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INVITED REVIEW

Large igneous provinces and silicic large igneous provinces: Progress in our understanding over the last 25 years

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ABSTRACT

Large igneous provinces are exceptional intraplate igneous events throughout Earth's history. Their significance and potential global impact are related to the total volume of magma intruded and released during these geologically brief events (peak eruptions are often within 1–5 m.y. in duration) where millions to tens of millions of cubic kilometers of magma are produced. In some cases, at least 1% of Earth's surface has been directly covered in volcanic rock, being equivalent to the size of small continents with comparable crustal thicknesses. Large igneous provinces thus represent important, albeit episodic, periods of new crust addition. However, most magmatism is basaltic, so that contributions to crustal growth will not always be picked up in zircon geochronology studies, which better trace major episodes of extension-related silicic magmatism and the silicic large igneous provinces. Much headway has been made in our understanding of these anomalous igneous events over the past 25 yr, driving many new ideas and models. (1) The global spatial and temporal distribution of large igneous provinces has a long-term average of one event approximately every 20 m.y., but there is a clear clustering of events at times of supercontinent breakup, and they are thus an integral part of the Wilson cycle and are becoming an increasingly important tool in reconnecting dispersed continental fragments. (2) Their compositional diversity in part reflects their crustal setting, such as ocean basins and continental interiors and margins, where, in the latter setting, large igneous province magmatism can be dominated by silicic products. (3) Mineral and energy resources, with major platinum group elements (PGEs) and precious metal resources, are hosted in these provinces, as well as magmatism impacting on the hydrocarbon potential of volcanic basins and rifted margins through enhancing source-rock maturation, providing fluid migration pathways, and initiating trap formation. (4) Biospheric, hydrospheric, and atmospheric impacts of large igneous provinces are now widely regarded as key trigger mechanisms for mass extinctions, although the exact kill mechanism(s) are still being resolved. (5) Their role in mantle geodynamics and thermal evolution of Earth as large igneous provinces potentially record the transport of material from the lower mantle or core-mantle boundary to the Earth's surface and are a fundamental component in whole mantle convection models. (6) Recognition of large igneous provinces on the inner planets, with their planetary antiquity and lack of plate tectonics and erosional processes, means that the very earliest record of large igneous province events during planetary evolution may be better preserved there than on Earth.

INTRODUCTION

Silicic large igneous provinces, along with their umbrella grouping of large igneous provinces, represent one the outstanding areas of major advance in the earth sciences over the past 25 yr. Large igneous provinces are currently defined as magmatic provinces with areal extents >0.1 Mkm^2, igneous volumes >0.1 Mkm^3, and maximum life spans of 50 m.y. that have intraplate tectonic settings and/or geochemical affinities, and are characterized by igneous pulse(s) of short duration (1–5 m.y.), during which a large proportion (>75%) of the total igneous volume was emplaced (Bryan and Ernst, 2008). Continental flood basalt provinces, such as the Deccan Traps, Siberian Traps, and Columbia River flood basalt province, are some of the best recognized examples of continental large igneous provinces (Fig. 1). While continental flood basalt provinces had been widely recognized prior to 1988, it was not until the formative work of Coffin and Eldholm in the early 1990s and the recognition of major igneous provinces submerged along continental margins and in ocean basins that a global record of episodic but relatively frequent catastrophic igneous events was identified and collated (Coffin and Eldholm, 1991, 1992, 1993a, 1993b, 1994, 2005). Much of this initial recognition of large igneous provinces focused on the relatively well-preserved Mesozoic and Cenozoic record (Fig. 1), which has been critical to the development of many key concepts for large igneous provinces (Ernst, 2007a). Plate-tectonic theory has focused our attention on plate-boundary processes to explain magmatism, but the realization that large igneous province events recorded major mantle melting processes unrelated to "normal" seafloor spreading and subduction has been an important addition to plate-tectonic theory. Consequently, large igneous provinces have been critical to the development of the mantle plume hypothesis (e.g., Morgan, 1971; Richards et al., 1989; Griffiths and Campbell, 1990; Ernst and Buchan, 1997; Campbell, 2007) to explain intraplate magmatism, including hotspots, far removed from plate boundaries. Many large igneous provinces have been attributed to deep mantle plumes (e.g., Richards et al., 1989; Griffiths and Campbell, 1990, 1991;

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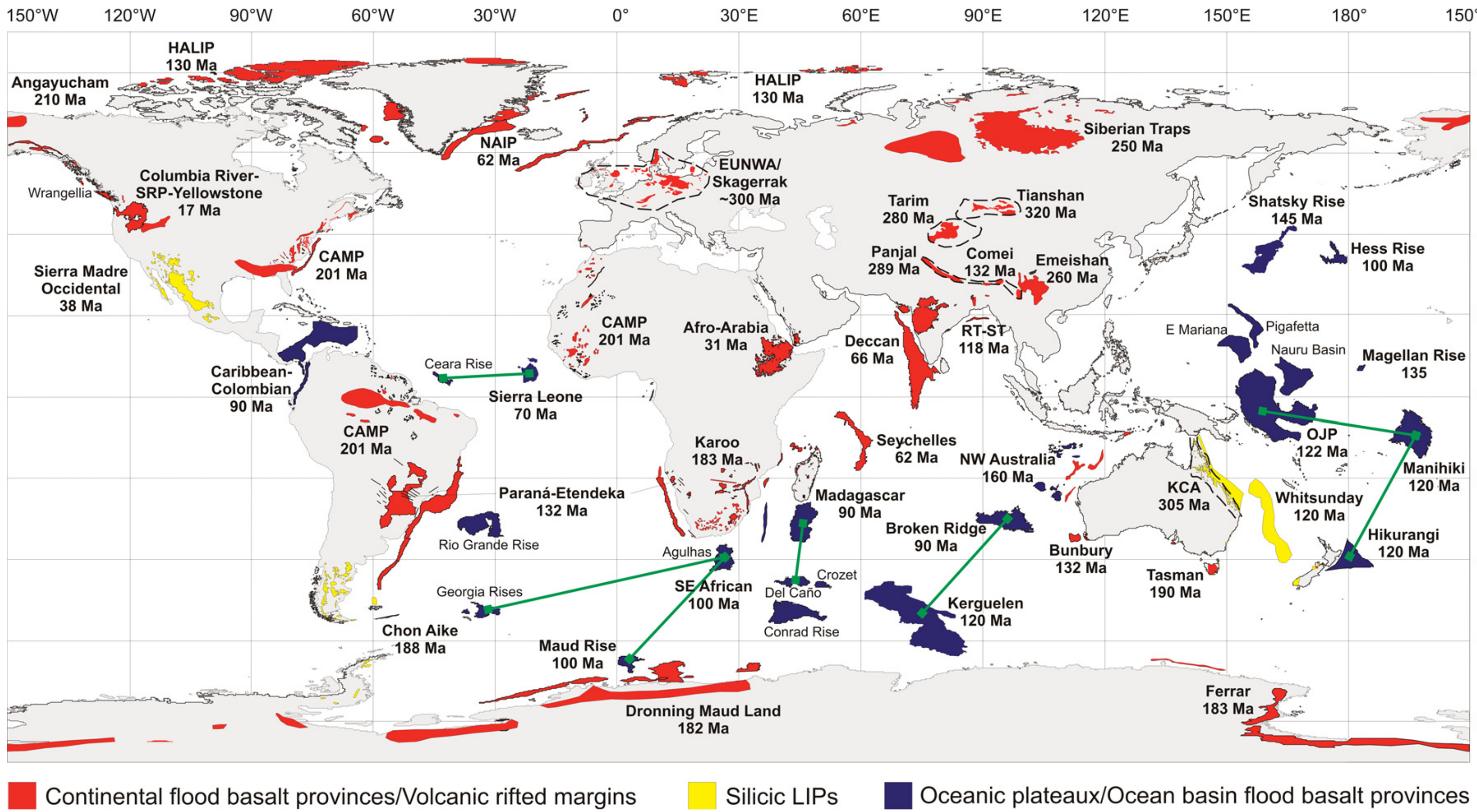

Figure 1. Global distribution of large igneous provinces (LIPs) following assembly of Pangea ca. 320 Ma. Annotated ages denote the onset of the main phase or first pulse of magmatism to the large igneous province event; note that some large igneous provinces may have precursor magmatism at lower intensity up to 10 m.y. prior, and age constraints on maximum ages for oceanic large igneous provinces remain poorly constrained. Green tie lines connect oceanic large igneous provinces subsequently rifted apart by seafloor spreading. The inferred extent of some of the oldest large igneous province events is shown by a dashed line, as many remain poorly mapped and studied. Some large igneous provinces are shown in small typeface to aid in figure clarity. Abbreviations: CAMP—Central Atlantic magmatic province; EUNWA—European, northwest Africa; HALIP—High Arctic large igneous province; NAIP—North Atlantic igneous province; OJP—Ontong Java Plateau; RT-ST—Rajmahal Traps–Sylhet Traps; SRP—Snake River Plain; KCA—Kennedy-Connors-Auburn. Figure is updated and modified from Bryan and Ernst (2008).

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Campbell, 1998, 2001, 2005, 2007; He et al., 2003). However, observed geological inconsistencies with predictions of the mantle plume theory (e.g., Frey et al., 2000; Korenaga, 2005; Ukstins Peate and Bryan, 2008) have led many authors to propose alternative models, including decompression melting in a rift setting (White and McKenzie, 1989, 1995), slab roll-back and backarc extension (Carlson and Hart, 1987; Rivers and Corrigan 2000; Long et al., 2012), edge-driven convection (Anderson, 1996, 1998; King and Anderson, 1998; Hames et al., 2003), meteorite impact (Jones et al., 2002; Ingle and Coffin, 2004; Hagstrum, 2005), and mantle lithospheric instabilities where downwellings may occur in response to mantle plume impact and fracturing/heating of the base of the lithosphere (e.g., Sengör, 2001), or which may be generated by gravitational instabilities (e.g., Hales et al., 2005; Elkins Tanton, 2005, 2007).

AREAS OF ADVANCEMENT IN OUR UNDERSTANDING OF LARGE IGNEOUS PROVINCE EVENTS SINCE 1988

Since 1988, substantial headway has been made in many aspects of large igneous provinces. Underpinning the significance of this topic and as a global research focus over the past 25 yr, flood basalt volcanism, and its linkage to mass extinction events, represented one of the top 100 research fronts in geosciences in 2012 (Web of Knowledge, accessed 30/1/2013). The aim of this review paper is to first provide a "then and now" snapshot of our understanding of the importance of large igneous provinces. In the second part of the paper, we then discuss in more detail, one of the new classes of large igneous provinces recognized in the past 25 yr—silicic large igneous provinces—with the Sierra Madre Occidental of western Mexico used as an example to illustrate the inter-relationships between magmatism and continental rifting. Two topics that are not discussed in detail here are the substantial advancement in knowledge of the physical volcanology of large igneous provinces, particularly continental large igneous provinces, and magnitude of large igneous province basaltic and silicic supereruptions. These topics have recently been extensively reviewed by White et al. (2009) and Bryan et al. (2010), respectively. To summarize, it is now generally recognized that flood basalt eruptions are not the catastrophic and fast-flowing floods of lava originally envisaged (Shaw and Swanson, 1970), but instead, they are more analogous to the largest historic basaltic eruptions in terms of effusion rate, but where eruption life time is sustained for years or decades along very long fissures (Swanson et al., 1975) to build up >1000 km^3 lava flow fields (e.g., Self et al., 1996, 1997, 1998). Large igneous provinces are home to the largest known basaltic and silicic eruptions (or supereruptions) on Earth, with eruption magnitudes up to ~10,000 km^3 or magnitude 9.4 now recognized; many examples of both basaltic and rhyolitic supereruptions are now known that far exceed the erupted volume of the ~5000 km^3 Fish Canyon Tuff, which is widely reported as the largest known eruption (Bryan et al., 2010).

Large Igneous Province Events in the Geologic Record

The large igneous province record has now been extended back through the Paleozoic and into the Precambrian, with the oldest recognized large igneous province potentially as old as 3.79 Ga (Isley and Abbott, 1999, 2002; Ernst and Buchan, 2001; Ernst, 2013). For ancient examples, this task has been made more difficult due to the effects of erosion, burial, and tectonic fragmentation, where only the plumbing systems may now be preserved or remnants now exist on different continents (e.g., Ernst and Buchan, 1997; Bryan and Ernst, 2008). As observed for the Mesozoic–Cenozoic large igneous province record, many large igneous provinces have been deconstructed by subsequent tectonic fragmentation, reducing their size and preserved volumes such that it becomes unclear if the dispersed igneous rocks were originally part of a large-volume igneous event, and where its conjugate parts now reside. Establishing the full extent of Paleozoic and older large igneous provinces requires well-constrained plate reconstructions, and a precise knowledge of pre-Pangean supercontinental configurations is currently lacking (Pisarevsky et al., 2003; Bryan and Ernst, 2008; Ernst et al., 2008; Li et al., 2008; Evans, 2009; Evans and Mitchell, 2011; Meert, 2012; Zhang et al., 2012). Paleomagnetic, geochemical, and especially geochronological studies have been pivotal to show that widely distributed dikes, sills, layered intrusions, batholiths, and any erosional remnants of volcanic rocks were emplaced synchronously, have geochemical similarity, and, therefore, likely to belong to the same event. This is the large igneous province barcode approach of Bleeker and Ernst (2006), Ernst et al. (2008), Ernst and Bleeker (2010), and Ernst et al. (2013). One successful example of the way in which an ancient, deeply eroded large igneous province has been reconstructed is the ca. 1270 Ma Mackenzie large igneous province of North America (LeCheminant and Heaman, 1989; Ernst and Baragar, 1992; French et al., 2002). High-precision radiometric (e.g., U-Pb) age constraints of extensive, widely scattered igneous rocks and dikes at a range of distances along the >2400 km strike of the dike swarm (>2.7 million km^2 area) have helped to establish that emplacement was essentially contemporaneous across the enormous geographical extent.

