

LARGE IGNEOUS PROVINCES AND SCIENTIFIC OCEAN DRILLING

STATUS QUO AND A LOOK AHEAD

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A rich mosaic of disparate crustal types characterizes the Earth beneath the sea. Although “normal” oceanic crust approximately 7-km thick is by far the most prevalent, abnormally thick oceanic-type crust of large igneous provinces (LIPs) also forms a significant component of the marine realm (e.g., Coffin and Eldholm, 1994; Mahoney and Coffin, 1997; Saunders, 2005). Sci-

entific ocean drilling has significantly advanced understanding of LIPs. Herein we focus on significant outcomes of ten LIP-dedicated expeditions between 1985 and 2000 and also highlight prospects for future drilling efforts. The ten expeditions include three to the volcanic margins of the North Atlantic Tertiary Igneous Province, four to the Kerguelen Plateau/Broken Ridge LIP in the Indian

Ocean, two to the Ontong Java Plateau in the western equatorial Pacific Ocean, and one to the Chagos-Maldives-Laccadive Ridge and Mascarene Plateau in the Indian Ocean (Table 1). Complementary geophysical and/or onshore geological investigations have added significant value to all of these expeditions.

Terrestrial LIPs are massive and rapid crustal emplacements of predominantly mafic (Fe- and Mg-rich) rock that did not form by seafloor spreading or subduction (Coffin and Eldholm, 1994). LIPs may be the dominant type of magmatism on other terrestrial planets and moons of the solar system (e.g., Head and Coffin, 1997). On Earth, LIP rocks are readily distinguishable from mid-ocean ridge and subduction-related arc rocks on the basis of petrology, geochemistry, geochronology, physical volcanology, and geophysical data. LIPs occur within continents and oceans, and include continental flood basalts in the

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Table 1. Large Igneous Provinces, ODP Legs, and References

Large Igneous Province	ODP Leg	References
North Atlantic Tertiary	104	Eldholm, Thiede, Taylor, et al., 1987, 1989
	152	Larsen, Saunders, Clift, et al., 1994; Saunders, Larsen, and Wise, 1998
	163	Duncan, Larsen, Allan, et al., 1996; Larsen, Duncan, Allan, and Brooks, 1999
Kerguelen Plateau/ Broken Ridge	119	Barron, Larsen, et al., 1989, 1991
	120	Schlich, Wise, et al., 1989; Wise, Schlich, et al., 1992
	121	Peirce, Weissel, et al., 1989; Weissel, Peirce, Taylor, Alt, et al., 1991
	183	Coffin, Frey, Wallace, et al., 2000; Wallace, Frey, Weis, and Coffin, 2002; Frey, Coffin, Wallace, and Quilty, 2003
Ontong Java Plateau	130	Kroenke, Berger, Janecek, et al., 1991; Berger, Kroenke, Mayer, et al., 1993
	192	Mahoney, Fitton, Wallace, et al., 2001; Fitton, Mahoney, Wallace, and Saunders, 2004a, 2004b
Chagos-Maldives-Laccadive Ridge/ Mascarene Plateau	115	Backman, Duncan, et al., 1988; Duncan, Backman, Peterson, et al., 1990

former, and volcanic passive margins, oceanic plateaus, submarine ridges, and ocean-basin flood basalts in the latter (Figures 1 and 2). Transient LIPs and associated persistent, age-progressive volcanic chains (“hot-spot tracks”) are commonly attributed to decompression melting of hot, buoyant mantle ascending from Earth’s interior (e.g., Morgan, 1971) and thus provide a window into mantle processes. Magmatism associated with LIPs currently represents ~ 10 percent of the mass and energy flux from Earth’s deep interior to its surface (e.g., Sleep, 1992). This flux shows distinct episodicity over geological time, in contrast to the relatively steady-state crustal accretion at seafloor spreading

centers (e.g., Eldholm and Coffin, 2000). LIP observations therefore suggest that dynamic, non-steady-state circulation within Earth’s mantle has been important for at least the last 250 million years and probably much longer, and there is a strong potential for LIP emplacements to contribute to, and perhaps even instigate, major environmental changes.

COMPOSITION, PHYSICAL VOLCANOLOGY, CRUSTAL STRUCTURE, & MANTLE ROOTS

The uppermost crust of LIPs is dominantly mafic extrusive rock similar to basalt originating at mid-ocean ridge spreading centers; it most typically is found as gently dipping subaerial or sub-

marine flows. Individual flows can extend for hundreds of kilometers, be tens to hundreds of meters thick, and may have volumes of more than 10^3 km³ (e.g., Tolan et al., 1989). In addition to mafic rock, silica-rich rock occurs in LIPs as lavas, intrusive rocks, and pyroclastic deposits, and is mostly associated with the initial and late stages of LIP magmatic activity (e.g., Bryan et al., 2002). Relative to mid-ocean ridge basalts, LIP basalts are compositionally more diverse (e.g., Kerr et al., 2000), and LIP rocks form in both subaerial and submarine settings.

