Driving Global Change One LIP at a Time

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Row of craters made by the 1783–1784 Laki fissure eruption, Iceland, the closest historical analogue to a LIP flood basalt eruption. Photo: Anne Schöpa.

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Earth's history has been punctuated by extraordinary magmatic events that produced large igneous provinces (LIPs). Many LIPs induced global changes, including millennial-scale warming, terrestrial and oceanic mass extinctions, oceanic anoxic events, and even glaciations. Research over the past 20 years has shown that shallow crustal degassing is an important factor contributing to the environmental impact of LIPs. Contact metamorphism in sedimentary basins can generate huge gas volumes, and operates as a function of magma volume and the architecture of LIP plumbing systems. Numerous open questions remain concerning the role of LIPs in triggering rapid and lasting changes, whose answers require collaboration across geoscientific disciplines. In this issue, we present the status of five key research themes and discuss potential ways forward to better understanding these large-scale phenomena.

Keywords: large igneous province; sedimentary–volcanic basin; magma plumbing system; volatiles; environmental crises

INTRODUCTION

It has been almost 20 years since large igneous provinces (LIPs) were spotlighted as a thematic issue in the first volume of *Elements* in 2005 (vol. 1, no. 5). Since then, the scientific literature on LIPs has proliferated. For example, the term "large igneous province" was cited in the title and/or abstract of 550 original or review articles published in 1989–2005, whereas a staggering 3400 papers were published thereafter (2006–2022), demonstrating the tremendous research efforts that have since been put into understanding the significance of LIPs in Earth history. As the articles in this issue of *Elements* show, our understanding of LIPs has evolved considerably over the past 20 years (see also Svensen et al. 2019). Some key areas where advances have been made involve high-precision geochronology and the role that sill emplacement plays in modulating outgassing of sedimentary rock units. Magma–host rock interaction, including crustal assimilation and contact metamorphism, has therefore become central in understanding how LIPs may have driven local and planetary-scale changes. Progress has also been made using sedimentary geochemical proxies (e.g., Hg, Ni, Te, and isotope geochemistry; Percival et al. 2018) to trace both environmental processes and the pulsed nature of LIP eruptions.

The key attributes of LIPs are widely understood to include: i) formation during anomalously productive mantle melting events with significantly higher magmatic fluxes than those associated with modern volcanic activity, ii) eruption of mostly mafic (basaltic) lavas, and iii) vertically and laterally extensive magma feeding zones (also known as magma plumbing systems) characterized by the emplacement of enormous amounts of mafic magma into the lithosphere as sheet intrusions (sills and dikes; e.g., Black et al. 2021; Mittal et al. 2021). Important to note for this issue of *Elements* is that many continental LIPs have plumbing systems that developed within sedimentary basins, which together can be termed sedimentary–volcanic basins, or simply volcanic basins. These include the Central Atlantic Magmatic Province (CAMP), the High Arctic LIP (HALIP), the Karoo LIP, the North Atlantic Igneous Province (NAIP), and the Siberian Traps. Seismic profiles from offshore areas have shed light on both the structure of these volcanic basins and the fate of gases generated when sedimentary rocks are heated around sills and dikes (Planke et al. 2005). In turn, field and petrological studies have shown how contact metamorphism in volcanic basins can trigger the massive production of metamorphic (i.e., thermogenic) gases that could have amplified the environmental impacts of LIPs (e.g., Svensen et al. 2009; Bédard et al. 2023).

Earth's past is dotted with LIP events (e.g., Kasbohm et al. 2021), which helped to shape its tectonic evolution, the location of valuable resources such as metallic ores, and the history of life. This is partly because LIP events facilitated large-scale redistribution of energy and mass from the Earth's mantle to the lithosphere, surface, and atmosphere (conversely, LIPs can also act as volatile sinks through weathering processes, as discussed below). Because of the unusually high melt production rate of LIPs and the fact that magma batches were emplaced in pulses, the bulk of the mass transfer took place over geologically short periods of time. Significant carbon degassing episodes may have, therefore, taken place on timescales as short as centuries

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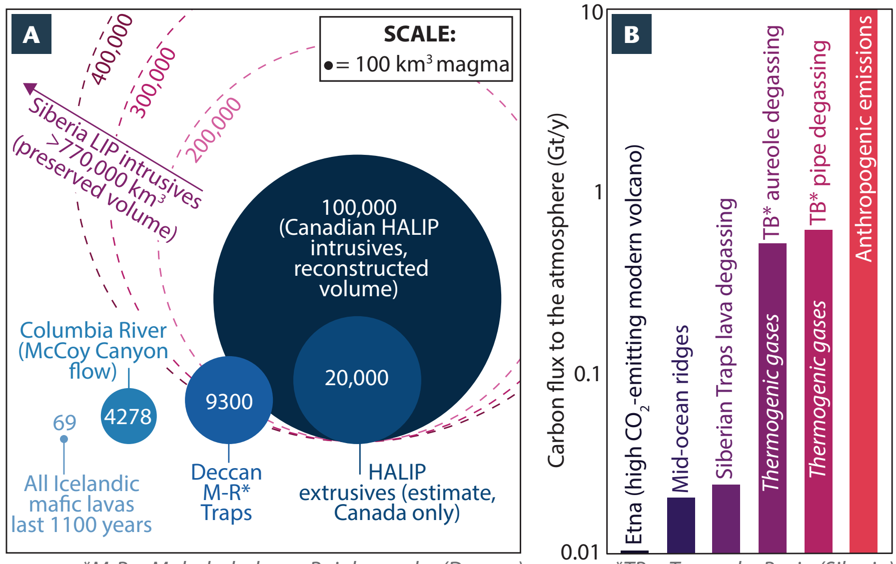
and millennia, making LIP-related events relevant for understanding changes during the "Great Acceleration" and the Anthropocene. For these reasons, LIP research continues to attract a wide diversity of scientists, including igneous petrologists, organic and inorganic geochemists, geodynamicists, Earth system modelers, climate scientists, economic geologists, and more. The study of LIPs is thus fertile ground for inter- and trans-disciplinary research approaches and has consequently fostered the development of a vibrant and ever-growing research community. The 2021 IODP expedition 396 offshore Norway, targeted to further understand the relationships between the NAIP and the Paleocene–Eocene thermal maximum, is a recent example of the enormous scale of resources and energy devoted to international LIP-related research (Planke et al. 2022).