Large Igneous Province Clusters

Large igneous province events are not distributed evenly through geologic time, and from the Phanerozoic record, their frequency is clearly linked to the supercontinent cycle, being principally related to the period of Pangea breakup (Fig. 1; e.g., Storey, 1995; Ernst et al., 2005; Bryan and Ernst, 2008). Based on the well-defined large igneous province record for the past 150 m.y., a rate of ~1 large igneous province per 10 m.y. has been estimated (Coffin and Eldholm, 2001), whereas a longer-term rate of 1 large igneous province per 20 m.y. has been estimated from the Proterozoic–Phanerozoic continental large igneous province record (Ernst and Buchan, 2002; Ernst et al., 2005). As the record has been expanded and improved over the past 25 yr, principally driven by many, and higher-precision geochronology studies, researchers have realized the temporal coincidence of several large igneous province events (large igneous province clusters of Ernst et al., 2005; see also Ernst and Buchan, 2002; Prokoph et al., 2004). Although with temporally overlapping igneous activity, these events have independently occurred on different tectonic plates (large igneous province nodes of Bryan and Ernst, 2008; Ernst et al., 2008). Four clear examples of a temporal clustering of events include clusters at ca. 130 Ma, 120 Ma and 90 Ma, with the most recent at 30 Ma (Fig. 2). Large igneous provinces with dated igneous activity at ca. 130 Ma include: (1) the Paraná-Etendeka (Fig. 3), (2) Comei-Bunbury (Di-Cheng et al., 2009), (3) High Arctic (Maher, 2001), (4) the onset of magmatism in the Whitsunday; and (5) terminal magmatism in the Shatsky Rise (Papanin Ridge). Within 10 m.y., another major large igneous province cluster had developed, by ca. 120 Ma, with (1) the emplacement of the megaoceanic plateau of Ontong Java, Manihiki, and Hikurangi, (2) Pigafetta–East Marianas ocean basin flood basalts (Tarduno et al., 1991; Pringle, 1992) and probably the onset of Nauru Basin flood basaltic volcanism (e.g., Saunders, 1989; Mochizuki et al., 2005); (3) Kerguelen–Rajmahal Traps ± Wallaby Plateau (Kent et al., 2002); (4) the onset of the peak of volcanism in the Whitsunday silicic large igneous province (Bryan et al., 1997, 2012), (5) formation of the Mozambique Ridge (Gohl et al., 2011); and (6) continued tholeiitic volcanism in the High

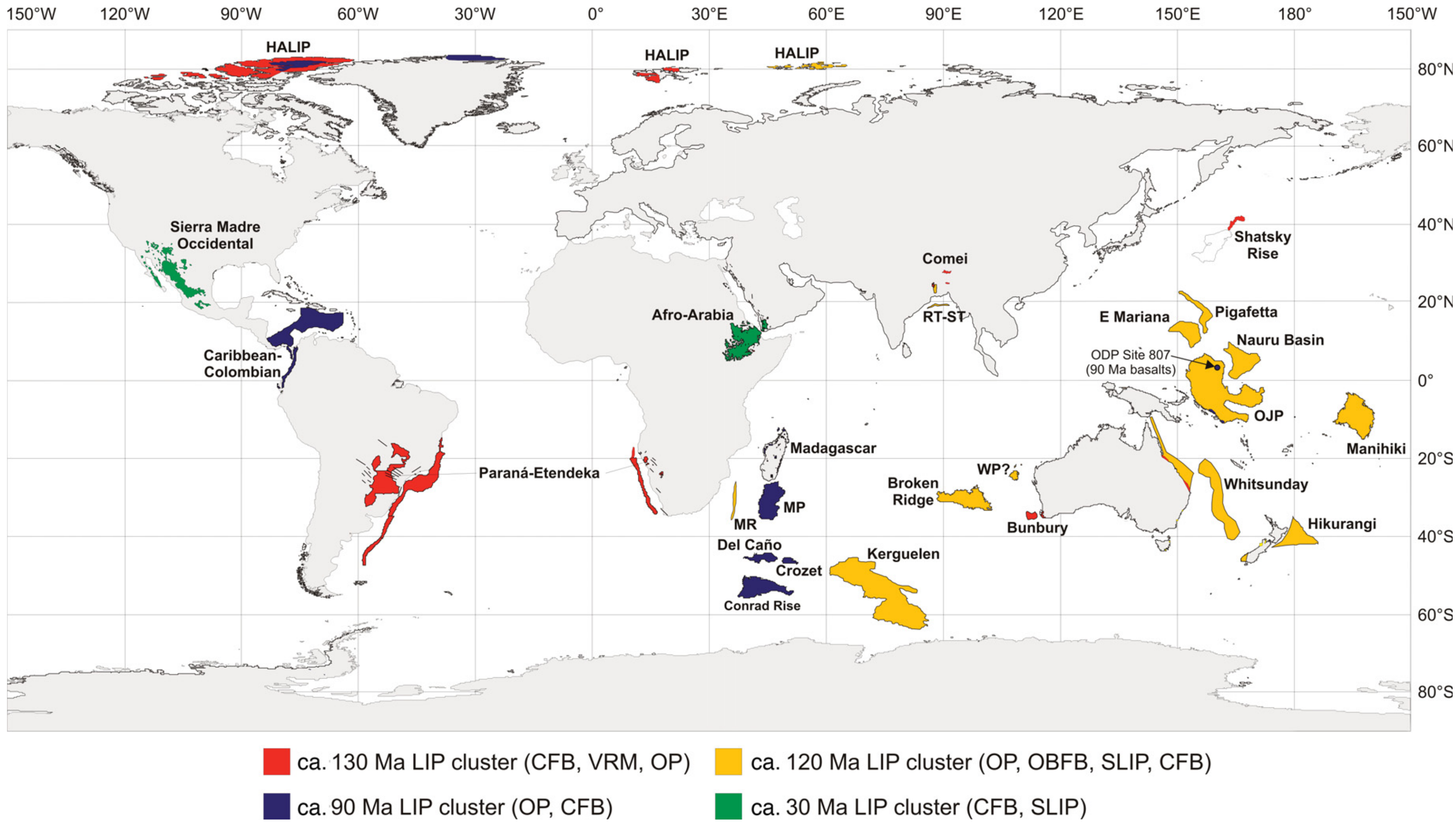

Figure 2. Examples of large igneous province (LIP) clusters formed at ca. 130 Ma, ca. 120 Ma, ca. 90 Ma, and the most recent at 30 Ma. Large igneous province types: CFB—continental flood basalt; OBFB—ocean basin flood basalt; OP—oceanic plateau; SLIP—silicic large igneous province; VRM—volcanic rifted margin. Abbreviations: HALIP—High Arctic large igneous province; MP— Madagascar Plateau; MR—Mozambique Ridge; OJP—Ontong Java Plateau; RT—Rajmahal Traps; ST—Sylhet Traps; WP—Wallaby Plateau; ODP—Ocean Drilling Program.

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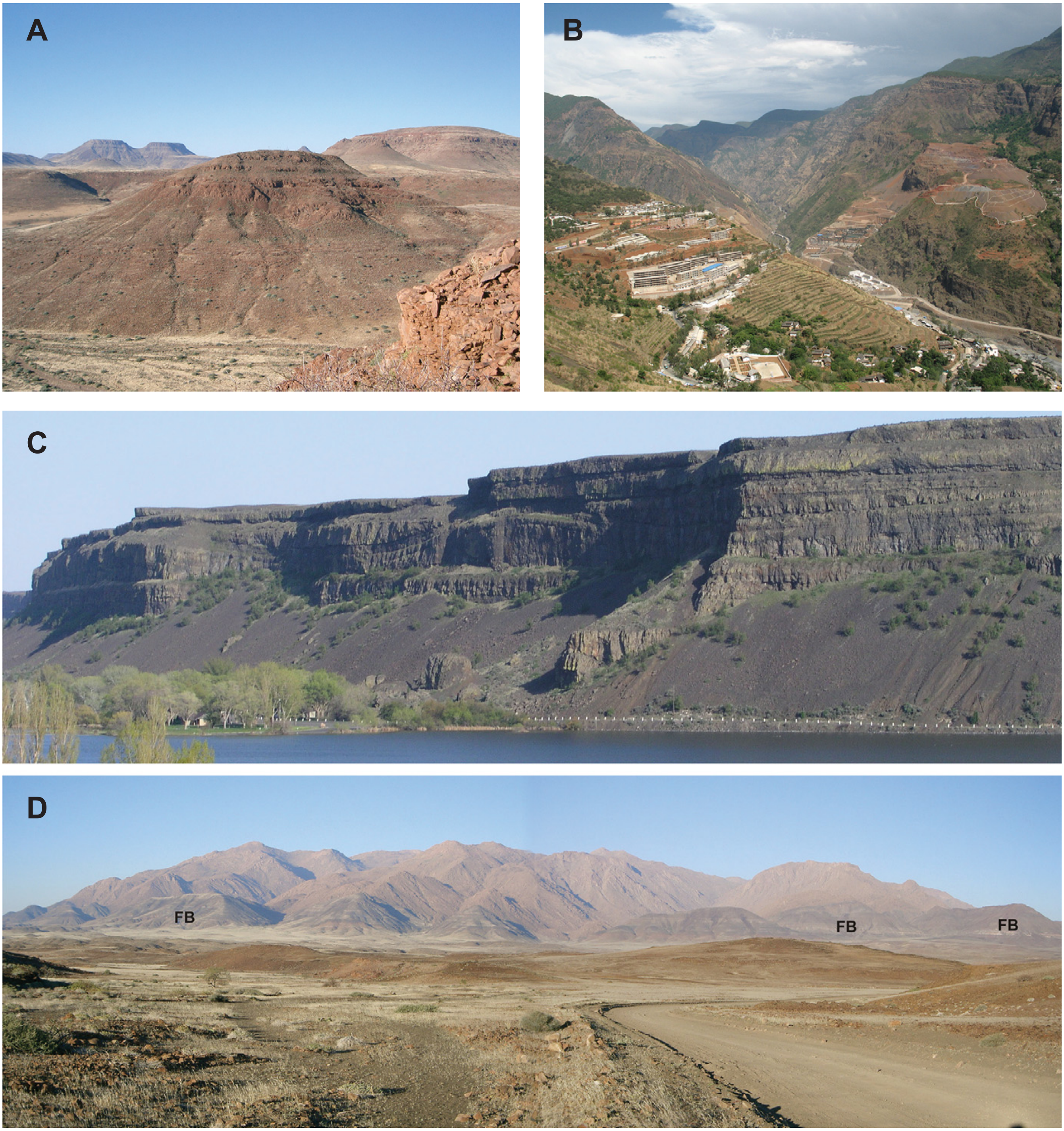

Figure 3. Outcrop characteristics of the continental flood basalt provinces, the most intensely studied large igneous provinces. (A) View across mesas in the Awahab region in the southern Etendeka (Paraná-Etendeka) large igneous province, exposing flat-lying flood basalt lavas with the ~6866 km³ Springbok quartz latite rheomorphic ignimbrite capping mesas in the distance. (B) A deeply incised section through the central part of the Permian Emeishan flood basalt province near Lijang, Yunan Province (China), where an ~1-km-thick, gently tilted flood basaltic lava succession is exposed and rises to elevations >3000 m above sea level. The Emeishan large igneous province has come to prominence over the last 10 yr due to interpretations that it provides the best-documented example of mantle plume–induced domal uplift (He et al., 2003; Campbell, 2007), but this has recently been discounted (Ukstins Peate and Bryan, 2008). (C) A cliffed section of mainly Wanapum Basalt Formation lavas from the Columbia River large igneous province exposed at Blue Lake, Washington. The cliff height is 120 m from lake to top. Photo courtesy of Steve Self. (D) Panoramic view of the imposing ca. 132–130 Ma Brandberg anorogenic granitic massif of the Paraná-Etendeka large igneous province, Namibia, which is ~23 km diameter, rises ~2000 m above the surrounding plains, and is flanked by flood basalt lavas (FB) that gently dip in toward the intrusive complex.

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Arctic large igneous province (Maher, 2001; Buchan and Ernst, 2006). The ca. 90 Ma large igneous province cluster includes the Madagascar flood basalt province (and probably the offshore Madagascar Ridge, Crozet Plateau, and Conrad Rise), the first peak of volcanism in the Caribbean large igneous province (Colombia-Caribbean oceanic plateau; see review of age data in Serrano et al., 2011), and terminal phases of the High Arctic large igneous province and Ontong Java oceanic plateau (see also Ernst and Buchan, 2002). Oceanic plateaus emplaced at 90 Ma were volumetrically substantial, with an estimated combined igneous volume of >18 million km^3 (Kerr, 2013). The youngest large igneous province cluster at 30 Ma is represented by the overlap of peak activities in the Afro-Arabian continental flood basalt and Sierra Madre Occidental silicic large igneous provinces (e.g., Hofmann et al., 1997; Ukstins et al., 2002; Cather et al., 2009; Bryan et al., 2013).

The occurrence of large igneous province clusters is significant for a number of reasons. First, it has led to the suggestion of superplumes, where large igneous province events are interpreted to record one or more large core-mantle boundary–derived mantle plumes, triggering increased convection in the outer core, halting the magnetic reversal process for tens of millions of years, and increasing oceanic crust production and mantle outgassing (Larson, 1991; cf. plume-clusters of Ernst and Buchan, 2002). It is now clear that any Cretaceous "superplume" event was not restricted to the Pacific Basin (Larson, 1991), but was much more global in its extent (Fig. 2), and other explanations have been proposed (e.g., Anderson, 1994). Second, large igneous provinces are playing a key role in Precambrian supercontinent reconstructions (e.g., Bleeker and Ernst, 2006), where ages of large igneous provinces present on different terranes are compared, and age matches in a given interval are established. These are then used as supporting evidence for those terranes being nearest neighbors during that time interval (Ernst, 2007a). Reconstruction is further enhanced by paleomagnetic studies, geochemical comparisons, and identification of intraplate compositions, and the use of the geometry of dike swarms (linear, radiating) to orient the terranes (Bleeker and Ernst, 2006; Ernst, 2007a). However, the Mesozoic–Cenozoic record highlights the problem of deciding whether coeval magmatic units that are located on different cratons actually should be reconstructed into a single large igneous province or whether they represent simultaneous but independent events (Bryan and Ernst, 2008). Temporal overlaps and geochemical similarities will not be sufficient for robust terrane reconstructions in the Precambrian (see also Ernst et al., 2008). Third, large igneous province events have been considered important drivers of environmental change, coinciding with mass extinctions (e.g., Courtillot and Renne, 2003; Wignall, 2001, 2005). Therefore, the co-occurrence of multiple large igneous province events globally and both in the oceans and on the continents would be predicted to greatly enhance their capacity to drive mass extinctions. Interestingly, the 130 and 120 Ma large igneous province clusters, which represent in excess of 100 million km^3 of new, dominantly mafic igneous crust, and which account for the majority of new igneous rock produced by large igneous province events in the breakup of Pangea, do not correlate with the largest mass extinction events or extreme environmental changes (see following). Instead, the largest mass extinction events have coincided with a single continental large igneous province event, and why a single large igneous province event may be more significant than global clusterings of events remains unclear.

Large Igneous Province Events and Continental Breakup

Large igneous provinces are intimately linked to continent and supercontinent plate breakup (e.g., Courtillot et al., 1999; Ernst and Bleeker, 2010). Large igneous province–related breakup produces volcanic rifted margins, new and large (up to 10^8 km^2) ocean basins, and new, smaller continents that undergo dispersal and ultimately, reassembly (e.g., India). It is now recognized that up to 90% of the global rifted continental margins are volcanic rifted margins (Skogseid, 2001; Menzies et al., 2002), with only a few margin segments characterized as being unusually magma poor. Most continental-scale rifts that proceed to seafloor spreading develop in association with large igneous provinces, and recent studies are recognizing the importance of magmatism and dike intrusion in rift evolution, such that large magma volumes can facilitate the transition to tectonic rifting (Corti et al., 2003; Bialas et al., 2010). Nevertheless, the rift stage for many volcanic rifted continental margins lasts between ~20 and 40–50 m.y. (Umhoefer, 2011). More recently, large igneous province fragmentation has also been recognized as an important process in the oceanic realm, where propagation of mid-ocean-ridge spreading centers and ridge jumps break up oceanic large igneous provinces, as suggested for the Ontong Java–Manihiki and Hikurangi plateau fragments (Taylor, 2006). Rifting apart of oceanic large igneous provinces by new oceanic spreading centers seems commonplace (Fig. 1), and in some cases, rifting appears to occur soon after the termination of large igneous province magmatism (within 5–20 m.y.; e.g., Worthington et al., 2006; Parsiegla et al., 2008). It remains unclear why thickened and strengthened oceanic crust of an oceanic plateau should be preferentially rifted apart, where crustal thicknesses may be up to 40–45 km (Coffin et al., 2012). It is interesting to note that at the first-order, the sequence of events in lithospheric rupturing shows little difference between continental and thickened oceanic crust.