The maximum crustal thickness, including an extrusive upper crust, an intrusive middle crust, and a lower crustal body, of an oceanic LIP can be as great

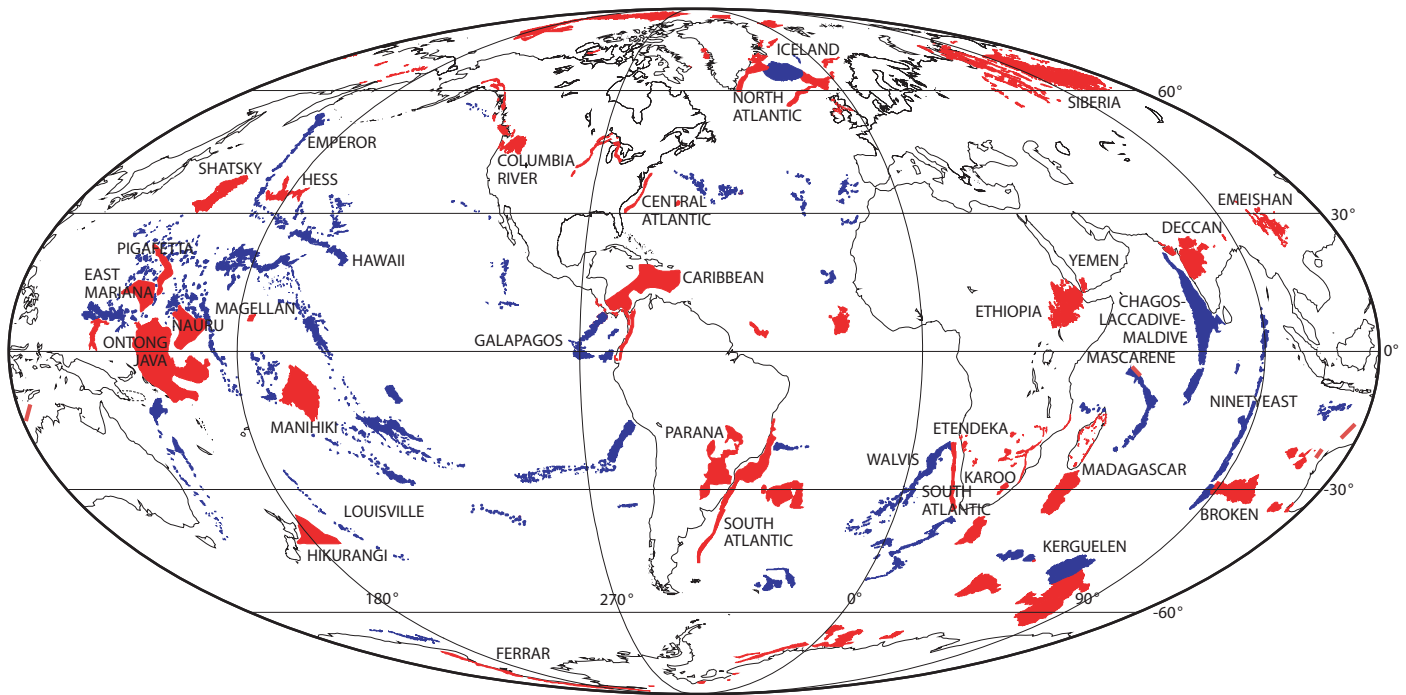


Figure 1. Phanerozoic global LIP distribution, with transient (“plume head”) and persistent (“plume tail”) LIPs indicated in red and blue, respectively. LIPs are better preserved in the oceans where they are not subject to terrestrial erosional processes, offering a prime target for scientific ocean drilling. Modified from Coffin and Eldholm (1994).

as ~ 40 km, determined from seismic and gravity studies of Iceland (Figure 1) (Darbyshire et al., 2000). Nearly all of our knowledge of LIPs, however, is derived from the most accessible lavas forming the uppermost portions of crust. This extrusive upper crust may exceed 10 km in thickness (e.g., Coffin and Eldholm, 1994). On the basis of geophysical, predominantly seismic, data from LIPs, and from comparisons with normal oceanic crust, it is believed that the extrusive upper crust is underlain by an intrusive middle crust, which in turn is underlain by lower crust (“lower crustal body”) characterized by compressional seismic wave velocities of 7.0–7.6 km s⁻¹ (Figure 2). Dikes and sills are probably common in the upper and middle crust.

Seismic wave velocities suggest that the middle crust is most likely gabbroic, and that the lower crust is mafic to ultramafic, and perhaps metamorphic (e.g., Eldholm and Coffin, 2000).

Low-velocity zones have been observed by seismic imaging of the mantle beneath the oceanic Ontong Java Plateau (e.g., Richardson et al., 2000), as well as under the continental Deccan Traps (Kennett and Widiyantoro, 1999) and Paraná flood basalts (Vandecar et al., 1995) (Figure 1). Interpreted as lithospheric roots or keels, the zones can extend to at least 500–600 km into the mantle. In contrast to high-velocity roots beneath most continental areas, and the absence of lithospheric keels in most oceanic areas, the low-velocity zones

beneath these three LIPs apparently reflect residual effects, primarily chemical and perhaps secondarily thermal, of mantle upwelling (Gomer and Okal, 2003). If proven to be common, roots extending well into the mantle beneath oceanic LIPs would suggest that such LIPs contribute to continental initiation as well as continental growth. Instead of being subducted like normal oceanic lithosphere, LIPs may be accreted to the edges of continents, for example, obduction of Ontong Java Plateau basalts onto the Solomon Island arc (e.g., Hughes and Turner, 1977), and terrane accretion of Wrangellia (e.g., Richards et al., 1991) and Caribbean (e.g., Kerr et al., 1997) LIPs to North and South America, respectively.

