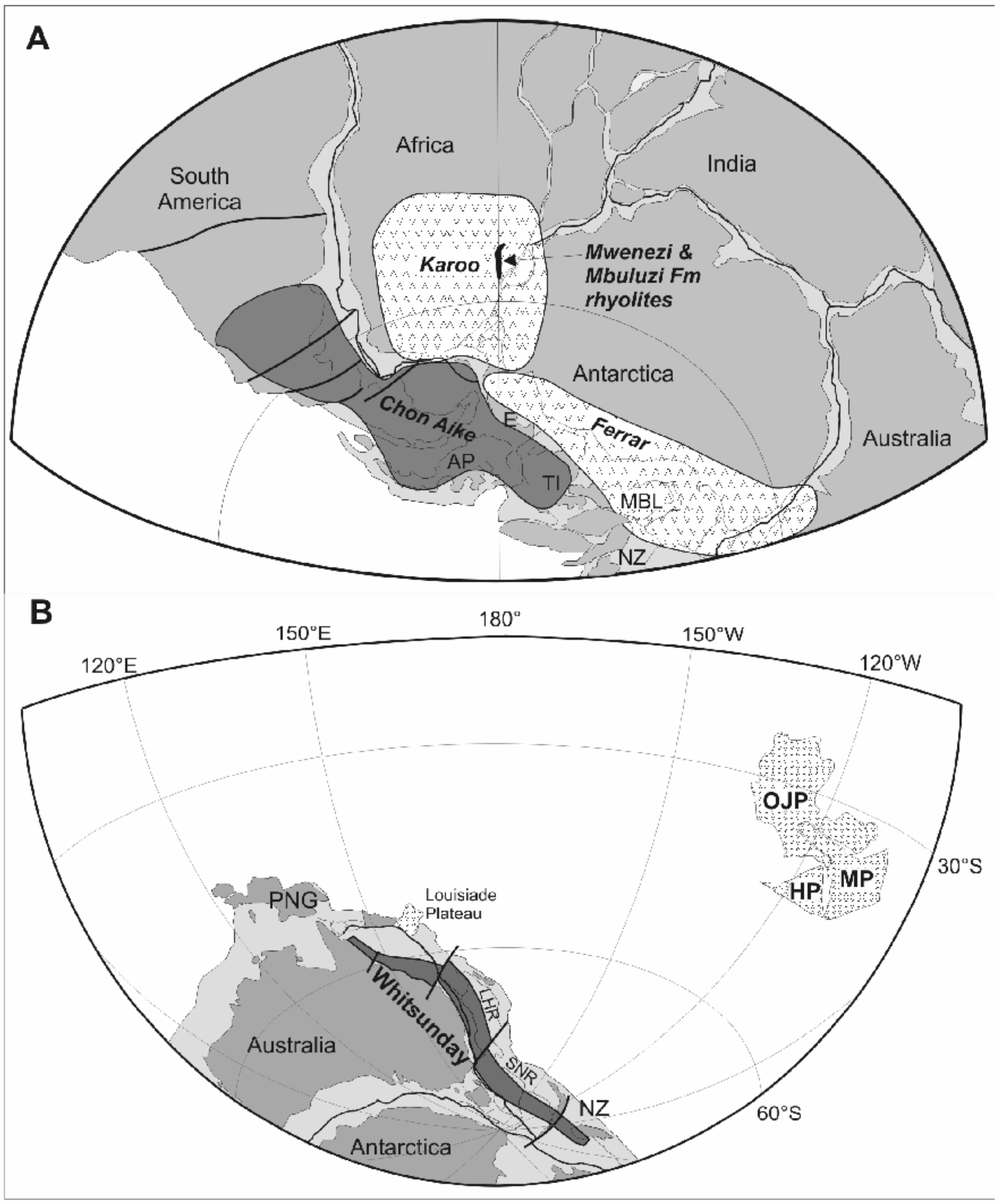

Figure 6. Bryan & Ernst