However, not all continental large igneous provinces lead to continental rupture, and the controls on which large igneous provinces lead to breakup remain poorly understood. This is despite the fact that all Mesozoic to Cenozoic continental large igneous provinces were emplaced into regions of either prior or coeval extension (Bryan and Ernst, 2008). One factor that may prevent continental rupturing is whether or not the adjacent continental margin is undergoing subduction, such that contractional forces are transmitted into the overriding plate. However, evidence for upper-plate contraction at the time of large igneous province emplacement is poorly documented, and the relative distance of large igneous province magmatism to the active plate boundary (often >500 km), coupled with evidence for crustal extension, suggests that plate-boundary forces are not strongly controlling the ability of the lithosphere to rupture at the site of large igneous province magmatism. As discussed later herein, new research is now suggesting the Sierra Madre Occidental was the prerift large igneous province event to the Gulf of California (Bryan et al., 2013), which is a young ocean basin that has opened in close proximity to the plate boundary.

The Central Atlantic magmatic province, emplaced at ca. 201 Ma, is widely recognized as heralding the breakup of Pangea (e.g., Marzoli et al., 1999, 2011; McHone, 2000), but in detail, the earliest magmatism was partly emplaced into and across preexisting extensional basin structures (e.g., Olsen, 1997; Schlische et al., 2003; Marzoli et al., 2004; Nomade et al., 2007). This is a feature of most late Paleozoic to Cenozoic continental large igneous provinces (Bryan and Ernst, 2008; see also Meyer et al., 2007). Continental large igneous provinces generally precede continental rupture and ocean basin opening, and the correlation of eruptive units across the South Atlantic for the Paraná-Etendeka large igneous province (Milner et al., 1995; Marsh et al., 2001; Bryan et al., 2010) supports, in this case, the large igneous province principally being a prerift event. Several provinces also have synrift igneous pulses (e.g., North Atlantic—Saunders et al., 1997; Meyer et al., 2007). Ancient large igneous provinces

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are now being used to piece together the ancient supercontinents of Rodinia, Nuna, and Superior, and also constrain the timing of ancient supercontinent cycles (e.g., Ernst, 2007a; Ernst et al., 2008; Ernst and Bleeker, 2010). Large igneous provinces are thus a critical component of the Wilson cycle, and the Atlantic, Indian, and Antarctic Ocean ridge spreading systems can therefore be considered as the consequence of large igneous province events (Bryan and Ernst, 2008).

Crustal Setting of Large Igneous Provinces

Following recognition of large igneous province events throughout the geologic record, a clearer picture of the range of crustal settings (cratons, continental margins, ocean basins) has emerged (Bryan and Ernst, 2008). Although a wide variety of large igneous province types were initially recognized by Coffin and Eldholm (1992, 1994), this was strongly influenced by Mesozoic to Cenozoic examples, and by volcanic features on the seafloor, such that seamount groups and submarine ridges dominated the initial large igneous province inventory. However, these province types are no longer considered to be large igneous provinces (Bryan and Ernst, 2008), and the term "large igneous province" is now restricted to encompassing the continental flood basalts, volcanic rifted margins, silicic large igneous provinces, oceanic plateaus, ocean basin flood basalts, Archean greenstone-komatiite belts, and giant continental dike swarms, sills, and mafic-ultramafic intrusive provinces (Bryan and Ernst, 2008). Many Proterozoic–Paleozoic large igneous provinces occur as eroded flood basalt provinces, exposing their intrusive underpinnings, while the greenstone belts of the tholeiite-komatiite association most likely represent Archean large igneous provinces (Ernst, 2007a; see also Campbell and Hill, 1988). Silicic large igneous provinces reflect their crustal setting along young, fertile continental margins (Fig. 1) built up by paleosubduction processes, and where crustal partial melting overwhelmed the igneous system (Bryan et al., 2002; Bryan, 2007).

Large Igneous Province Events and Crustal Growth

Large igneous province events typically represent the outpouring of >1 Mkm^3 of magma, which can cover millions of square kilometers of the Earth's surface. However, a large proportion of the igneous volume generated during a large igneous province event does not reach the surface and remains stored at all depths in the lithosphere. Deeply eroded large igneous provinces, as represented by the giant continental dike swarms and mafic-ultramafic intrusive provinces (Ernst and Buchan, 1997; Ernst, 2007a; Bryan and Ernst, 2008; Ernst and Bleeker, 2010), provide windows into the plumbing system and subsurface storage of large igneous province magmas. Some estimates suggest that the ratio of extruded to intruded magma is 1:10 (White and McKenzie, 1989; Bryan and Ernst, 2008). Oceanic plateaus are the largest large igneous provinces preserved on Earth in terms of area and igneous volume, and the Cretaceous marked a peak in oceanic plateau formation (e.g., Larson, 1991; Kerr, 1998, 2003, 2005). To emphasize the continental scale of some large igneous province events, the prerift reconstruction of the oceanic plateau fragments of Ontong Java, Manihiki, and Hikurangi (Taylor, 2006) results in a single plateau originally the size of the Indian subcontinent. Due to their excess crustal thicknesses, oceanic plateaus are difficult to subduct (e.g., Cloos, 1993, but cf. Liu et al., 2010), such that at least their uppermost sections are accreted to continental margins, and thus, the accretion of oceanic plateaus is an important contributor to crustal growth (Kerr, 2013). Consequently, large igneous province events represent major, juvenile lithosphere-building episodes and are important to factor into crustal growth models (e.g., Condie, 2001; Hawkesworth and Kemp, 2006) and orogenesis (van Hunen et al., 2002; Liu et al., 2010). The clustering of large igneous province events at times of supercontinent breakup, when hundreds of millions of cubic kilometers of magma are emplaced, and the substantial development of volcanic rifted margins during the breakup of Pangea (e.g., Skogseid, 2001; Menzies et al., 2002) confirm that magma volumes are actually very high in continental breakup settings (cf. Cawood et al., 2013). However, because magmatism is fundamentally basaltic, large igneous province magmatism typically yields little to no age signature of new zircon growth (except for silicic large igneous provinces), and their substantial mafic igneous contribution to crustal growth will largely go unrecorded in zircon-based crustal growth studies (e.g., Condie, 1998; Condie et al., 2009; Condie and Aster, 2010; Iizuka et al., 2010; Cawood et al., 2013). Although the long-term average is ~1 event every 20 m.y. (Ernst et al., 2005), large igneous province events are relatively strongly linked to supercontinent breakup and, for example, show a very strong clustering in the last ~300 m.y., related to Pangea breakup (Fig. 1). For example, 25 continental large igneous provinces are recognized from 325 to 0 Ma, but only five have so far been recognized from 325 to 550 Ma, a period of Pangea assembly (Bryan and Ernst, 2008; Groflin and Bryan, 2012). In contrast, six well-defined large igneous province events can be recognized for the relatively short breakup history of Rodinia between ca. 825 Ma and 700 Ma, which may also include another two possible fragments of continental large igneous provinces (Ernst et al., 2008). This large igneous province episodicity is consistent with a more pulsed history to lithospheric growth.

Large Igneous Provinces and Mass Extinction Events

The origin of sudden mass extinction events has attracted substantial research effort, and extraordinary and geologically rapid events such as large igneous provinces and large, high-velocity impacts of asteroids or comets with Earth are widely considered to be the most plausible causes for the five major mass extinction events at the end-Ordovician, mid-Devonian (Frasnian–Fammenian), end-Permian, end-Triassic, and end-Cretaceous (Hallam and Wignall, 1997). In particular, a near-perfect association exists between extinction events and large igneous province events over the last 300 m.y., such that the general consensus now is that large igneous province events are sufficiently global in their occurrence and impact that they can trigger mass extinction events (Courtillot and Renne, 2003; Wignall, 2005). This is because large igneous provinces are unique in being the loci for both basaltic and silicic supereruptions (magnitude >8 or >360 and >410 km^3 of basaltic and rhyolitic magma, respectively) throughout Earth history, and for the substantial cumulative volumes (>10^5–10^7 km^3) of magma emplaced over brief periods (1–5 m.y.), which ultimately results from tens to hundreds of M >8 eruptions and intrusions (Bryan et al., 2010).

However, it has also been recognized that many large igneous province events do not coincide with major environmental change or a mass extinction. This is also the case for large asteroid impacts (White and Saunders, 2005), with only the end-Cretaceous extinction event being clearly linked with an asteroid impact (e.g., Alvarez et al., 1980; see review in Schulte et al., 2010), although greater numbers of large meteorite impacts are now being recognized that have coincided with extinction events (e.g., Tohver et al., 2012). Additionally, no correlation exists between the magnitude of the large igneous province event and the corresponding mass extinction (see Fig. 9 *in* Wignall, 2001), as might be predicted for the severity of an extinction event due to an asteroid impact. For example, the end-Permian mass extinction was the most devastating in Earth history and was characterized by the sudden loss of >90% of marine species and >70% of terrestrial species (Erwin, 1994), yet the Siberian Traps large igneous province, which is proposed as the trigger for this mass extinction, with an estimated sizeable volume of ~4 million km^3 (Fedorenko et al., 2000), is dwarfed by many of the oceanic large igneous provinces, such as the prerifted Ontong Java–Manihiki–Hikurangi megaplateau, which has an igneous volume of up to 77 million km^3 (Kerr and Mahoney, 2007). In addition, large igneous province clusters (e.g., Fig. 2) do not seem to correlate with mass extinction events. Consequently, proof of the nature of the causal links between large igneous provinces and extinction events, and whether the juxtaposition of effects from large igneous province volcanism and an asteroid impact is required to cause the largest mass extinctions (White and Saunders, 2005), is far from resolved (Wignall, 2005).

There are three main issues in establishing a causal link between large igneous province event(s) and a mass extinction: (1) The large igneous province event(s) must coincide with an extinction event, and this temporal coincidence is strongly dependent on our ability to precisely date the duration and peak(s) of large igneous province events, as well as the timing of the mass extinction, which is generally thought to last ~100,000 yr or less (e.g., Rampino et al., 2000; Rampino and Kaiho, 2012; cf. Huang et al., 2011); (2) the kill mechanism(s) must be constrained; and (3) the eruptive mechanisms by which large igneous province eruptions can perturb global climate or modify the environment must be identified, and their impact on a wide variety of terrestrial and marine ecosystems must be explored.

Contemporaneity of Large Igneous Province Events and Mass Extinctions

Linking mass extinction with the onset and tempo of large igneous province eruptions has proved difficult because of the geographic separation between large igneous provinces and stratigraphic sequences preserving evidence of the extinction (Blackburn et al., 2012). Consequently, an accurate temporal relationship between the onset of eruption and the main pulse of large igneous provinces and a correlated mass extinction requires precise geochronology, but this remains unclear for a number of large igneous provinces (see Fig. 3 *in* Kelley, 2007, for example), despite improved instrumentation (e.g., see review by Corfu, 2013) and geochronological advances (e.g., Mundil et al., 2004). This includes the Siberian Traps (Bowring et al., 1998; Kamo et al., 2003; Black et al., 2012), the Afro-Arabian large igneous province (Ukstins et al., 2002), and until recently, the Central Atlantic magmatic province (e.g., Nomade et al., 2007), as recent studies are now more clearly establishing peak volcanic activity at the Triassic-Jurassic boundary (Marzoli et al., 2011; Blackburn et al., 2012; Kerr, 2012). Early work, including sampling of flood basalt lava piles, assumed overly simplistic layer-cake stratigraphies for large igneous provinces, and much more complex lava stratigraphies and facies architectures are now apparent (e.g., Jerram, 2002; Jerram and Widdowson, 2005; Jay et al., 2009); the consequence is that while the main phase or some pulses of volcanism in some parts of the large igneous province may be well constrained, the entire eruptive history of a large igneous province in many cases still remains very poorly constrained. This is particularly the case for oceanic large igneous provinces, where, often, only the top few hundred meters in a few widely separated locations have been sampled by ocean drilling programs (e.g., Tejada et al., 2004). Furthermore, recent studies are now finding missing pieces to large igneous provinces where they had been rifted away following continental breakup (e.g., Comei province; Di-Cheng et al., 2009), raising the possibility that any one flood basalt province may be a partial record to a larger large igneous province event. For older large igneous provinces where significant erosion has removed much of the volcanic pile (e.g., giant continental dike swarms, sills and mafic-ultramafic intrusive provinces of Bryan and Ernst, 2008), identification of the main eruptive pulse(s) is dependent on the exposed intrusive record. Studies of younger large igneous provinces such as the Afro-Arabian have shown that temporal differences can exist between extrusive and intrusive events, such that the exposed hypabyssal, plutonic rocks and dike swarms are younger and biased toward dating crustal extension (Menzies et al., 1997).

High-resolution chronology using zircon or feldspar is commonly hindered in large igneous provinces because phenocrystic zircon is not present in the flood basalt lavas/volcaniclastic rocks (but can be present in intrusions), and the basalts are commonly either aphyric or altered, lacking fresh feldspar for $^{40}Ar/^{39}Ar$ dating. A further complication arises in that where flood basalt lavas do contain crystals, they can be recycled (i.e., antecrystic; Ramos et al., 2005; Vye et al., 2009). Dating stratigraphic boundaries has also been fraught with difficulties (e.g., Mundil et al., 2004). Other studies have drawn attention to issues regarding interlaboratory variability (e.g., Thiede and Vasconcelos, 2010) or discrepancies in the comparison of U-Pb and $^{40}Ar/^{39}Ar$ ages (e.g., Min et al., 2000; Nomade et al., 2007) in pinning down the main eruptive phase(s) of large igneous provinces and their coincidence with time boundaries. Consequently, while more recent studies are now illustrating that some key large igneous province events, based on the dated main phase of volcanism, may slightly either pre- or postdate the corresponding mass extinction event (e.g., Kelley, 2007), the true age duration of large igneous province events and the way in which they precisely correspond to extinctions and environmental changes require further study, and still face geological (i.e., preservation) and analytical limitations.

Kill Mechanisms of Large Igneous Province Events

While large igneous province events are considered the trigger mechanism initiating reactions that lead to environmental conditions resulting in the death of organisms (Knoll et al., 2007), the kill mechanism(s) or the nature of the actual environmental condition that caused death and mass extinction remains unclear. This is because of the observation that only some large igneous province events have coincided with mass extinctions and others have not, and that little correlation exists between the magnitude of the large igneous province event and the corresponding mass extinction. The implications are that large igneous province events may not always be triggers, the coincidence with an asteroid impact may be required (White and Saunders, 2005), ecosystems may have already been under stress in those cases where mass extinction occurred, or large igneous provinces may lead to more than one type of kill mechanism. Several specific kill mechanisms have been identified (e.g., Wignall, 2005), such as greenhouse warming and ocean acidification resulting from CO_2 overloading of the atmosphere; atmospheric cooling due to stratospheric SO_2 injections; oceanic anoxia/euxinia (e.g., Kump et al., 2005) triggered by ocean warming, increased atmospheric carbon dioxide or H_2S levels and nutrient supply, and decreased ocean circulation; ozone depletion and mutagenesis (Visscher et al., 2004; Beerling et al., 2007); methane clathrate release (e.g., McInerney and Wing, 2011); and thermogenic methane release due to large igneous province magma interaction with coal-rich sedimentary basins (Svensen et al., 2004, 2007, 2009).