DISTRIBUTION, TECTONIC SETTING, AND TYPES

LIPs occur throughout the global ocean in purely intraplate settings and along present and former plate boundaries (Figure 1), although the tectonic setting of formation for many features (e.g., Kerguelen Plateau/Broken Ridge and Ontong Java Plateau) is unknown. If a LIP forms at a seafloor-spreading axis, the entire crustal section may be LIP crust (Figure 2a, lower). Conversely, if one forms in an intraplate setting or at a locus of continental breakup, pre-existing crust must be intruded and sandwiched by LIP magmas, albeit to an extent not easily resolvable by current geological or geophysical techniques (Figure 2a, upper, 2c). Volcanic passive margins form by excessive magmatism during continental breakup along the trailing, rifted edges of continents (e.g., Figure 2d; White and McKenzie, 1989). Continental breakup may be accompanied (e.g., North Atlantic), preceded (e.g., Central Atlantic), followed (e.g., Kerguelen Plateau), or unaccompanied by LIP emplacement; passive continental margins span a continuum from magma-poor to volcanic. The deep ocean basins contain three morphologic types of transient LIPs. (1) Oceanic plateaus, commonly isolated from major continents, are broad, typically flat-topped features generally lying 2000 m or more above the surrounding seafloor. They can form at triple junctions (e.g., Shatsky Rise), mid-ocean ridges (e.g., Iceland), or in intraplate settings (e.g., northern Kerguelen Plateau). (2) Submarine ridges are elongated, steep-sided elevations of the seafloor. Some may form along transform plate boundaries (e.g., parts of

