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How Large Igneous Provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record

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ABSTRACT

Large Igneous Provinces (LIPs) can have a significant global climatic effect as monitored by sedimentary trace and isotopic compositions that record paleo-seawater/atmosphere variations. Improved U-Pb dating (with better than 0.1 Myr resolution) for several LIPs is confirming a long-proposed mass extinction-LIP link. The most dramatic climatic effect is global warming due to greenhouse-gases from LIPs. Subsequent cooling (and even global glaciations) can be caused by CO_2 drawdown through weathering of LIP-related basalts, and/or by sulphate aerosols. Additional kill mechanisms that can be associated with LIPs include oceanic anoxia, ocean acidification, sea level changes, toxic metal input, essential nutrient decrease, producing a complex web of catastrophic environmental effects. Notably, the size of a LIP is not the only important factor in contributuing to environmental impact. Of particular significance are the rate of effusion, and the abundance of LIP-produced pyroclastic material and volatile fluxes that reach the stratosphere. While flood basalt degassing (CO_2, SO_2, halogens) is important (and is also from associated silicic volcanism), a significant amount of these gases are released from volatile-rich sedimentary rocks (e.g. evaporites and coal horizons) heated by the intrusive component of LIPs. Feedbacks are important, such as global warming leading to destabilization of clathrates, consequent release of further greenhouse gases, and greater global warming. In the broadest sense LIPs can affect (or even induce) shifts between Icehouse, Greenhouse and Hothouse climatic states. However, the specific effects, their severity, and their time sequencing is specific to each LIP. Based on the robust array of environmental effects due to LIPs, as demonstrated in the Phanerozoic record, it is suggested that LIP events represent useful time markers in the Precambrian Era as proxies for some significant global environmental changes that are preserved in the sedimentary record.

1. Introduction

The distribution of life through the Phanerozoic and in the Proterozoic is highly discontinuous, primarily driven by environmental changes. The most dramatic and sudden environmental changes are associated with mass extinction events; these define many of the boundaries in the Phanerozoic biostratigraphic time scale (e.g. Gradstein et al., 2012a, 2012b; Ogg et al., 2008, 2016). Less extreme environmental changes and minor extinction events are also recognized by excursions in isotopic proxies for the composition of seawater and atmosphere, in the timing of anoxia events, and by sea-level changes, all reflected in the sedimentary record. This is a fast-evolving vibrant field of research that is increasingly revealing the pivotal role of LIPs in environmental changes, particularly those that are abrupt and of short duration (on the scale of a few million years). In contrast, those broad 10s to 100s of Myr changes recorded in sedimentary rocks are more likely linked to plate-boundary processes. Environmental changes can also be linked to other macro-properties such as changes in solar luminosity, Earth's orbit, and perhaps in the Earth's magnetic field, and due to True Polar Wander (e.g. Van Der Meer et al., 2014; Torsvik and Cocks, 2016). Herein we provide an overview of the environmental impacts of LIPs, and their role as catalysts for faunal and floral collapse and extinction events. Given the robust link that is becoming increasing evident between LIPs and abrupt global climatic change, a final section addresses the utility of LIPs as natural time markers in Precambrian time, where they represent proxies for 'golden spikes' in the sedimentary record that mark key natural boundaries in Earth history.

1.1. Large Igneous Provinces (LIPs)

Large Igneous Provinces (LIPs) represent large volume (>0.1 Mkm^3; frequently above >1 Mkm^3), mainly mafic (-ultramafic) magmatic

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events of intraplate affinity, that occur in both continental and oceanic settings, and are typically of short duration (<5 Myr) or consist of multiple short pulses over a maximum of a few 10s of Myr (Coffin and Eldholm, 1994, 2005; Bryan and Ernst, 2008; Bryan and Ferrari, 2013; Ernst, 2014 and references therein; cf. Sheth, 2007). They comprise volcanic packages (flood basalts), and a plumbing system of dyke swarms, sill complexes, layered intrusions, and a crustal underplate. LIPs can also be associated with silicic magmatism (including dominantly silicic events termed Silicic LIPs, or SLIPs, sometimes including so-called super-eruptions), carbonatites and kimberlites. LIPs occur at a variable rate that averages approximately every 20–30 Myr but with possible peaks associated with supercontinent breakup, back at least to 2.5 Ga (Figs. 1 and 2).The rate of LIP occurrence in the Archean is less certain due to its poorer preservation (Ernst, 2014).