Volcanic aerosol release associated with flood basaltic volcanism during large igneous province events is thought to have influenced the environment in two ways (Self et al., 2005): (1) Sulfuric acid (H_2SO_4) aerosols generated from volcanic SO_2 emissions that scatter and absorb incoming solar radiation increase atmospheric opacity and cause atmospheric cooling (e.g., Rampino and Self, 2000); or (2) greenhouse gas CO_2 emissions contribute to atmospheric warming (e.g., Olsen, 1999; Wignall, 2001, 2005). For oceanic plateaus, CO_2 emissions are thought to be particularly important, contributing to ocean acidification, global warming, and potentially runaway greenhouse conditions (see summary in Kerr, 2013). Oceanic plateaus are commonly related to periods of black shale deposition and evidence for oceanic anoxia (e.g., Sinton and Duncan, 1997; Kerr, 1998, 2005, 2013), and the combination of subsurface anoxia and ocean acidification may have been important in marine extinctions at the end of the Permian Period (see summary in Knoll, 2013). In addition, the physical emplacement of the basaltic plateaus in the oceans is thought to have resulted in sea-level rises, disturbance of oceanic circulation systems and thus nutrient upwelling events, causing increased biological productivity in surface waters, and the catastrophic release of ocean-floor clathrates, all of which contribute to ocean anoxia (Kerr, 1998, 2005, 2013). However, other studies, based on continental flood basalt provinces have concluded that warming due to CO_2 release from lava/magmas is likely to have been insignificant because the mass of CO_2 was less than that already present in the atmosphere for some large igneous province events (Self et al., 2005). Furthermore, it also appears that annual anthropogenic CO_2 emissions may already exceed the estimated annual CO_2 emissions of continental flood basalt eruptions (Gerlach, 2011).

In contrast, SO_2 emissions and the atmospheric burden of sulfate aerosols generated during large igneous province events appear to be unprecedented at any other time in Earth history (Self et al., 2005, 2006). The mass of H_2SO_4 aerosols injected into, and produced in, the stratosphere (and the upper troposphere) appears to be the single most significant factor controlling the magnitude of the climatic impact (Thordarson et al., 2009); acid rain (Self et al., 2005) and ocean anoxia (Kump et al., 2005) are also likely consequences. Petrologic estimates of SO_2 released during large igneous province flood basaltic eruptions would have formed considerable amounts of sulfate aerosols, with effects lasting at least as long as the eruptions persisted (decades and possibly longer; Self et al., 2005, 2006), and recent melt inclusion–based studies of the Siberian Traps have estimated that magmatic degassing contributed prodigious amounts of sulfur (~6300–7800 Gt) to the atmosphere (Black et al., 2012). However, strong atmospheric cooling trends are not apparent for all large igneous province events and those correlated with mass extinctions (Wignall, 2005), and delivery to the stratosphere, which is dependent on eruptive mechanisms, is a critical prerequisite for ozone depletion and global climatic effects (Thordarson et al., 2009; Black et al., 2012). It has also been suggested that an upper limit may exist as to how much sulfate aerosol can be stored in the stratosphere as larger, negatively buoyant sulfate particles may form through coagulation and rain out, limiting the potential increase in the optical depth of the atmosphere (Pinto et al., 1989; Timmreck et al., 2010). However, this potential self-limiting process will depend on the location(s), rate, and height of aerosol delivery into the stratosphere, and stratospheric wind patterns that can quickly disperse aerosols globally and minimize aerosol particle interactions.

Recent studies have focused on the emplacement environments of those large igneous provinces that were contemporaneous with mass extinction events. In particular, large igneous province emplacement through, and onto, hydrocarbon- and/or evaporite-rich sedimentary basins particularly distinguishes those events at the Permian-Triassic and Paleocene-Eocene boundaries (e.g., Svensen et al., 2004, 2009). In these cases, contact metamorphism of coal and other carbonaceous sediments generated carbon gases and probably halocarbons, bolstering the volcanic aerosol emissions (Retallack and Jahren, 2008; Svensen et al., 2009; Black et al., 2012). In the case of the end-Permian mass extinction, the end-Permian negative carbon isotope excursion and global warming are consistent with basinwide thermogenic methane generation resulting from contact metamorphism with intruded flood basaltic magmas (Svensen et al., 2009). Additional evidence for ozone destruction at the time of the end-Permian extinction comes from the prevalence of mutant pollen tetrads, which has been related to volcanic emissions of chlorine and fluorine compounds (Visscher et al., 2004). Recent studies support substantial F, Cl, and Br emissions from Siberian Traps eruptions that would have had profound effects on atmospheric chemistry and substantial ozone destruction (Beerling et al., 2007; Svensen et al., 2009; Black et al., 2012).

Virtually all these kill mechanisms have been linked to basaltic magmas intruded and extruded in large igneous province events. However, recent studies (e.g., Cather et al., 2009) are drawing attention to the role of large-volume silicic magmatism during large igneous province events that can more efficiently contribute to aerosol loading of the stratosphere. In addition, the large-volume explosive silicic volcanism during large igneous province events can significantly force global cooling by iron fertilization of oceans triggered by volcanic ash deposition (Cather et al., 2009; Olgun et al., 2011). Iron fertilization may decrease oceanic and subsequently atmospheric CO_2 concentrations by increasing the photosynthetic conversion of CO_2 to organic carbon (e.g., Cooper et al., 1996).

In summary, rather than thermal perturbations to global climate, large igneous province events may have their greatest environmental impact through prolonged ozone-layer destruction. Directions for future research will be in examining the paired effects on atmospheric chemistry/structure and ocean chemistry of repeated closely spaced and even synchronous large-volume mafic and silicic eruptions that can characterize the main pulses of continental large igneous province events, determining the gases that are most effective in causing environmental damage/deterioration, or ascertaining whether it is a cocktail of gases and the combined effects of S, Cl, F, Br, and CO_2/CH_4.

Large Igneous Province Eruptive Mechanisms

Delivery of volcanic aerosols to the stratosphere is a critical prerequisite for ozone depletion and global climatic effects (Black et al., 2012). This is because precipitation will remove volcanic aerosol contributions from the troposphere quickly, and effects will be only regional in extent (Thordarson et al., 2009). Work over the past 15 yr on continental flood basalt provinces has shown that the massive lava flows that typify large igneous provinces (Figs. 3 and 4) are giant pahoehoe and rubbly pahoehoe flow fields produced by many, but prolonged supereruptions that most likely lasted for years to decades (Self et al., 1996, 1997, 1998; Thordarson and Self, 1996, 1998; see review in White et al., 2009). Importantly, aerosol emissions associated with these eruptions would also have lasted over the eruption duration, lasting several years to a few decades (Thordarson et al., 2009). This contrasts with silicic explosive supereruptions, including those during large igneous province events, where magma and volatile discharge is brief (days to weeks; e.g., Bryan et al., 2010), and based on observations of modern explosive eruptions, aerosol and ash residence times in the stratosphere are expected to be in the order of a few years. While basaltic supereruptions are prolonged, the eruptions that feed flood basalt lava fields have generally low eruption heights (≤10 km), and estimated effusion rates approach the largest witnessed basaltic eruptions (Self et al., 1997). Unlike silicic explosive eruptions, flood basalt eruptions therefore lack obvious eruptive mechanisms to inject huge volumes of ash and aerosols directly and quickly into the stratosphere (Bryan, 2007), even if they are associated with large SO_2 and other gas emissions (Self et al., 2005, 2006; Black et al., 2012).

Mafic volcaniclastic deposits are common to many large igneous provinces, and the most

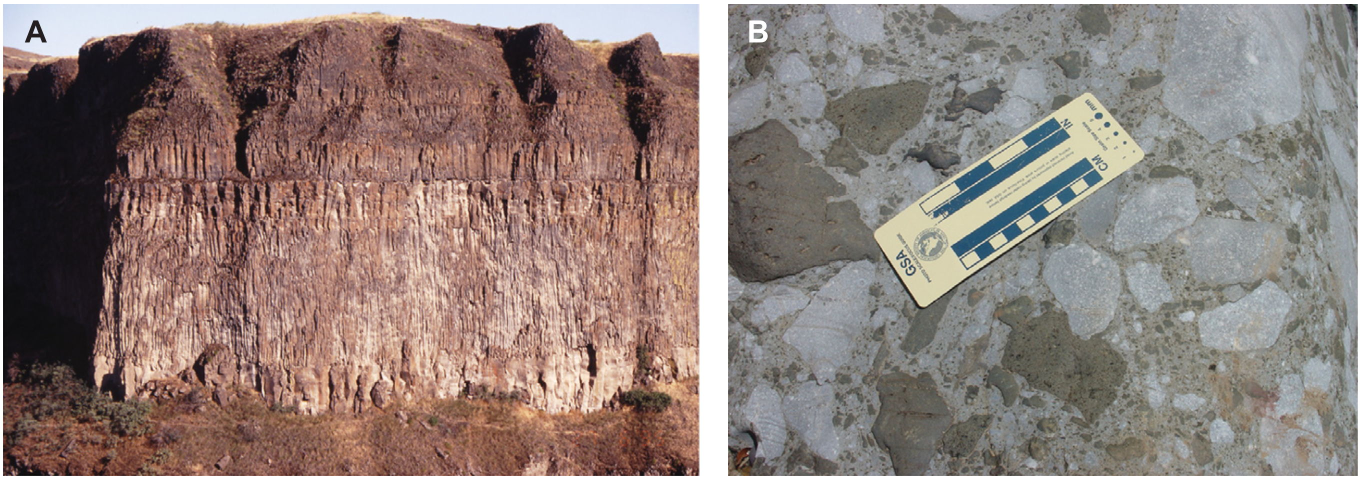

Figure 4. (A) Cliffed section of the 2660 km³ (M8.86) Sand Hollow flood basalt flow from the Columbia River large igneous province (Palouse Falls, Washington), illustrating the internal morphology and potential thickness (~60 m height) of a single, large-magnitude sheet lobe (from Bryan et al., 2010). (B) Close-up of a proximal mafic volcaniclastic deposit of phreatomagmatic origin from the Emeishan large igneous province (Daqiao, near Huidong, China), produced by the explosive interaction between flood basaltic magmas, seawater, and living carbonate reefs during the early stages of volcanism (Ukstins Peate and Bryan, 2008). Note the ragged shapes to the basaltic lava clasts (dark colored) and textural evidence for their ductile state at time of emplacement, such as indentations from limestone clasts (light colored). Mafic volcaniclastic deposits can provide sensitive records of eruption and emplacement environments and subtle variations in tectono-volcanic evolution not found in a thick and extensive flood basalt lava stratigraphy. Figure 4A is reprinted from Earth-Science Reviews, vol. 102, Bryan, S.E., Ukstins Peate, I.A., Self, S., Peate, D., Jerram, D.A., Mawby, M.R., Miller, J., and Marsh, J.S., The largest volcanic eruptions on Earth, p. 207–229, 2010, with permission from Elsevier.

significant deposit volumes are present where they result from phreatomagmatic eruptions (see reviews by Ross et al., 2005; White et al., 2009; Fig. 4B). In these cases, explosivity and thus potentially higher eruption column heights have resulted from the water interaction, thus enabling Plinian-type dispersal and stratospheric delivery of aerosols (Ross et al., 2005; Black et al., 2012). Several tephra layers in the North Atlantic large igneous province have Plinian-like distributions, indicating that tall basaltic eruption plumes were developed (see Ross et al., 2005, and references therein). However, unlike magmatically driven explosive eruptions, the ingestion of cold water and a potentially high content of cold rock fragments increases plume density, such that they will be prone to collapse, producing density currents. Reflecting this, in many large igneous provinces, mafic volcaniclastic deposits of phreatomagmatic origin commonly include abundant coarse lapilli-tuffs and tuff-breccias (e.g., Ferrar, Emeishan, Karoo, Siberia; Fig. 4B), which are interpreted to have been deposited proximal to the source vents (White et al., 2009). Therefore, basaltic phreatomagmatic volcanism does not appear to be a primary mechanism for sustained delivery of aerosols to the stratosphere from flood basaltic magmas.

The general model interpreted for effusive flood basalt eruptions is that they are fissure-fed eruptions and often scaled-up versions of relatively large historic eruptions (e.g., Self et al., 1996, 1997; White et al., 2009). Important aspects of this analogy are that: (1) each flood basalt eruptive event likely featured multiple eruption episodes, where each episode began with a relatively short-lived (hours to days?) explosive phase, followed by a longer-lasting effusive phase; and (2) at any one time, eruptive activity was confined to distinct segments on the fissure vent system, such that estimated mean eruption rates of ~4000 $m^3 s^{-1}$ would have been able to maintain 5–9-km-high columns throughout the eruption and potentially penetrate into the stratosphere with up to 20-km-high columns, but only during periods of peak lava flux and under favorable atmospheric conditions (Thordarson et al., 2009). A critical factor, then, to the success of flood basalt eruptions in delivering aerosols to the stratosphere is the height of the tropopause, which is strongly latitude and climate dependent, and currently varies from 17 km at the equator to <10 km near the poles. Flood basaltic eruption plumes may have been able to regularly inject SO_2 and other aerosols into the stratosphere at high latitudes, where the tropopause boundary is lower. However, large-scale subsidence through the stratosphere dominates at high latitudes (e.g., Holton et al., 1995), preventing interhemispheric circulation and effectively limiting aerosol and ash dispersion to the high latitudes and troposphere (Bryan, 2007). At low latitudes, it appears less likely that eruption plumes from flood basalt eruptions would be able to penetrate into the stratosphere and for any length of time.

Silicic supereruptions during large igneous province events are expected to have produced substantial and tall plumes, both at the vent, given the tremendously high eruptive mass flux (up to 10^{11} kg s^{-1}; Bryan et al., 2010), and as buoyant coignimbrite ash plumes that would have reached the stratosphere, collectively delivering prodigious amounts of ash and aerosols at multiple locations over large areas (up to 10^5 km^2). In addition, the magnitude and frequency of silicic supereruptions were far greater during large igneous province events than when compared to global, long-term averaged frequencies of silicic supereruptions (Bryan et al., 2010). As several recent studies have demonstrated, silicic volcanic rocks represent a significant cumulative eruptive volume of continental large igneous provinces and were principally erupted during the peak and final stages of flood volcanism (e.g., Marsh et al., 2001; Bryan et al., 2002; Ukstins Peate et al., 2005). While the silicic supereruptions have an obvious eruption mechanism for stratospheric aerosol injection, the much shorter duration (days to weeks) suggests that their impact may not have been as long-lasting as potentially decadal flood basalt eruptions (Thordarson et al., 2009). However, this may be less of an issue if the main kill mechanism is ozone destruction rather than thermal perturbations. The penecontemporaneity of mafic and

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silicic magmatism is now recognized in continental large igneous provinces (Bryan et al., 2010), raising the possibility that large-volume mafic and silicic eruptions may have worked together in causing aerosol loading of the troposphere and stratosphere, as well as causing additional effects such as iron fertilization of oceans (Cather et al., 2009). No quantitative constraints currently exist on volatile degassing from large igneous province–related silicic explosive supereruptions that can be used to compare with the flood basalts, and to constrain better the total volatile loads generated during large igneous province events. These would be ideal topics for future investigation.