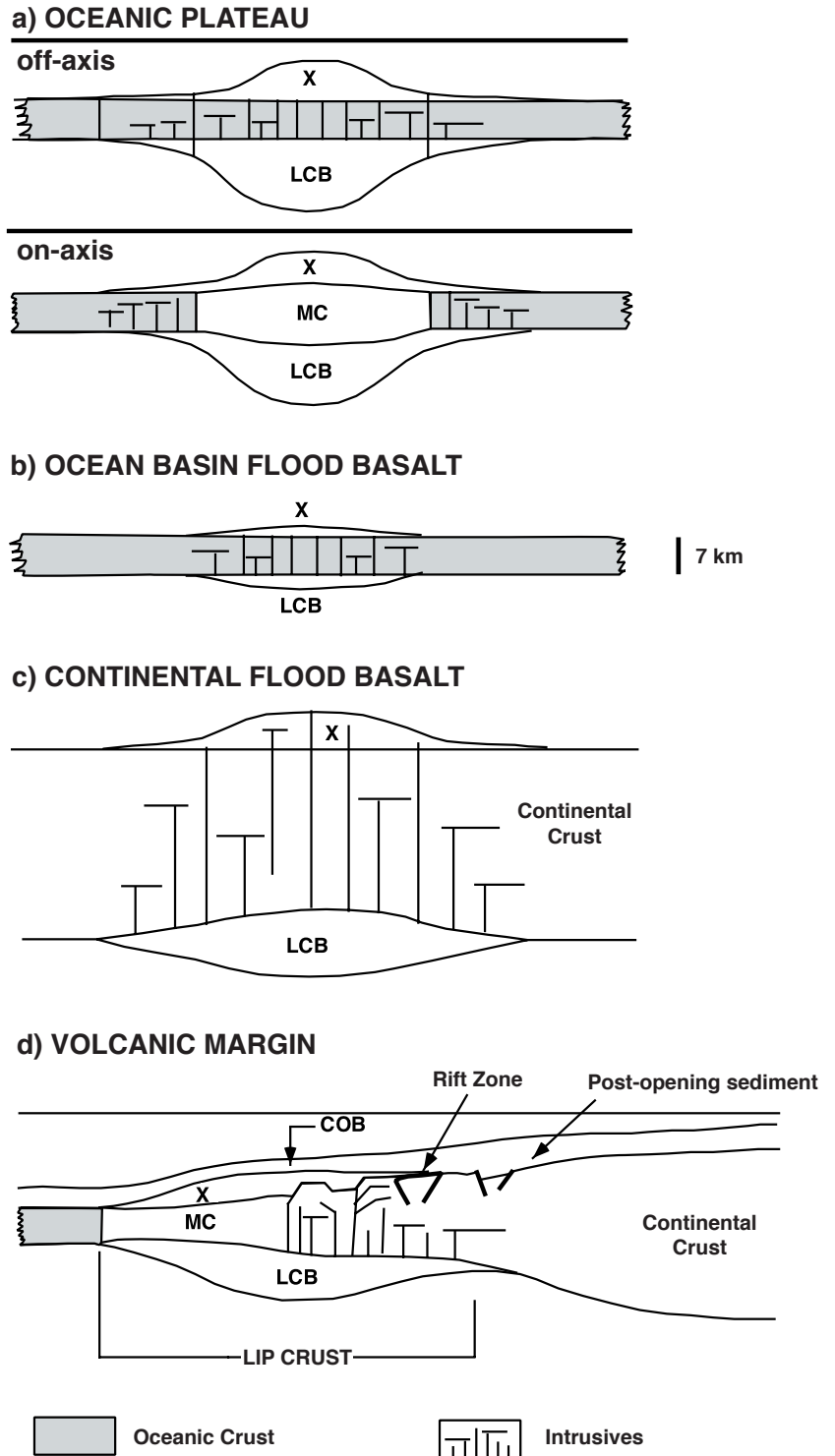


Figure 2. Schematic LIP plate tectonic settings and gross crustal structure. LIPs are emplaced in a variety of plate tectonic settings, yet are characterized by a common three-layer crustal structure, although crustal thickness varies considerably. LIP crustal components are: extrusive upper crust (X), middle crust (MC), and lower crustal body (LCB). Normal oceanic crust, 7-km thick, is gray. Horizontal scale varies from a few hundred to more than a thousand kilometers. Modified from Eldholm and Coffin (2000).

the Ninetyeast Ridge, Chagos-Maldives-Laccadive Ridge, Mascarene Plateau). Oceanic plateaus and submarine ridges are the most enigmatic with respect to the tectonic setting in which they formed. (3) Ocean-basin flood basalts (e.g., Nauru Basin and Caribbean LIP) are the least-studied type of LIP, at least *in situ*, and consist of extensive submarine flows and sills lying above and post-dating normal oceanic crust. In contrast to oceanic plateaus, ocean basin flood basalts do not form topographic plateaus (Figure 2b).

AGES

Age control for marine LIPs is sparse because of their relative inaccessibility, generally low-potassium contents in mafic rocks, and extensive alteration, but

nevertheless the $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating radiometric technique is having a particularly strong impact on studies of LIP volcanism. Geochronological studies of continental flood basalts (e.g., Siberian, Karoo/Ferrar, Deccan, Columbia River; Figure 1) suggest that many LIPs are initially constructed from huge volumes ($\sim 10^5\text{--}10^7 \text{ km}^3$) of mafic magma erupted and intruded into localized regions of the crust over short intervals ($\sim 10^5\text{--}10^6$ years). Subsequently, as observed in the ocean basins, chains of volcanoes associated with LIPs may be constructed over significantly longer intervals ($10^7\text{--}10^8$ years). Transient magmatism during initial LIP formation commonly has been attributed to mantle plume “heads” reaching the base of the lithosphere following transit through

nearly all or only part of Earth’s mantle; persistent magmatism has been considered to result from steady-state mantle plume “tails” penetrating the lithosphere, which is moving relative to the plume (e.g., Richards et al., 1989) (Figures 1 and 3). Although plume models appear to explain the North Atlantic volcanic margins relatively well, both the Ontong Java Plateau (with its lack of significant uplift or subsidence and submarine emplacement environment) and Kerguelen Plateau/Broken Ridge (with its prolonged and voluminous emplacement history) present significant challenges for current versions of plume theory, despite the fact that the latter has been modeled numerically (Farnetani and Samuel, 2005; Lin and van Keken, 2005).