LIPs are systematically linked to continental breakup (or attempted breakup) events, ore deposits of a variety of commodity types (Ernst and Jowitt, 2013), can have an influence on hydrocarbon and aquifers (Ernst, 2014; Jowitt and Ernst, 2016), and in the context of this paper, on global climate change including extinction events (Ernst, 2014). The origin of LIPs has been controversial with a range of mechanisms proposed including: lithospheric delamination, rift related decompression melting, and edge convection (e.g. King and Anderson, 1998; Coffin and Eldholm, 1994, 2005; Foulger, 2007, 2012; Ernst, 2014). However, more accurate age dating (emphasizing the short duration of many of these huge events), the presence of giant radiating mafic dyke swarms, seismic tomography, and compositional data for elevated mantle potential temperatures provide a strong case for a LIP link with mantle plumes whose buoyancy is mainly thermal (e.g. Campbell, 2005; Ernst, 2014 and references therein). A recent paper by Wang et al. (2016) demonstrates a higher rate of water content (1–2 wt%) in the primary magmas and trace element compositions consistent with water-flux contribution to melting for several Phanerozoic LIPs (such as the 251 Ma Siberian Traps, 201 Ma Central Atlantic Magmatic Province (CAMP), 66 Ma Deccan, and 16 Ma Columbia River), suggesting a model in which an upwelling deep mantle plume interacts with subduction-transported water at the mid-mantle boundary.

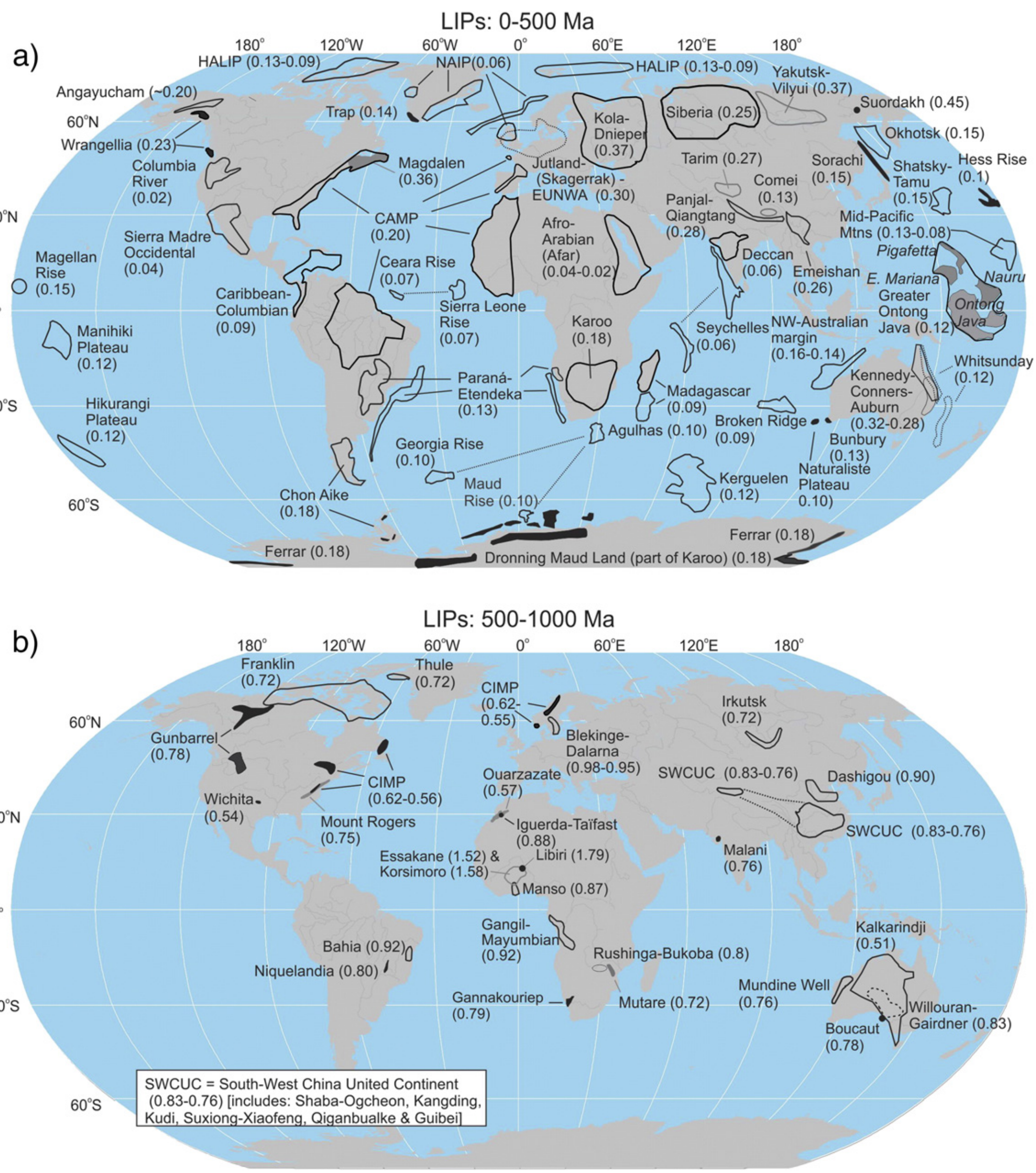

Fig. 1. Part a–e. Generalized distribution of LIPs and interpreted LIP fragments through time, back to 2.5 Ga (updated from Ernst, 2014). Numbers are in Ga. Selected associated silicic LIPs (SLIPs) are shown (i.e. 0.32–0.28 Ga Kennedy-Connors-Auburn, 0.04 Ga Sierra Madre Occidental and 0.12 Whitsunday. Maps are in Robinson Projection.