Large Igneous Province Events and Mantle Dynamics

Large igneous provinces fundamentally record major mantle melting events and thus require large amounts of thermal energy expended over a geologically short period of time (Saunders, 2005). Because of the vast spatial dimensions of large igneous provinces, understanding why such magmatism takes place could potentially provide first-order constraints on mantle dynamics (Korenaga, 2011), such as instability at the core-mantle boundary (e.g., Richards et al., 1989; Larson, 1991; Hill et al., 1992) and the efficiency of convective mixing (e.g., Takahahshi et al., 1998; Korenaga, 2004). Studies of large igneous provinces have been fundamental to development of the mantle plume theory (e.g., Richards et al., 1989; Campbell and Griffiths, 1990; Campbell, 2005, 2007), and also to whole-mantle convection models, as mantle plumes represent a rising counter flux to deep subduction into the lower mantle, which is increasingly being supported by seismic evidence (e.g., van der Hilst et al., 1997; Grand, 2002; Ren et al., 2007).

Large igneous provinces have generally been interpreted to be the result of decompression melting of the large spherical head of a new mantle plume (Richards et al., 1989; Campbell and Griffiths, 1990), likely originating from the core-mantle boundary, while associated hotspot trails or aseismic ridges are related to melting of the narrow plume tail (Wilson, 1963; Morgan 1971). This theory gained ascendancy through the 1990s, and potentially some of the strongest evidence for mantle plumes may come from studies of planetary large igneous provinces (e.g., Ernst et al., 2001; Hansen, 2007). The common spatial-temporal connection of large igneous provinces with age-progressive hotspots or aseismic ridges representing chains of overlapping hotspot-type volcanoes (e.g., Paraná-Etendeka large igneous province–Tristan de Cunha hotspot; Deccan large igneous province–Reunion hotspot; North Atlantic large igneous province–Iceland hotspot) provided an initial compelling argument (e.g., Richards et al., 1989). The isotopic and trace-element compositional similarities between large igneous provinces and associated hotspot-related igneous rocks are consistent with melt derivation from similar sublithospheric mantle source regions, and they are distinct from magmas typically produced at plate boundaries (Hawkesworth and Scherstén, 2007).

There are several geologically testable predictions of the mantle plume theory: (1) Is there a connection between a large igneous province and (active) hotspot representing the products of melting of the plume head and tail, respectively? (2) What is the extent of the rift zone? Large igneous province magmatism and the length of thickened oceanic crust developed within a rift zone should have extents of ~2000–2500 km, which will represent the calculated dimensions of a core-mantle boundary–derived plume head that flattens beneath the lithosphere. (3) Is there evidence of the presence of high-temperature, magnesium-rich igneous rocks (picrites, komatiites) within the large igneous province and hotspot, which would have erupted early and be most abundant near the inferred center of the province (plume head)? (4) Is there regional domal uplift of 1000 ± 500 m preceding flood volcanism? (5) Is there a short duration to the main pulse of flood volcanism (Campbell, 2005, 2007)?

As more detailed studies of large igneous provinces and hotspot-related seamount volcanoes, and geophysical imaging of deep Earth have been undertaken, particularly in the last 10–15 yr, it has been realized that many large igneous provinces and seamounts do not show geologic evidence for these predictions and for volcanism to have formed above a mantle plume (e.g., Czamanske et al., 1998; Ingle and Coffin, 2004; Korenaga, 2005; Ukstins Peate and Bryan, 2008; Koppers, 2011; Serrano et al., 2011). Mantle plumes have proven difficult to image down to the core-mantle boundary using seismology (e.g., Hwang et al., 2011), with several appearing to be restricted to the upper mantle (e.g., Yellowstone, Iceland; Christiansen et al., 2002; Montelli et al., 2004). In some cases, the predictions may be too simplistic; it has been suggested that the type and passage of a mantle plume through the mantle and the way in which a plume interacts with lithosphere may explain, for example, the general absence of prevolcanic domal uplift (e.g., Leng and Zhong, 2010; Sobolev et al., 2011). Nevertheless, many geological inconsistencies have resulted in a variety of models being proposed to explain the origin of large igneous provinces (see summaries in Saunders, 2005; Ernst et al., 2005; Bryan and Ernst, 2008; and the Introduction section herein). Recently, opposing sets of literature on the existence of mantle plumes have been published (for example, compare Campbell and Kerr [2007] with Foulger et al. [2005] and Foulger and Jurdy [2007]; and Humphreys and Schmandt [2011] with Anderson [2012]). The debate about whether mantle plumes exist or not, and what other mechanisms could cause melting anomalies that generate large igneous provinces and hotspots has led to the establishment of the Web site www.mantleplumes.org, where wide varieties of ideas and theories are presented, serving as a valuable resource on this topic.

Part of the issue stems from a "one size fits all" approach to interpreting the origin of large igneous provinces (and hotspots; see Courtillot et al., 2003; Foulger, 2007), because large igneous province events may have a number of origins. The fact that all large igneous province events show a number of key features (Bryan and Ernst, 2008) that make them distinctive and unique in Earth history, and are fundamentally intraplate igneous events, does suggest a common origin. If planetary large igneous province examples are validated (see following), then this common process for large-volume magma generation in the mantle cannot be intimately linked to plate-boundary processes. It is underappreciated that much of what is observed and sampled in large igneous provinces reflects processes at crustal depths, including magma generation and extraction, transport, storage, contamination, crystallization, and emplacement (Bryan et al., 2010); the revelation that large igneous province magmas can undergo substantial lateral transport in the crust over distances exceeding 3000 km and be so far removed from their place of origin in the mantle is also quite astounding (Ernst and Baragar, 1992; Elliot et al., 1999). Province-specific models (e.g., Ingle and Coffin, 2004; Long et al., 2012) that might satisfactorily explain geologic observations locally remain unsatisfying in providing a broader framework for understanding the origin of all large igneous provinces. If large igneous provinces (and hotspots) do have different origins, then a future challenge will be recognizing geologic features that can unequivocally discriminate the different models; otherwise, these models become untestable. Vigorous debate is expected to continue for many years to come on this topic.

Resource Significance of Large Igneous Provinces

Over the past 25 yr, large igneous provinces have been increasingly explored for mineral and energy resources. They are a key target

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for magmatic Ni-Cu and platinum group elements (PGEs), Cr, Fe-Ti-V, and other mineral deposit types (Naldrett, 1997, 1999; Pirajno, 2000, 2007; Schissel and Smail, 2001; Borisenko et al., 2006; Eckstrand and Hulbert, 2007; Ernst, 2007b; Begg et al., 2010; Jowitt and Ernst, 2013). In terms of ore-forming systems, two general end members are recognized: (1) those associated with magma, and (2) hydrothermal systems powered by the thermal energy released by the cooling of anorogenic magmas in the crust (Pirajno, 2007). Orthomagmatic ore deposits are typically hosted by mafic-ultramafic layered intrusions or volcanic rocks in large igneous provinces, with key ore deposit types being: (1) intrusion-hosted Cu-Ni-PGE–rich sulfides, chromite, and Fe-Ti-V oxides (e.g., Bushveld Complex—Bushveld large igneous province, Great dike of Zimbabwe, southern Africa); (2) Cu-Ni sulfide mineralization in basaltic and gabbroic rocks (e.g., Duluth—Keweenawan large igneous province, USA; Noril'sk-Talnakh—Siberia Traps, Russia; Jinchuan—Guibei large igneous province, China); and (3) Archean komatiite Ni sulfides (e.g., Kambalda, Western Australia) (Pirajno, 2007). Two styles of orthomagmatic ore deposits are now also known from granitic rocks in large igneous provinces: iron-oxide copper gold (IOCG), and Sn, W, U, Nb, Ta, and Th mineralization associated with A-type granites (Pirajno, 2007; McPhie et al., 2011). Voluminous banded-iron formations that formed between 2.6 and 1.8 Ga along intracratonic passive margins or in platform basins likely have temporal and genetic links to large igneous province events (e.g., Barley et al., 1997). Consequently, two specific ore systems (komatiite-hosted Ni-Cu deposits and iron formations) associated with large igneous provinces are age dependent, being restricted to Archean and Paleoproterozoic-Mesoproterozoic rocks. Hydrothermal ore systems are also associated with large igneous provinces, particularly where active rift systems act as major conduits for both magmas and hydrothermal fluids. Carlin and epithermal Au mineralization are key expressions of hydrothermal mineralization associated with large igneous provinces, but they appear to be more commonly associated with silicic large igneous provinces (Bryan, 2007; Pirajno, 2007).

Petroleum exploration over the past 25 yr has had considerable focus on a number of hydrocarbon-rich volcanic rifted margins such as the North Atlantic, South Atlantic, and Northwestern Australia. The nature and timing of large igneous province magmatism have several implications for hydrocarbon generation/maturation and storage, as well as creating "volcanic risk" for exploration companies in ultradeep-water (>2000 m) environments. Consequently, this has driven an improved understanding of the thickness, architecture, and timing of large igneous province–related volcanism in these sedimentary basins (e.g., Mohriak et al., 2002; Nelson et al., 2009; Aarnes et al., 2011), and it will continue to be an area of applied research in the foreseeable future. In addition, oceanic plateau volcanism has been linked to the deposition of organic-rich sediments during anoxic conditions, such that many of the world's most important occurrences of mid-Cretaceous oil source rocks may owe their existence to the formation of oceanic plateaus at this time in the Pacific and Indian Oceans (Kerr, 2013).

Planetary Large Igneous Provinces

Following analysis of fly-by data from the inner planets over the last four decades, and recovery of mare rocks from the Moon, it has been concluded that Mars, Venus, Mercury, and the Moon have had a significant history of large igneous province–scale basaltic to ultramafic volcanism (Head and Coffin, 1997; Wilson, 2009; Thordarson et al., 2009; Head et al., 2011; Head and Wilson, 2012). Planetary large igneous provinces can provide important contributions to our understanding of terrestrial large igneous provinces and geodynamics because they record planetary evolution and the transport of a significant amount of internal heat and material (Wilson, 2009). Furthermore, unlike on Earth, the lack of convincing evidence for Earth-like plate tectonics on the other rocky planets means the planetary large igneous provinces have not been affected by tectonic deformation or fragmentation (e.g., Hansen, 2007), and exposure and preservation will be better due to fewer erosional agents and minimal erosional rates. The antiquity of the other inner planets means that the very earliest large igneous province record of a planet is likely to be better preserved than on Earth (Head and Coffin, 1997). Consequently, the inner planets are considered to preserve an excellent record of large igneous provinces in space (their areal distribution over the planet) and through time, providing information on temporal variations of large igneous province events over the geological history of a planet.

Potential planetary analogues to terrestrial large igneous province types include the lunar maria (continental flood basalt provinces), Venusian crustal plateaus (oceanic plateaus), and rift-dominated volcanic rises on Mars and Venus (volcanic rifted margins) (Head and Coffin, 1997; Ernst et al., 2001; Hansen, 2007). Unlike Earth, no silicic large igneous provinces or large-volume silicic magmatism associated with planetary large igneous provinces have so far been recognized. The recent discovery and documentation of laterally and areally extensive sets of narrow ridges that are interpreted to be shallowly exhumed major dike systems (Head et al., 2006) and extensive radial graben systems interpreted to be a surface manifestation of mantle-derived dike intrusion complexes (Wilson and Head, 2002) provide interesting planetary analogues to the giant dike swarms recognized on Earth (e.g., Ernst and Buchan, 1997; Ernst et al., 2001). The lateral extents of the giant dike swarms, the Martian ridges, and other dike-related features (Ernst et al., 2001) are similar (hundreds of kilometers and discontinuously for thousands of kilometers), as are thicknesses: Dike widths are typically up to 20–40 m, with maximum widths of 100–200 m on Earth, and high-resolution imagery indicates ridge crests ~60 m wide across the Hesperian plains of Mars (Head et al., 2006). The continuity and thickness of the dikes are consistent with being developed during very high-effusion-rate, large-volume flood basalt–type eruptions (Head et al., 2006), and as on Earth, significant lateral transport (>1000 km) is inferred for magma along these planetary giant dike swarms (Ernst et al., 2001).

Planetary large igneous province recognition so far has been based primarily on areal extent, which is generally well constrained from the high-resolution surface images now available. Several regions on the planets with areas >1 million km^2 have been interpreted as large igneous provinces (e.g., Head and Coffin, 1997; Hansen, 2007; Head et al.., 2011), and, internally, lava fields on the scale of flood basalts exhibiting a variety of flood basaltic lava surface features, such as extensive and lobate flow fronts and sinuous rilles or evidence for thermal erosion by lava channels, have been identified in images (see summary in Head and Coffin, 1997). In the extreme, early studies had suggested that up to 80% of the surface of Venus had been covered by massive outpourings of flood basaltic lava to a depth of ~2.5 km, taking 10–100 m.y., making this the largest large igneous province in the solar system (e.g., Strom et al., 1994; Basilevsky and Head, 1996; Head and Coffin, 1997). However, the basis for this event has recently been challenged (Hansen, 2007), and it highlights the difficulties in constraining igneous volumes and event durations for planetary large igneous provinces. As has been discussed for terrestrial large igneous provinces, volume, duration, and evidence for brief, large-volume igneous pulses are critical and distinguishing features (Bryan and Ernst, 2008).

Volume, both of individual eruptions and at the provincial scale, and eruption rate/duration are critical parameters to establish equivalence

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to terrestrial large igneous provinces. Ghost craters, which are preexisting craters that have been partially or completely buried by lava, provide a useful approach in constraining deposit thickness, as well as potentially informing the mode of emplacement of the concealing volcanic rocks (Head et al., 2011). While the inner planets essentially lack weathering, erosion, sediment transport, and deposition processes that play dominant roles in shaping Earth's surface (Hansen, 2007), these processes actually provide a vital role in helping us to identify the products and scale of individual large igneous province eruptions (Bryan et al., 2010), potentially important time breaks during large igneous province events, and also the relative chronology of large igneous provinces based on their state of preservation. Consequently, large igneous province–sized volcanic constructs such as Olympus Mons on Mars, with an edifice volume of ~2 million km^3, may simply result from long-term mantle melting anomalies lasting billions of years (Head and Coffin, 1997) and the lack of plate tectonics and erosional processes. The lunar maria, widely considered to be large igneous provinces and which cover ~17% of the Moon, are interpreted to have been emplaced over periods of time (10^8 to 10^9 yr) substantially longer than for terrestrial large igneous provinces (<50 m.y.; Bryan and Ernst, 2008), and at very low averaged magma emplacement rates (~0.01 km^3/yr; Head and Coffin, 1997). As pointed out by Bryan and Ernst (2008), all plate-boundary processes generating magma (i.e., mid-ocean ridges, subduction zones, continental rifts), as well as other mantle-melting processes on planets, given sufficient time and space, can also produce igneous rock of large igneous province–scale dimensions. While volcanic coverage of the inner planets is extensive, it remains unclear if many of the provinces result from very long-term or more rapid (<50 m.y.) accumulations akin to terrestrial large igneous provinces. At present, absolute geologic time cannot be constrained for the inner planets, and the surface density of impact craters provides the only means by which to constrain absolute time on planet surfaces (Hansen, 2007).