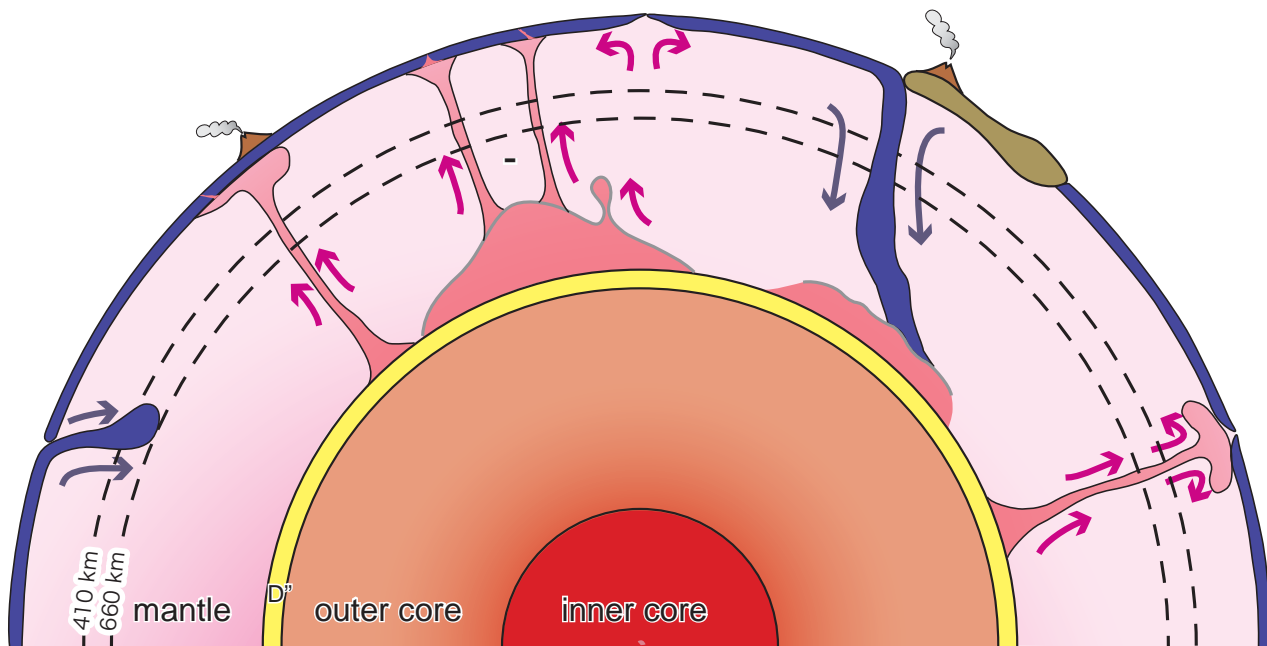


Figure 3. Schematic cross section of Earth depicting sources of LIPs and hot spots and fate of subducting lithosphere. Transient LIPs are believed to originate either from a thermal boundary layer near the core-mantle boundary (D'') or from thermal or mechanical boundary layers associated with large low-velocity zones. Modified from Coffin and Eldholm (1994).

LIPS AND MANTLE DYNAMICS

Transient, rapidly erupted LIPs are not distributed uniformly in time. For example, many LIPs formed between 50 and 150 million years ago, whereas relatively few have formed during the past 50 million years (Figure 4). Episodicity of LIP emplacement likely reflects variations in rates of mantle circulation, perhaps caused by growth and instability of thermal boundary layers in Earth's interior; this episodicity is supported by interpreted high rates of seafloor spreading during a portion of the 50–150-million-year interval, specifically during the long Cretaceous Normal Superchron (~ 120 to ~ 80 million years ago). Thus, although LIPs manifest types of mantle processes distinct from those driving seafloor spreading, waxing and waning rates of overall mantle circulation probably affect both sets of processes.

Although LIPs are commonly ascribed to having originated from mantle upwelling related solely to convection (Figure 3), alternative mechanisms have also been proposed. Some LIPs may result from plate divergence or fracturing above hotter-than-average shallow mantle (e.g., Courtillot et al., 2003). Alternatively, the spatial, if not temporal, association of flood basalts and impact craters on the Moon, as well as limited evidence on Earth, suggests that bolide impacts may result in massive decompression melting of the mantle, accounting for the emplacement of some LIPs, for example, the Ontong Java Plateau (e.g., Ingle and Coffin, 2004). Thus, multiple mechanisms may be required to account for all LIPs, both on Earth and elsewhere in our solar system.

LIPS AND THE ENVIRONMENT

The environmental effects of LIPs likely have been global (e.g., Wignall, 2005), particularly when conditions have been at or near a threshold state. Continental flood basalts, volcanic passive margins, and oceanic plateaus have formed by widespread and voluminous subaerial

basaltic eruptions that released enormous volumes of volatiles such as CO₂, S, Cl, and F. These extensive eruptions likely have caused massive melting of hydrates and explosive methane release where magma intruded carbon-rich sedimentary strata along rifting continental margins (e.g., North Atlantic; Svensen

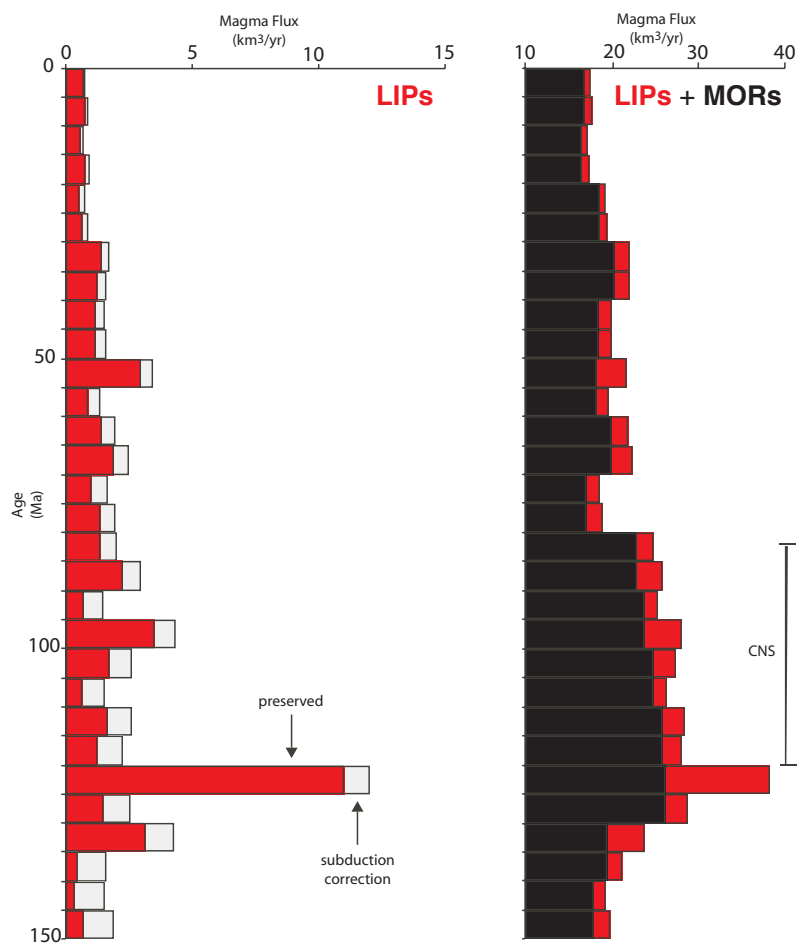


Figure 4. Large igneous province (LIP) magma production, corrected for subduction (left), and summed LIP and mid-ocean ridge (MOR) magma production (right) for the last 150 million years. Overall, mafic magma flux from both LIPs and mid-ocean ridges (MORs) was highest in mid-Cretaceous time. The subduction correction assumes that all oceanic crust is recirculated to the mantle over 200 million years and a constant average LIP 5-million-year production volume over the same period. Note difference in x-axis scales. CNS: Cretaceous Normal Superchron. Modified from Eldholm and Coffin (2000).

et al., 2004) or in subaerial permafrost settings (Figure 5). A key factor affecting the magnitude of volatile release has been whether eruptions were subaerial or submarine; hydrostatic pressure inhibits vesiculation and degassing of relatively soluble volatile components (H_2O , S, Cl, F) during deep-water submarine eruptions, although low-solubility components (CO_2 , noble gases) are mostly degassed even at abyssal depths (e.g., Moore and Schilling, 1973; Dixon and Stolper, 1995).

Another important factor determining the environmental impact of LIP

volcanism has been the latitude at which the LIP formed. In most basaltic eruptions, released volatiles remain in the troposphere. However, at high latitudes (e.g., Kerguelen Plateau), the tropopause is relatively low, allowing larger mass flux (via basaltic fissure eruption plumes for transport) of SO_2 and other volatiles into the stratosphere. Sulfuric acid aerosol particles that form in the stratosphere after such eruptions have a longer residence time and greater global dispersal than if the SO_2 remains in the troposphere; therefore, they have greater effects on climate and atmospheric chem-

istry (e.g., Devine et al., 1984; Stothers et al., 1986). Subaerial eruptions of large volumes of basaltic magma at high-latitude LIPs over relatively brief geological intervals, including phreatomagmatic eruptions (an explosive eruption resulting from the interaction of magma with water) (e.g., Ross et al., 2005), would have increased potential to contribute to global environmental effects.

Highly explosive felsic eruptions, such as those documented from the North and South Atlantic volcanic passive margins, the Red Sea, the Kerguelen Plateau, and continental flood basalts (e.g., Bryan