SILICIC LARGE IGNEOUS PROVINCES

Within the broad research area of large igneous provinces, one particular advance over the past 25 yr has been in the recognition and understanding of "silicic" large igneous provinces, including their geologic/tectonic settings, key characteristics, origins of the magmas, and economic resources. In some cases, the scale of these provinces had been recognized for some time (e.g., Sierra Madre Occidental; McDowell and Keizer, 1977; McDowell and Clabaugh, 1979). In other cases, the true size and immensity of silicic magmatism were revealed through an integration of igneous and sedimentary records that now reside both onshore and offshore (e.g., Whitsunday; Bryan et al., 1997, 2012), or on adjacent continents (e.g., Chon Aike; Pankhurst et al., 1998, 2000) following tectonic fragmentation (Fig. 1). Many early studies simply considered the silicic-dominant magmatism as a continental magmatic arc emplaced above an active subduction zone (e.g., Cameron et al., 1980; Jones and Veevers, 1983; Wark et al., 1990; Wark, 1991). Such interpretations on the tectonic setting of the magmatism have been strongly influenced by the continent-margin position, calc-alkaline affinity, relatively primitive isotopic characteristics, the presence of andesitic or intermediate composition volcanic rocks, and a subduction heritage along the continental margin (Bryan et al., 2013). A fundamental revision then has been our understanding of a tectonic setting for the silicic magmatism that is often remote (up to or >500 km) and disconnected from suprasubduction-zone processes and relative plate motions (Bryan et al., 1997, 2008; Pankhurst and Rapela, 1995; Pankhurst et al., 1998, 2000; Bryan, 2007; Wong et al., 2010), and that spatial-temporal relationships exist with ocean basin formation (Bryan et al., 2012, 2013).

The potential long-term significance of silicic (granitoid) magmatism during large igneous province events has been the ever-growing record of U-Pb igneous zircon ages derived from granitoid and sedimentary rocks, which has particularly delineated major silicic granitoid igneous events at ca. 2.7 Ga and 1.9 Ga (e.g., Gastil, 1960; Campbell and Hill, 1988; Condie, 1998; Condie et al., 2009, 2011; Iizuka et al., 2010). These periods have been linked to catastrophic superplume events in the mantle (e.g., Campbell and Hill, 1988; Condie, 1995), based on the presence of 2.8–2.7 Ga flood basalts (e.g., Blake, 1993; Cheney and Winter, 1995) and widely occurring flood basalt volcanics and mafic-ultramafic intrusive rocks at 1.9 Ma (e.g., Ernst and Buchan, 2001, and references therein). However, the temporally related granitoid magmatism, the source for the detrital zircons, has been considered as orogenic and thus unrelated (e.g., Condie and Aster, 2010). An important observation that has been evident from zircon studies in volcanic rocks (Charlier et al., 2005; Bryan et al., 2008) is that zircon generally only appears as a new crystallizing phase in silicic magmas (~>70 wt% SiO_2; see also Watson and Harrison, 1983). Suprasubduction-zone magmatism is dominantly basaltic andesite to andesite-dacite at modern oceanic and continental arcs, respectively; the consequence is that these magma compositions are zircon undersaturated and will not crystallize new zircon. Large-volume silicic (new zircon-bearing) magmatism that will have a measurable effect on the detrital zircon age record occurs in intraplate continental regions, and along continental margins or island arcs undergoing rifting. Thus, major peaks in new igneous zircon ages more likely reflect crust instability, extension, and possible successful rupturing events, and should not be so closely tied to periods of supercontinent assembly (cf. Condie and Aster, 2010; Cawood et al., 2013). Consequently, the origin of the widespread 2.7 and ca. 1.9 Ga zircon peaks may alternatively be linked to large igneous province events at this time and enhanced melting of continental crust that would have been composed of larger volumes of juvenile material (e.g., Campbell and Hill, 1988).

The following section focuses on western Mexico and the Sierra Madre Occidental silicic large igneous province to illustrate some of these major advances in understanding of large igneous province magmatism, associated crustal extension, and subsequent ocean basin formation.

Sierra Madre Occidental

The Sierra Madre Occidental (SMO, Fig. 5) is the largest silicic igneous province in North America (McDowell and Keizer, 1977; McDowell and Clabaugh, 1979; Ward, 1995), and it is contiguous with silicic volcanism through the Basin and Range Province of the western United States to the north (Lipman et al., 1972; Gans et al., 1989; Best and Christiansen, 1991), and also with the ignimbrite province of the Sierra Madre Sur, south of the Trans-Mexican volcanic belt (Morán-Zenteno et al., 1999, 2007; Cerca-Martínez et al., 2007). It forms a prominent elevated plateau region up to 3 km high, where ignimbrite sections are at least 1 km thick (Fig. 6), and, notably, crustal thicknesses are their highest in Mexico (up to 55 km; Fig. 5). Through this elevated core of the province, ignimbrite sections are flat lying, but along the flanks, ignimbrite sections are increasingly faulted and tilted. Along the eastern edge of the Gulf of California, crustal thicknesses have been reduced to ~22 km (Fig. 5).

A minimum volume of 400,000 km^3 of dominantly rhyolitic ignimbrite was erupted mostly between ca. 38 and 18 Ma, but age dating over the past 40 yr has identified two main pulses or "flare-ups" of ignimbrite activity (Fig. 7): at ca. 34–28 Ma and ca. 24–18 Ma (Ferrari et al., 2002, 2007; Bryan et al., 2013). Significantly, age dating has further revealed the very rapid (~1 m.y.

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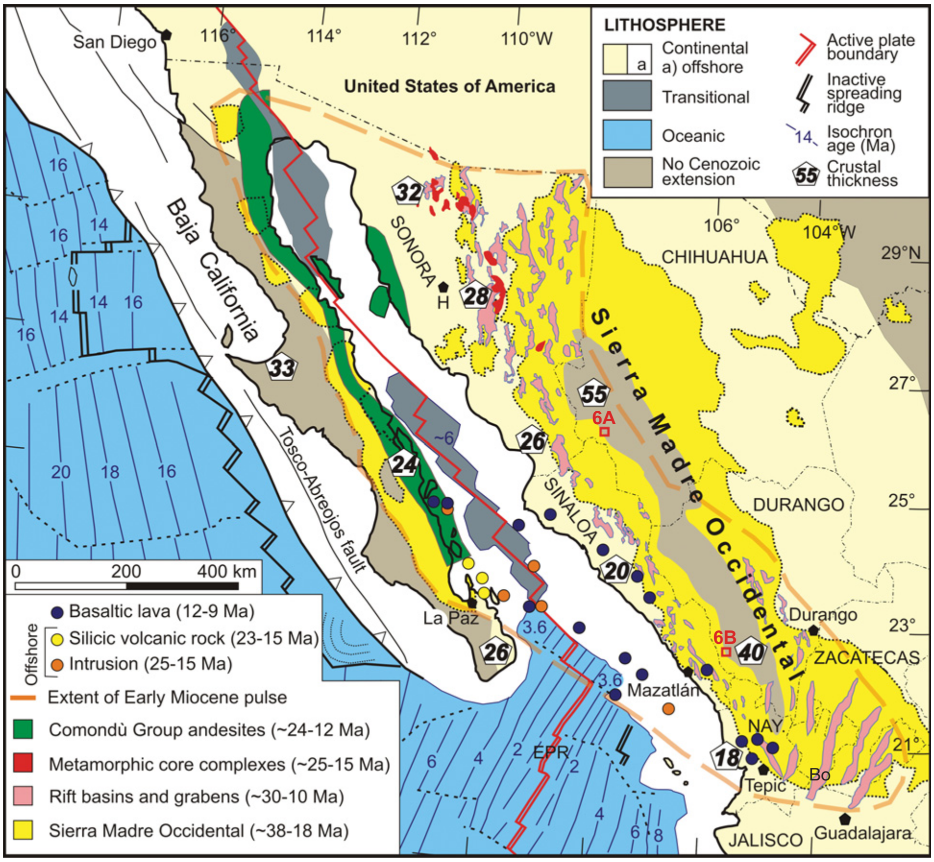

Figure 5. Tectonic map of northwestern Mexico showing the main volcano-tectonic elements, including: (1) the preserved extents of the Oligocene–early Miocene silicic-dominant volcanic activity of the Sierra Madre Occidental (Ferrari et al., 2002; Bryan et al., 2008); (2) extents of the dominantly bimodal early Miocene pulse that coincided with the wide development of grabens and rift basins (McDowell et al., 1997; Ferrari et al., 2002), and a restricted belt of metamorphic core complexes in the state of Sonora (Nourse et al., 1994; Wong et al., 2010); (3) distribution of the middle Miocene Comondú Group andesites (from Umhoefer et al., 2001); and (4) recently dated Miocene igneous rocks from offshore (Orozco-Esquivel et al., 2010). Lithospheric variation across the region is also shown, including unextended and extended continental regions, and transitional to new oceanic crust formed by the propagating spreading center in the Gulf of California. Red boxed areas near Mazatlán and Chihuahua-Sinaloa state border refer to locations of photographs in Figure 6. Abbreviations: EPR—East Pacific Rise; H—Hermosillo; Nay.—Nayarit; Bo—Bolaños graben. Figure is modified from Bryan et al. (2013).

duration), large igneous province–like emplacement rates for kilometer-thick sections of ignimbrite across the province (e.g., McDowell and Keizer, 1977; Ferrari et al., 2002; Swanson et al., 2006; McDowell and McIntosh, 2012), attesting to rapid rates of silicic magma generation and eruption (Bryan et al., 2008). The Oligocene pulse is thought to be responsible for at least three quarters of the erupted volume, whereas a volume of at least 100,000 km^3 was erupted in the early Miocene. Rhyolitic ignimbrite represents at least 85%–90% of the erupted volume, with the remaining volume being rhyolitic lavas/domes and basaltic lavas.

The early Miocene pulse was largely superimposed on the Oligocene volcanic pulse, but it also extended further west (Fig. 5) to be present on Baja California (e.g., Umhoefer et al., 2001). Recent dredge surveys and age dating of recovered rocks through the southern Gulf of California have confirmed the presence of early Miocene bimodal volcanic and exhumed intrusive rocks offshore (Fig. 5), improving the prerift connection between Baja California and mainland Mexico (Orozco-Esquivel et al., 2010; Ferrari et al., 2012). The early Miocene pulse shows significant differences from north to south. Silicic volcanism appears to have been more volumetrically dominant in the SW part of the Sierra Madre Occidental, with thick rhyolitic ignimbrite packages, similar to the Oligocene sections, characterizing some areas (e.g., Espinazo del Diablo and El Salto successions—McDowell and Keizer, 1977; Mesa del Nayar area—Ferrari et al., 2002). Elsewhere, graben-focused bimodal volcanism was characteristic (Ferrari et al., 2002; Ramos Rosique, 2013). Graben margins are commonly defined by rhyolite domes, whereas basaltic lava packages up to 200 m thick and rhyolitic ignimbrites (some fissure fed; Aguirre-Díaz and Labarthe-Hernández, 2003; Murray et al., 2010) partly infill the grabens (Ramos Rosique et al., 2010; Ramos Rosique, 2013). In contrast, early Miocene volcanism was less abundant and dominantly mafic in composition across the northern Sierra Madre Occidental (McDowell et al., 1997).

Association with Synvolcanic Extension

A general temporal and spatial overlap between volcanism and extension has been recognized for many continental large igneous provinces (Bryan and Ernst, 2008), including the silicic large igneous provinces (Bryan, 2007), but large igneous province initiation may be prerift, with no initial surface expression of rifting. Some large igneous provinces such as the North Atlantic large igneous province have pulses of igneous activity that correspond to prerift (62–58 Ma) and synrift phases (56–53 Ma; Saunders et al., 1997). Since many large igneous provinces, both continental and oceanic, are subsequently ruptured to produce new ocean basins (Fig. 1) and coincide with supercontinent breakup (e.g., Bryan and Ernst, 2008; Ernst et al., 2008), lithospheric extension is a fundamental part of large igneous province events. Crustal extension is generally considered to be important for generating large volumes of silicic magma (e.g., Hildreth, 1981; Ward, 1995; Hanson and Glazner, 1995; Gans and Bohrson, 1998), and petrogenetic studies have demonstrated the substantial contribution to silicic large igneous province magmatism by crustal partial melting (e.g., Ewart et al., 1992; Pankhurst and Rapela, 1995; Riley et al., 2001; Bryan et al., 2002, 2008). However, for many large igneous provinces, the relative timings of the onset of large igneous province magmatism and extension remain unclear, as well as if significant changes in the rate of synvolcanic extension also occur, and how this may affect magmatism in terms of magma production, magmatic processes, eruptive styles, and eruptive products. Previous studies have suggested that synvolcanic extension can promote smaller-volume effusive eruptions over larger caldera-forming eruptions (e.g., Axen et al., 1993), intermediate magma

Figure 6. Examples of elevated, dissected plateaus of flat-lying ignimbrite along the core of the Sierra Madre Occidental silicic large igneous province. This "step-like" topography, a product of posteruption erosion, is also characteristic of many continental flood basalt provinces (cf. Fig. 3). (A) Approximately 1-km-thick Oligocene ignimbrite pile exposed on the southeastern side of Copper Canyon, northern Sierra Madre Occidental (27°31.670′N, 107°49.687′W), reaching an elevation of 2240 m above sea level (asl), with the base of the canyon at 1320 m asl. The lowermost exposed unit is the Copper Canyon Tuff (29.6 Ma), for which the intracaldera facies is up to 1 km thick (Swanson et al., 2006). (B) View west from the Mazatlán-Durango old highway (23°39.927′N, 105° 43.340′W) to the flat-lying 24.0–23.5 Ma Espinazo–El Salto sequence (McDowell and Keizer, 1977) with a thick section of basaltic lavas at the base overlain by numerous rhyolitic welded ignimbrites; the exposed cliff section is ca. 250 m high, and the prominent cliffed and columnar jointed rhyolitic ignimbrite near the top of the section has been mapped up to 150 m thickness.

compositions instead of bimodal magma compositions (Johnson and Grunder, 2000; Bryan et al., 2012, 2013), and, where extension is rapid (high magnitude), a suppression of volcanism (Gans and Bohrson, 1998).

Significant extension began across the northern Sierra Madre Occidental at ca. 30 Ma, marked by the eruption of basaltic andesite lavas chemically resembling flood basalts (Southern Cordilleran Basaltic Andesite [or SCORBA] of Cameron et al., 1989), followed by the development of grabens at 27 Ma (McDowell et al., 1997), and by 25 Ma, a prominent belt (>300 km long) of high-magnitude extension was initiated in the state of Sonora (Gans, 1997; Wong et al., 2010), producing metamorphic core complexes (Fig. 5). This high-magnitude extension may have contributed to a suppression of large-volume silicic volcanism (Gans and Bohrson, 1998) through the NE Sierra Madre Occidental during the latest Oligocene and early Miocene, when volcanism was occurring along strike to the south in the Sierra Madre Occidental (Bryan et al., 2013). As inferred by Cameron et al. (1989), the potential initiation of upper-crustal extension at ca. 30 Ma was marked by the widespread and increased eruption of the SCORBA, and immediately followed the peak in silicic explosive volcanism and coincided with a decline in silicic explosive volcanism (Fig. 7).

Bimodal volcanism during the early Miocene pulse was clearly enhanced by active extension, particularly across the southern Sierra Madre Occidental at this time (Ferrari et al., 2002; Bryan et al., 2013). Typically crystal-poor, high-silica rhyolites were emplaced as both numerous lava domes sited along active faults or graben-bounding structures and as ignimbrites from fault-controlled explosive fissure eruptions (Aguirre-Díaz and Labarthe-Hernández, 2003; Murray et al., 2010; Ramos Rosique, 2013). Welded pyroclastic dikes exposed within faults demonstrate that graben faults were utilized by silicic magmas for explosive eruptions (Aguirre-Díaz and Labarthe-Hernández, 2003; Ramos Rosique, 2013). Basaltic dikes are also found intruding along graben-bounding faults, and relatively thick lava piles (up to 200 m in the Bolaños graben, Fig. 5) ponded within the grabens, and in some locations invaded developing lacustrine sedimentary sequences. The active faulting thus provided enhanced pathways for basaltic magmas to invade the upper crust and erupt at the surface. Previously, during the Oligocene pulse, while material and thermal inputs from the upper mantle were requisite to generate the widespread crustal partial melting and silicic ignimbrite flare-up, an extensive zone of silicic magma generation would have acted as a density barrier to the mafic magmas, preventing their substantial eruption.

Relationship of Silicic Large Igneous Province Magmatism to Gulf of California Rifting

Sierra Madre Occidental silicic volcanism and opening of the Gulf of California have previously been considered two separate phenomena. This has mainly been due to two linked reasons. The first is that despite different models of opening (see review in Fletcher et al., 2007), rifting to open the Gulf of California has been considered to have developed rapidly following cessation of subduction of the Guadalupe and Magdalena plates at about ca. 12.3–12.5 Ma (Stock and Hodges, 1989; Ferrari et al., 2007; Fletcher et al., 2007; Lizarralde et al., 2007; Umhoefer, 2011; Sutherland et al., 2012). Secondly, the margins of the Gulf of California were the site of eruption of distinctive, albeit

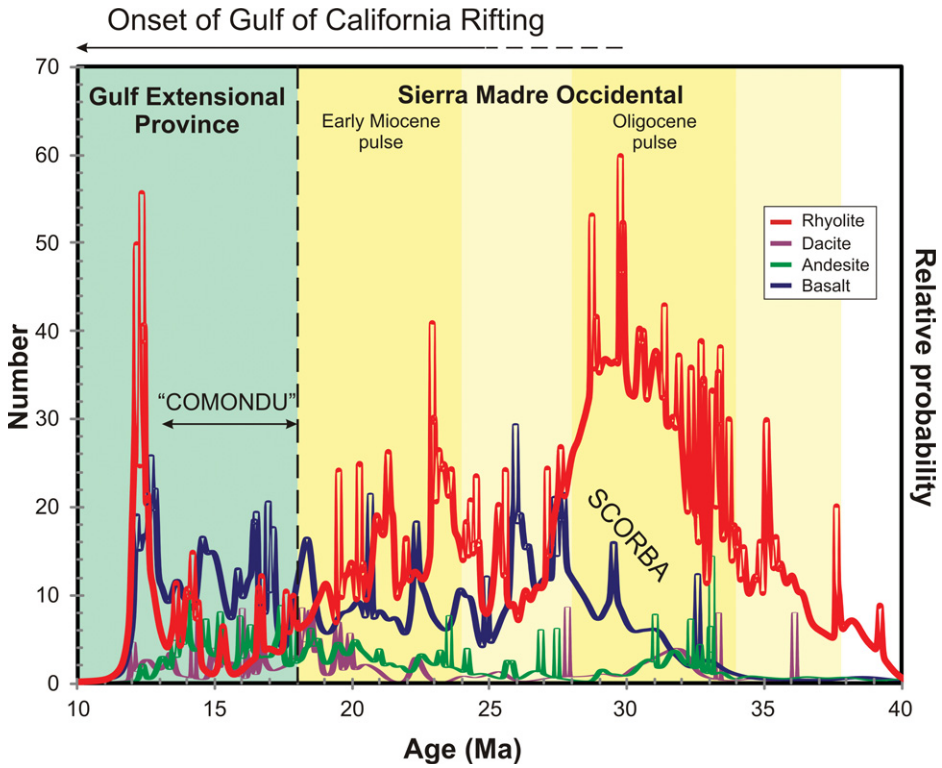

Figure 7. Probability density plot of igneous ages from western Mexico for the period 40–12 Ma. Dated rocks have been grouped into four main compositional groupings: basalt (includes basaltic andesites and tholeiitic, calc-alkaline and rare alkaline varieties), andesite, dacite, and rhyolite (includes high-silica rhyolites and rare peralkaline compositions). Important features of the diagram are: (1) the silicic-dominant character of the Oligocene Sierra Madre Occidental pulse; (2) the appearance of basalts (Southern Cordilleran Basaltic Andesite [SCORBA] of Cameron et al., 1989) during the Oligocene silicic ignimbrite pulse and an increase in the frequency of basaltic eruptions up to the start of the early Miocene pulse ca. 25–24 Ma; (3) the bimodal character of the early Miocene pulse; (4) the increase in andesitic compositions beginning ca. 20 Ma until ca. 14 Ma; and (5) the abrupt decline in rhyolite magma generation and eruption beginning ca. 19–18 Ma, when dacite-andesite eruptions were more predominant, representing the Comondú period of igneous activity centered on the Gulf of California. Figure is modified from Bryan et al. (2013); age data were plotted using Isoplot (Ludwig, 2003).

relatively volumetrically minor, andesitic volcanic rocks in the early to middle Miocene (the Comondú arc; Hausback, 1984; Sawlan and Smith, 1984; Sawlan, 1991; Umhoefer et al., 2001). This andesitic magmatism was widely interpreted to mark the termination of the Sierra Madre Occidental, and its broad zone of silicic-dominant magmatism and extension beginning ca. 40 Ma (Fig. 7), and the re-establishment of typical suprasubduction-zone arc magmatism (e.g., Ferrari et al., 2007). Consequently, magmatism and Oligocene–early Miocene extension observed in the Sierra Madre Occidental were thought to be temporally separated from Gulf of California opening by a suprasubduction-zone volcanic arc occupying the site of the future Gulf of California (Fig. 5).

New studies have questioned the nature and tectonic setting of the middle Miocene andesitic volcanism (Bryan et al., 2013). Several dating studies from the Sierra Madre Occidental, the Gulf of California margins and Baja California indicate bimodal volcanism of the early Miocene pulse continuing to ca. 17 Ma (Hausback, 1984; Martín-Barajas et al., 2000; Umhoefer et al., 2001; Drake, 2005; Bryan et al., 2008; Ferrari et al., 2012; Ramos Rosique, 2013). However, the onset of "arc" volcanism along Baja California has been interpreted at ca. 19.5 Ma (Umhoefer et al., 2001), whereas others have suggested that "arc" volcanism began earlier in northern Baja California at ca. 21 Ma (e.g., Martín-Barajas et al., 1995). These new age data also indicate that, regionally, mafic to weakly bimodal volcanism continued during the middle Miocene, although at much lower intensity (Fig. 7). Consequently, this age overlap suggests no abrupt termination to Sierra Madre Occidental bimodal volcanism (and extension) when rejuvenation of suprasubduction-zone arc volcanism was apparently initiated, despite some of the bimodal and andesitic volcanism spatially overlapping. Nevertheless, a strong compositional shift from dominant bimodal volcanism to more intermediate-composition volcanism beginning ca. 19 Ma is evident, as is a concentration of volcanic activity around the future position of the Gulf of California (Figs. 5 and 7).

The onset of extension in the Gulf Extensional Province, a region of Basin and Range–style extension bordering the Gulf of California (Henry and Aranda-Gomez, 2000), was thought to have been ca. 13–12 Ma, being associated with the termination of subduction along this part of the western North American plate boundary (e.g., Stock and Hodges, 1989; Henry and Aranda-Gomez, 2000; Umhoefer, 2011). Recent studies along the southeastern and eastern margins of the Gulf of California through Sinaloa and Nayarit, however, have revealed that kilometer-thick ignimbrite sections of the Sierra Madre Occidental, dated to as young as 20 Ma, have been tilted by up to 35°. These large tilt blocks of Sierra Madre Occidental ignimbrite face a low-relief coastal plain where flat-lying and undeformed basaltic lava fields distributed for at least 700 km along the eastern margin of the Gulf of California were emplaced between 12 and 9 Ma (Fig. 5; Ferrari et al., 2012; see also Gastil et al., 1979). Similar-aged basalts have also been dredged from the submerged continental margins to the southern Gulf of California (Ferrari et al., 2012).

The fundamental implication of these structural-eruption timing relationships is that large-magnitude extension instrumental to successful rifting of the Gulf of California must have occurred between ca. 25 and 12 Ma. Along the southeastern Gulf of California margin, this extension must have postdated the final phases of bimodal and ignimbrite-dominant activity of the early Miocene pulse of the Sierra Madre Occidental (ca. 20–18 Ma), and preceded the widespread eruption of flat-lying, (undeformed) transitional intraplate basaltic lavas along the eastern margin of the gulf (Fig. 5). Importantly, most of the observed variation in crustal thickness across the region (Fig. 5) must also have been achieved by this time, occurring prior to the termination of subduction along the plate boundary at ca. 12 Ma and emplacement of the intraplate basaltic lava fields along the eastern Gulf of California coast (Bryan et al., 2013). Consequently, the period of enhanced andesitic volcanism during the middle

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Miocene (ca. 20–12 Ma) was spatially and temporally coincident with this extension and crustal thinning, which was principally localized in space and time around the nascent Gulf of California, and where crustal thicknesses were being reduced by up to 50%.

The middle Miocene period of andesitic volcanism is now alternatively interpreted to be a consequence of the active extensional environment. By ca. 18 Ma, rift modes had changed from wide to narrow as extension became focused in the Gulf of California region (Fig. 8). Several early Miocene grabens that had formed to the east were magmatically abandoned by ca. 18 Ma (Ferrari et al., 2002; Ramos Rosique, 2013). Bimodal magma systems, which had been active across the Gulf of California region (Ferrari et al., 2012), were now being more actively disrupted by extensional faulting, which was promoting large-scale magma mixing (Bryan et al., 2013) and the generation of intermediate magma compositions (e.g., Johnson and Grunder, 2000). This switch had an important effect on silicic magma generation rates, which appear to have significantly decreased during this period as mafic magma inputs to the crust became more focused in the gulf region, where eruption tendency increased (Fig. 7).

In summary, new age, stratigraphic, and structural data are confirming a spatial-temporal overlap and connections between silicic large igneous province volcanism of the Sierra Madre Occidental and extension that led to the opening of the Gulf of California. Like other large igneous provinces, the Sierra Madre Occidental igneous record was pulsed, with the early Miocene pulse clearly synrift in character (Ferrari et al., 2002, 2012; Murray et al., 2010; Ramos Rosique, 2013). As extension rate increased and/or became focused on the gulf region at ca. 18 Ma, this had a profound effect on magmatism, which was greatly reduced or switched off at the regional scale, but continued locally in and around the gulf. Here, the active extensional faulting modified erupted magma compositions, which were dominantly intermediate, and eruption styles became dominantly effusive, producing lavas and domes. At the same time, eruptive volumes were lowered as a consequence of reduced rates of crustal partial melting, which had been required to produce the large volumes of rhyolite that had previously dominated the Oligocene and early Miocene pulses of the Sierra Madre Occidental. Crustal rupturing to open the Gulf of California and form the Baja California microplate took at least 25 m.y., a time span comparable to the opening of the Red Sea (Menzies et al., 1997).

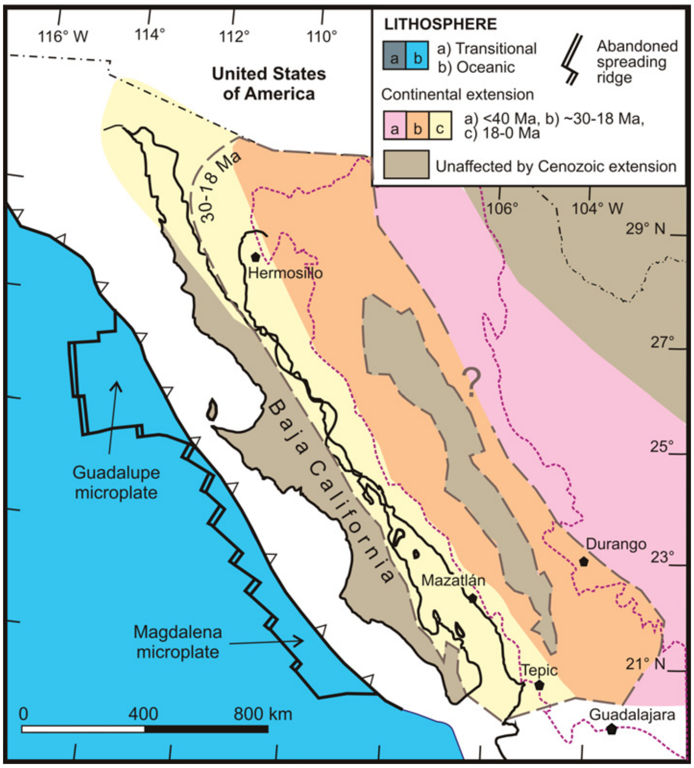

Figure 8. Space-time map of northwestern Mexico showing the progressive switch from wide rift and silicic-dominant to bimodal volcanic modes from ca. 30 Ma to 18 Ma, to a narrow rift and intermediate composition volcanic mode after 18 Ma focused on the current site of the Gulf of California. Dashed purple line denotes current extents of Sierra Madre Occidental Oligocene–early Miocene volcanism on mainland Mexico (see Fig. 5).

Crustal Melting and Igneous Recycling

Many previous studies have emphasized the fundamental role of crustal partial melting to generate the observed volumes and geochemical characteristics of the flood rhyolites that comprise silicic large igneous provinces (e.g., Ewart et al., 1992; Pankhurst and Rapela, 1995; Riley et al., 2001; Ferrari et al., 2007; Bryan, 2007; Bryan et al., 2008). The main controlling factor in the generation of large igneous province volumes of rhyolite, rather than basalt, is crustal setting (Bryan et al., 2002). The Phanerozoic silicic large igneous provinces, for example, are all restricted to continental margins, where fertile, hydrous lower-crustal materials (graywacke, andesite; e.g., Tamura and Tatsumi, 2002; Clemens et al., 2011) were built up by long-lived subduction. Large-scale and sustained mantle thermal and material inputs into the crust generate widespread crustal partial melting of these hydrous crustal materials and igneous underplate formed during previous episodes of subduction. The generation and accumulations of those melts within the crust will act as density barriers to the rise of flood basaltic magma. Additional basaltic magma fluxes from the mantle will provide additional heat for further crustal melting, and this concept supports interpretations that basaltic magmas erupted in large igneous provinces can also have significant crustal melt contributions (Carlson and Hart, 1987; Coble and Mahood, 2012). Consequently, the potentially widespread silicic melt density barrier that develops promotes mafic magma intrusion and crustal ponding and inhibits a substantial and more typical mafic surface expression for large igneous province events along paleo- and active continental margins (Bryan et al., 2002; Bryan, 2007). This has recently led to the notion that silicic large igneous provinces represent "hidden mafic large igneous provinces," where the mafic-ultramafic magmatic component becomes stalled in the lower crust (Ernst, 2013).