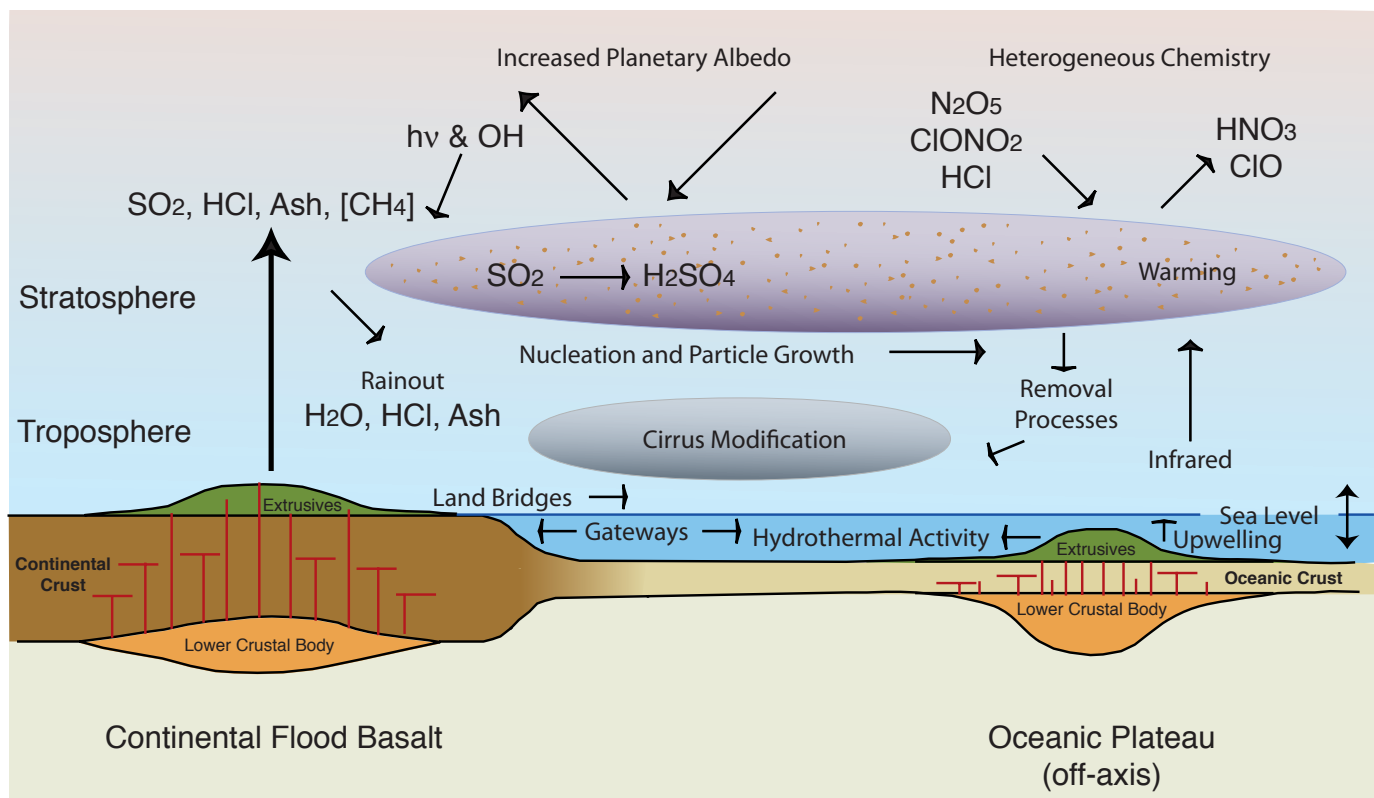


Figure 5. Complex chemical and physical environmental effects associated with LIP formation. LIP eruptions can perturb the Earth-ocean-atmosphere system significantly. Note that many oceanic plateaus form at least in part subaerially. Energy from solar radiation is $h\nu$, where h = Planck's constant, and ν = frequency of electromagnetic wave of solar radiation. Modified from Coffin and Eldholm (1994).

et al., 2002) (Figure 1), have likely also injected both particulate material and volatiles (SO₂, CO₂) directly into the stratosphere. The total volume of felsic volcanic rocks in LIPs is poorly known, but such rocks may account for a small, but important fraction of the volcanic deposits in LIPs. Significant volumes of explosive felsic volcanism would have further affected the global environment (e.g., Scaillet and MacDonald, 2006).

LIP formation may have been responsible for some of the most dramatic and rapid changes in the global environment. Between ~ 145 and ~ 50 million years ago, the global oceans were characterized by chemical and isotopic variations (especially in C and Sr isotope ratios, trace metal concentrations, and biocalcification), relatively high temperatures, high relative sea level, episodic deposition of

black shales (oceanic anoxic events), high production of hydrocarbons, mass extinctions of marine organisms, and radiations of marine flora and fauna. Temporal correlations between the intense pulses of igneous activity associated with LIP formation and environmental changes are far too strong to be pure coincidence (Figure 6)—far stronger, for example, than the association of impacts and mass extinctions. The most dramatic example is the eruption of the Siberian flood basalts ~ 250 million years ago (Figures 1 and 6), which coincided with the largest extinction of plants and animals in the geological record (e.g., Renne and Basu, 1991). Ninety percent of all species became extinct at that time. On Iceland, the 1783–1784 eruption of Laki provides the only historical record of the type of volcanism that constructs transient LIPs

(e.g., Thordarson and Self, 1993). Although Laki produced a basaltic lava flow representing only ~ 1 percent of the volume of a typical (10³ km³) transient LIP flow, the eruption’s environmental impact resulted in the deaths of 75 percent of Iceland’s livestock and 25 percent of its population from starvation.

LIPS—A KEY IODP INITIATIVE

Understanding the formation of LIPs constitutes a first-order problem in Earth science, and as such, is a major, high-priority initiative for the Integrated Ocean Drilling Program (IODP) (Coffin, McKenzie, et al., 2001). Strong evidence exists that many LIPs manifest a form of mantle dynamics not clearly related to plate tectonics; the processes involved in their formation are critically important for understanding both mantle and