A new discovery from recent U-Pb zircon chronochemical data for Sierra Madre Occidental rhyolites has been the identification of a very distinctive zircon age and chemical signature for the synextensional early Miocene rhyolites (Bryan et al., 2008; Ferrari et al., 2012;

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Ramos Rosique, 2013). Most igneous zircons typically have U concentrations between 100 and 2000 ppm (e.g., Harley and Kelly, 2007), but many of the dated early Miocene rhyolites contain zircons showing many orders of magnitude variation in U concentrations that range up to ~1.5 wt% U (~15,000 ppm). The chemical variation is commonly age related, with the youngest zircons showing the highest U and Th enrichments (Bryan et al., 2008). However, standard statistical treatments of the concordant age populations (e.g., Isoplot; Ludwig, 2003) fail to provide geologically reasonable emplacement age estimates for the rhyolites. The high mean square of weighted deviates (MSWD) values and polymodal age distributions, coupled with the extreme chemical variation, indicate substantial zircon inheritance. Recognition of zircon inheritance and the magnitude of inheritance is difficult because of often subtle age differences amongst the dated populations and because individual zircon grain ages overlap with the general duration of Sierra Madre Occidental igneous activity (i.e., 38–18 Ma; Bryan et al., 2008). A key approach to recognizing inheritance and confirming the magnitude of inheritance has been a "double-dating" approach by pairing the U-Pb zircon ages with $^{40}Ar/^{39}Ar$ feldspar or biotite ages from the same sample, supported by detailed stratigraphic information (Bryan et al., 2008; Ferrari et al., 2012; Ramos Rosique, 2013). The key assumption of the double-dating approach has been that the $^{40}Ar/^{39}Ar$ ages constrain the eruption age and serve as a reference age for the U-Pb zircon age data. Recent studies have recognized age discrepancies between the two dating techniques of up to 8 m.y., which are well outside the analytical errors of the two techniques (Bryan et al., 2008; Ferrari et al., 2012; Ramos Rosique, 2013). Lithologically, many of the samples showing the strongest age discrepancies are crystal-poor rhyolite to high-silica rhyolite lavas/domes, and thus represent relatively small-volume magma batches. The zircon population ages are consistently older than the corresponding $^{40}Ar/^{39}Ar$ age, and this leads to the conclusion that the majority, if not all, of the zircons present in these silicic magmas are inherited and antecrystic (Bryan et al., 2008). The ages of the antecrystic zircons indicate that they have been derived from mostly solidified plutonic rocks formed during earlier phases of silicic magmatism. The zircon chemistries give insight into the degree of differentiation of the remelted igneous rocks, and the high-U zircon subpopulations indicate highly fractionated igneous rock representing a component of the source region undergoing remelting. Additional outcomes of these studies are that these antecrystic zircon-bearing rhyolites:

(1) represent Zr-undersaturated magmas, where little to no new zircon crystallized prior to eruption;

(2) may contain other inherited crystal populations (e.g., feldspar, apatite);

(3) have most likely been generated and emplaced rapidly, based on zircon dissolution modeling (Bryan et al., 2008), which is a finding from studies of other rhyolitic magmatic systems (e.g., Charlier et al., 2005); and

(4) show A-type geochemical signatures (Ramos Rosique, 2013).

These age data thus indicate that while, at the first-order, silicic large igneous provinces, like the mafic large igneous provinces, record new crustal additions from the mantle through basaltic underplating and intrusion, and potentially substantial igneous crustal thickening (Fig. 5), with time, much of the silicic igneous activity instead reflects significant crustal remelting and recycling. This is also a feature of continental flood basalt provinces, where some workers have interpreted the origin of the associated flood rhyolites to be due to crustal remelting, including the basaltic igneous underplate (e.g., Garland et al., 1995; Ewart et al., 2004; Miller and Harris, 2007). For the Sierra Madre Occidental, rhyolites with high antecrystic zircon contents appear to be characteristic of the early Miocene pulse, but they do not dominate the zircon age populations of ignimbrites related to the Oligocene pulse. While zircon inheritance is present in the Oligocene ignimbrites, these inherited zircons are more xenocrystic in character, being sourced largely from Mesozoic and older crustal materials (Bryan et al., 2008). This difference in zircon inheritance between the two silicic volcanic pulses may reflect a long-term trend in changing crustal source regions for the silicic magmas. The dominance of antecrystic zircons, often with highly fractionated chemistries, indicates derivation from plutonic rocks emplaced at mid- to upper-crustal levels, whereas Mesozoic to Proterozoic xenocrystic zircons in the Oligocene ignimbrites may reflect derivation from partially melted lower-crustal source regions (Bryan et al., 2008).

A key question then is: What promoted crustal partial melting at mid- to upper-crustal levels in the early Miocene, where crustal lithologies had apparently become volumetrically dominated by young igneous rocks? Many of the antecryst-rich early Miocene rhyolites occur as domes or lavas emplaced along synvolcanic normal faults defining grabens and half grabens, or they occur as fissure-fed ignimbrites fed from these synvolcanic extensional fault systems (Bryan et al., 2008; Ferrari et al., 2012; Murray et al., 2010; Ramos Rosique, 2013). Spatially and temporally associated with these rhyolites, basaltic lavas and dikes also appear to have been fed from graben-bounding fault structures (Ferrari et al., 2002, 2012; Ramos Rosique, 2013). The active extensional faulting therefore appears to have been fundamental to generating much of the silicic volcanism in the early Miocene pulse of the Sierra Madre Occidental. The working hypothesis that requires further examination is that synvolcanic extension allowed basaltic magmatism to invade higher structural levels in the crust and cause remelting of largely Oligocene granitic rocks residing in the middle to upper crust. Here, relatively small volumes of rhyolite magma were generated rapidly and ascended quickly because of the active extensional regime. As suggested for synextensional volcanism in the western United States, the active faulting may have promoted degassing of magmas and thus more effusive eruptive styles (e.g., Gans et al., 1989; Axen et al., 1993). However, in the Sierra Madre Occidental, the differentiated and potentially degassed plutonic source rocks may also have contributed to generating gas-poor silicic magmas that promoted effusive eruption.

CONCLUSIONS

Large igneous provinces record episodic, but commonly multiple synchronous major mantle melting events during which large volumes (10^6 to 10^7 km^3 at the provincial scale; >10^8 million km^3 for event clusters or periods of supercontinent breakup) of mafic, and generally subordinate silicic and ultramafic, magmas were generated and emplaced by processes distinct from those observable at modern plate boundaries, and predicted in a simple way by plate-tectonic theory. This anomalous igneous volume is aided by an elevated frequency of large-volume eruptions or supereruptions during large igneous province events, where individual eruptions of basaltic and silicic magma commonly range from hundreds of cubic kilometers up to ~10,000 km^3 in volume, such that large igneous provinces are the only known locus of basaltic supereruptions on Earth (Thordarson et al., 2009; Bryan et al., 2010).

Research over the past 25 yr has focused on several aspects of large igneous provinces, often raising more questions than have been answered. These aspects include:

(1) Large igneous provinces in the geologic record. A terrestrial large igneous province record has been interpreted as far back as 3.79 Ga (Isley and Abbott, 1999, 2002; Ernst and Buchan, 2001), and an older and better-preserved record of large igneous provinces may occur on the inner planets (Head and Coffin, 1997). A long-term average of ~1 large igneous province every

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20 m.y. has been estimated (Ernst and Buchan, 2002), but the lack of an oceanic large igneous province record older than 200 Ma, and the increasing fragmentation of Paleozoic to Archean large igneous provinces by erosion and tectonism hinder efforts to constrain whether this long-term average has remained constant (Prokoph et al., 2004) or changed over Earth history. Importantly, the Late Proterozoic and Phanerozoic record highlights a strong clustering of large igneous province events, coinciding with supercontinent cycles.

(2) Large igneous provinces and continental breakup. Most large igneous province events are spatially and temporally linked to supercontinent cycles and their breakup (Fig. 1). Volcanic rifted margins are a major expression of supercontinent breakup, with up to 90% of the present-day rifted margins that developed in response to Pangea breakup being characterized by large igneous province magmatism. In some cases, the onset of new seafloor spreading may be delayed by up to 50 m.y. from the onset of large igneous province magmatism, preventing a recognition of clear links between the magmatism and subsequent ocean basin–forming processes. Not all large igneous provinces are succeeded by continental breakup, however, and the reasons why some large igneous provinces are torn apart and others are not remain unclear. Based on the breakup history of Pangea, greater proportions of large igneous provinces unrelated to breakup appear to occur during and initially after supercontinent assembly (Groflin and Bryan, 2012).

(3) Large igneous province clusters. Large igneous province events are not evenly distributed over geologic time, and even during periods of higher frequency, such as the breakup stage of supercontinents, multiple, temporally coincident but spatially separate large igneous province events have occurred (large igneous province cluster). Volumetrically, the largest known cluster of large igneous province events began ca. 120 Ma, when a volume of ~100 million km^3 of magma was added to the lithosphere. Put in perspective, this is equivalent to half the crustal volume of the Australian continent or ~1.5% of the total estimated volume of continental crust (Cogley, 1984) forming within 30 m.y. While the clustering of large igneous province events is strongly linked to supercontinental breakup, rather surprisingly, a very poor correlation exists between large igneous province clustering and the magnitude of these events with mass extinctions.

(4) Large igneous provinces and crustal growth. Large igneous provinces represent substantial but episodic additions of juvenile crust, such that the crust has had periodic growth spurts in addition to more steady-state growth by subduction processes (cf. Cawood et al., 2013). Large igneous provinces have large and extensive volcanic expressions, but the nature and volume of the associated intrusive underpinnings are less well known and are poorly constrained. Previous studies have estimated that the intrusive component to a large igneous province may be up to ten times the extrusive volume, and the tremendous crustal thicknesses developed for oceanic plateaus support this (e.g., Coffin and Eldholm, 1994). The contribution of large igneous provinces to crustal growth will often be absent in zircon-based studies (e.g., Condie, 1998; Condie et al., 2009, 2011; Cawood et al., 2013) because the flood basalts will almost always remain zircon undersaturated. However, it remains underappreciated that the silicic large igneous provinces will make major contributions to detrital zircon records. This is because the volumetrically silicic-dominant magmas are typically zircon saturated and contain abundant zircon, and the eruptive processes result in tremendous volumes of dominantly sand-grade pyroclastic material that can easily be resedimented and dictate the sediment provenance of many large basins (e.g., Bryan et al., 1997, 2012). While the best known examples of silicic large igneous provinces are found in the Phanerozoic (Bryan et al., 2002; Bryan, 2007), there is no reason why they would not also have occurred extensively in the Proterozoic and Archean.

(5) Large igneous provinces and mass extinctions. As a result of an improved understanding of the location, dimensions, age, and volcanic aerosol budgets of large igneous provinces, there is a growing consensus that large igneous province eruptions can cause environmental and climatic effects that are sufficiently severe to trigger mass extinctions (Wignall, 2005). Key aspects underpinning this are an improved understanding of the frequency and magnitude of basaltic and silicic supereruptions from large igneous provinces (Bryan et al., 2010), the environmental setting of the large igneous province (e.g., Svensen et al., 2004), and the substantial aerosol and ash budgets emitted (e.g., Self et al., 2005; Svensen et al., 2009; Cather et al., 2009; Black et al., 2012). However, many uncertainties and challenges remain to demonstrate that the onset and peak eruptions of large igneous provinces coincide with all extinction events, to determine the kill mechanism(s), and to integrate their effects on land and in the oceans, where the kill mechanisms may be different and multiple (e.g., Archibald et al., 2010). While most attention has been given to quantifying the aerosol budgets of large igneous province eruptions, issues still exist on the ways in which flood basaltic eruptions can sustain aerosol delivery to the stratosphere for maximum climatic effect over the eruption duration (years to decades).

(6) Large igneous provinces and mineral and energy resources. Large igneous provinces are major repositories for a range of orthomagmatic ore deposits, in particular PGEs and Cu-Ni sulfide mineralization. Given the tremendous heat fluxes associated with large igneous province magmatism, large ore-forming hydrothermal systems can also develop (Pirajno, 2007), and the silicic large igneous provinces are host to precious metal hydrothermal ore deposits. Large igneous province magmatism is also integral to many sedimentary basins, with the igneous rocks and emplacement processes exerting a major control on petroleum prospectivity. As petroleum exploration extends into deeper-water regions along rifted continental margins, future efforts will be required to reduce "volcanic risk"; volcanism can significantly impact reservoir presence and effectiveness, depending on its timing and mode of emplacement (i.e., intrusive or extrusive).

(7) Planetary large igneous provinces. Large igneous province–scale magmatism is now recognized on the Moon and inner planets. These examples can provide important constraints on terrestrial large igneous province origins because of their near-intact preservation due to minimal erosion rates and the lack of plate tectonics. Several flood basaltic lavas, the products of M >8 supereruptions, have also been mapped out. A variety of planetary igneous provinces have been identified that morphologically represent analogues to terrestrial large igneous province types; these include lunar maria and terrestrial continental flood basalts, mafic igneous crustal plateaus on Venus and terrestrial oceanic plateaus, rift-dominated volcanic rises on Mars and Venus and terrestrial volcanic rifted margins, and extensive radial grabens and ridges on Mars and dike swarms on Earth. Silicic large igneous provinces, however, appear to be absent from the other planets due to the absence of plate tectonics and subduction, which are required to build up hydrated crust for later partial melting. While the areal extent and inferred volume of planetary large igneous provinces are large, covering >5% of the surface area of each planet, few constraints currently exist on the absolute age and duration of the igneous activity and whether they record geologically rapid (<50 m.y.) events as on Earth, or if they are the end product of prolonged planetary mantle melting events lasting 10^8–10^9 m.y.

(8) Large igneous provinces and mantle geodynamics. Large igneous provinces have become integral to our understanding of mantle dynamics, and, along with hotspots, they potentially provide samples of, and windows into, the

lower mantle. Large igneous provinces have almost become synonymous with mantle plumes in the literature. It is widely accepted that large igneous provinces record major mantle melting events, but significant debate over the past 15 yr has largely become polarized into models proposing an origin from core-mantle boundary–derived mantle plumes (e.g., Campbell, 2007), or from shallow processes controlled by stress, plate tectonics, and upper-mantle fertility (e.g., Foulger, 2007). Large igneous provinces show a sufficient commonality and suite of features (Bryan and Ernst, 2008) that distinguish them from magmatism generated at modern plate boundaries, and this leads to the conclusion that a common process promoting excess and rapid mantle melting exists in their formation. At present, existing models remain unsatisfactory in explaining the key geologic features of *all* large igneous provinces, and, in particular, contrasts exist between models for oceanic and continental large igneous provinces and between those formed in the interiors and on the margins of continents.

(9) Silicic large igneous provinces. These represent a new class of large igneous provinces recognized in the past 25 yr, where the scale of the silicic magmatism is similar to the better-known continental flood basalt provinces and basaltic volcanic rifted margins, and eruptive volumes are an order of magnitude larger than silicic volcanism generated in arc-rift to backarc extensional settings (Bryan et al., 2002). The large volumes of rhyolite generated in these events require partial melting of the crust, and this is achieved by the underplating and intrusion of large igneous province–scale intraplate basaltic magmas, and thus silicic large igneous provinces can be thought of as "hidden" mafic large igneous provinces (Ernst, 2013). The Sierra Madre Occidental of western Mexico is the most recent silicic large igneous province event, and new research is revealing important links and feedbacks among the volcanism, extension, and continental rupture that recently opened the Gulf of California. In particular, the large-volume silicic volcanism coincided with wide rifting, but a change to a narrow rift mode resulted in the termination of large-volume silicic volcanism and a change in eruptive styles and to more intermediate magma compositions, promoted by the interaction between bimodal magma systems and active extensional faulting (Bryan et al., 2013). In addition, long-term temporal-compositional trends in the silicic magmas suggest a greater degree of crustal recycling as basaltic magmas penetrated higher crustal levels as extension proceeded to partially remelt igneous rocks formed during earlier phases of the silicic large igneous province (Bryan et al., 2008).

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