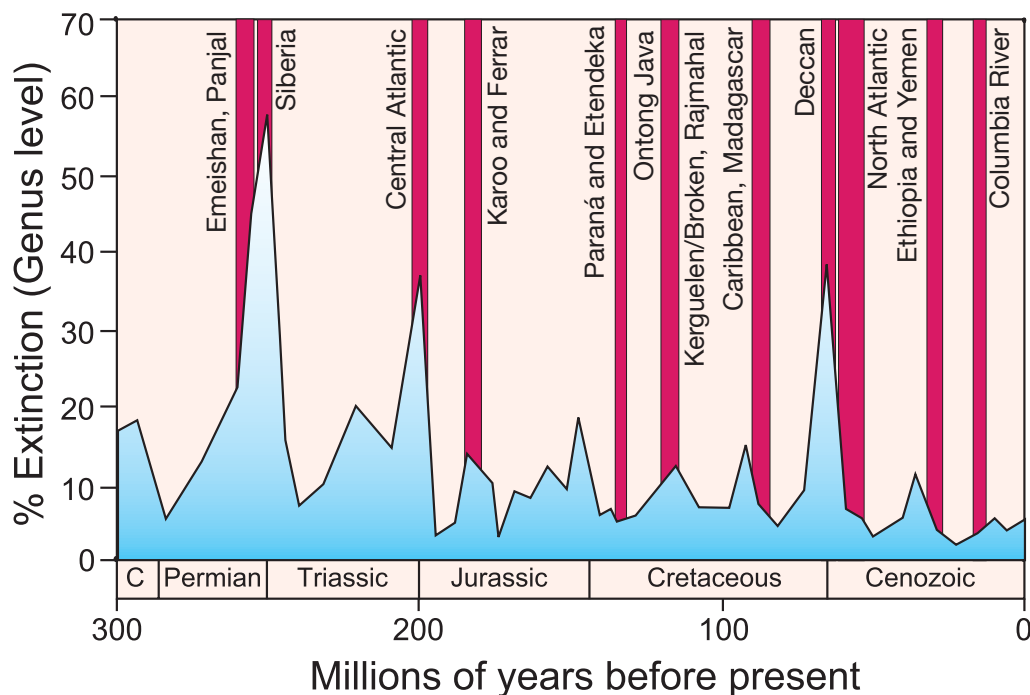


Figure 6. Extinction of marine genera versus time (continuous line, blue field), modified from Sepkoski (1996), compared with eruption ages of LIPs (red columns). Strong temporal correlation between LIPs and mass extinctions suggests causality. Three of the largest mass extinctions—the Permian-Triassic, Triassic-Jurassic, and Cretaceous-Tertiary—coincide with eruption ages of the Siberian Traps, the Central Atlantic Magmatic Province, and the Deccan Traps, respectively. Modified from White and Saunders (2005). See Figure 1 for locations of LIPs.

crustal geodynamics. Many data also suggest that LIPs contribute episodically, at times catastrophically, to global environmental change. Investigating relationships between their emplacements and major environmental changes is crucial for advancing understanding of the Earth system. Nevertheless, we have literally only scratched the surface of 20–40-km thick *in situ* oceanic LIP crust: 0.914 km into igneous crust is the deepest basement penetration of a volcanic passive margin (Norwegian) and 0.233 km is the deepest penetration of an oceanic plateau (Kerguelen). However, in at least one instance globally, 3–4 km of uppermost Ontong Java Plateau crust obducted onto the Solomon Islands (Pettersen et al., 1997) allows direct sampling and study of a thicker section of submarine LIP crust.

The full consequences of LIP formation have only recently begun to be appreciated, and scientific ocean drilling has a critical role in examining the following relationships between LIPs and both Earth and planetary evolution:

- implications for mantle convection and heat loss from the Earth's interior through understanding LIP mass and energy fluxes relative to those of mid-ocean ridges and arcs/backarcs through geologic time,
- interaction of LIP events and the plate tectonic cycle, especially continental rifting and breakup, to evaluate temporal relationships and causalities,
- temporal relationships between LIP events and changes in the reversal frequency of Earth's magnetic field to investigate potential causality,
- compositions of LIP magmatic rocks as “windows” into deep mantle petro-

logy and geochemistry,

- possible role of LIP volcanism as the dominant non-plate-tectonic heat-loss mechanism of all terrestrial planets,
- role of LIPs in the initiation of continents and continental growth,
- physical volcanology that modulates particulate and aerosol release into the oceans and atmosphere, and governs the eruption of basaltic flows covering many thousands of km², to understand paleoenvironmental forcing functions and feedback loops associated with LIPs,
- volatile concentrations in LIP magmas and the volatile load delivered to the oceans and atmosphere, to evaluate potential paleoenvironmental impacts of LIPs,
- trace metal inventory and potential consequences of LIP eruptions for oceanic and atmospheric chemistry, and hence for paleoenvironmental changes,
- possible connections between LIP events and acceleration/retardation of the evolution of life on Earth.

Since 1985, when we first began to focus scientific ocean drilling efforts on oceanic LIPs, we have witnessed exciting advances in LIP-related solid Earth and Earth system studies. In 2007, with the advent of three-platform IODP operations, scientists will have greatly enhanced two- and three-dimensional seismic site surveying (academic and commercial), drilling, logging, and borehole-monitoring capabilities to apply to LIP investigations. These new capabilities are stimulating community development of new strategies for understanding

LIPs, combining observation, sampling, remote and *in situ* data acquisition, and quantitative modeling to address the role of LIPs in planetary evolution. Strategies are also being developed for understanding the microbial ecosystems that may exist where fluids flow within LIP crust. Microorganisms may mediate chemical budgets by catalyzing and deriving energy from a wide variety of geochemical reactions. Scientists from a wide spectrum of Earth science are involved in developing these new research initiatives. Implementation of such ambitious strategies would benefit strongly both from a NASA-style “mission” framework as well as from new collaborative site surveying and drilling relationships between the IODP and industry.

Scientific ocean drilling has played a pivotal role in advancing knowledge of LIPs. In the future, IODP promises to play an even more critical role in identifying and describing the nature and consequences of LIP activity in the evolution of the solid Earth, and of its oceans, atmosphere, and biosphere.

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- www.largeigneousprovinces.org
- www.mantleplumes.org