*M-R = Mahabaleshwar-Rajahmundry (Deccan) *TB = Tunguska Basin (Siberia)

Figure 1 Visualizing the scale of LIP magma output and degassing. In (**A**), the area of each circle is directly proportional to the volume of magma it represents (numbers shown in or near the circles, in km^3). Note that the present-day volume of intrusives associated with the Siberian LIP would plot outside the diagram. (**B**) Carbon fluxes to the atmosphere. Estimates from degassing of Siberian Traps lavas and thermogenic gases from the Tunguska Basin are based on LIP calculations after Svensen et al. (2009) and references therein. Carbon fluxes for Etna volcano (~0.006 Gt/y), global spreading ridges (very uncertain, a value of 0.02 Gt/y is shown), and anthropogenic emissions (~10 Gt/y) are shown for comparison (after Lee et al. 2019). Additional data sources: Vasiliev et al. 2000; Thordarson and Larsen 2007; Bryan et al. 2010; Saumur et al. 2016.

IN THIS ISSUE

A testament to the longevity of interest in LIPs is that they have been featured in two previous issues of *Elements*: "Large Igneous Provinces: Origin and Environmental Consequences" in 2005 (vol. 1, no. 5) and "Catastrophic Perturbations to Earth's Deep Carbon Cycle" in 2019 (vol. 15, no. 5). A core goal of the current issue is to explore some of the ways in which LIPs were effective drivers of global change. Here we focus on processes that contributed to both climate warming and cooling events. Part of this issue is also dedicated to looking closer at some of the deleterious impacts that LIP events have induced in the terrestrial environment. An overview of the ways that LIP activity has triggered biotic crises is provided by Grasby and Bond (2023 this issue), a review of how contact metamorphic (i.e., thermogenic) volatiles are generated when LIPs are emplaced into sedimentary basins is given by Svensen et al. (2023 this issue), and an appraisal of how LIP-induced climate warming impacted land ecosystems is provided by Galloway and Lindström (2023 this issue). Although most LIPs are associated with climate warming, this issue spotlights a case where the emplacement of a LIP has been linked to the initiation of global icehouse conditions, potentially due to CO_2-drawdown as a result of the weathering of LIP basalts (Macdonald and Swanson-Hysell 2023 this issue). Finally, our understanding of the global impacts of LIPs depends critically on the rapidly evolving fields of sedimentary proxies (covered by several of the articles in this issue) and high-precision geochronology, as reviewed by Gaynor et al. (2023 this issue).

THE SCALE OF LIP MAGMATISM

Before discussing the intrusive components of LIPs, we will first attempt to put the scale of LIP magmatism into perspective. It is tempting to compare LIPs to present-day or historical volcanism, but in many respects, LIPs overshadow all other mafic volcanoes on the planet (Fig. 1). The closest historical analogue we have for outpourings of flood basalts by LIPs is the 1783–1784 Laki eruption in Iceland, which emitted ~15 km^3 of magma within eight months and is the only large-volume basaltic flood lava eruption witnessed by humans (Thordarson and Larsen 2007). Notably, these authors estimate the entire volume of basaltic lava emitted in Iceland over the past 1100 years to be ~69 km^3, which is a relatively small amount of magma compared with LIP eruptions. For instance, the Mahabaleshwar-Rajahmundry Traps in India, a single eruptive unit of the Deccan LIP, is thought to represent ~9300 km^3 of magma (Bryan et al. 2010). Individual eruptive units at LIPs are, in turn, dwarfed by their intrusive components, as illustrated by the Canadian portion of the High Arctic LIP, which has an estimated total intrusive magma volume of ~100,000 km^3 (reconstructed by Saumur et al. 2016; note that this volume estimate does not include any of the other circum-Arctic portions of the HALIP, such as Svalbard, the Barents Sea, or Greenland). Even more extreme is the Siberian LIP, whose present-day volume of sills, lavas, and pyroclastic deposits exceeds 1,700,000 km^3 (Vasiliev et al. 2000; Fig. 1A). Estimating magma volumes and rates of emplacement of LIPs is difficult, but studies of lava piles and volcanic basins suggest that the cumulative total amount of magma generated by individual LIPs exceeded 1 Mkm^3 during their main phases of activity. These peaks of magmatism typically lasted up to ca. 500 ky and comprised several intensive episodes or pulses lasting around 0.1–10 ky each. Relatively small-volume precursor and/or waning stage magmatism in many cases also occurred within 1–2 My of the main phase of activity. We emphasize here that LIPs are extraordinary not only in terms of their magma volumes and production rates, but with respect to their high rates of outgassing too (Fig. 1B).

LIP PLUMBING SYSTEMS

Humans have never witnessed a LIP eruption. Therefore, to understand them, we have to rely on the rock record (e.g., outcropping lavas, sills and dikes exposed through erosion, sills intersected by drill cores, sedimentary rock successions) and geochemical and geophysical models, such as seismic images of rifted margins (Fig. 2). Our current view of how LIPs are assembled is that they consist of multiple, rapidly emplaced, large-volume eruptions,

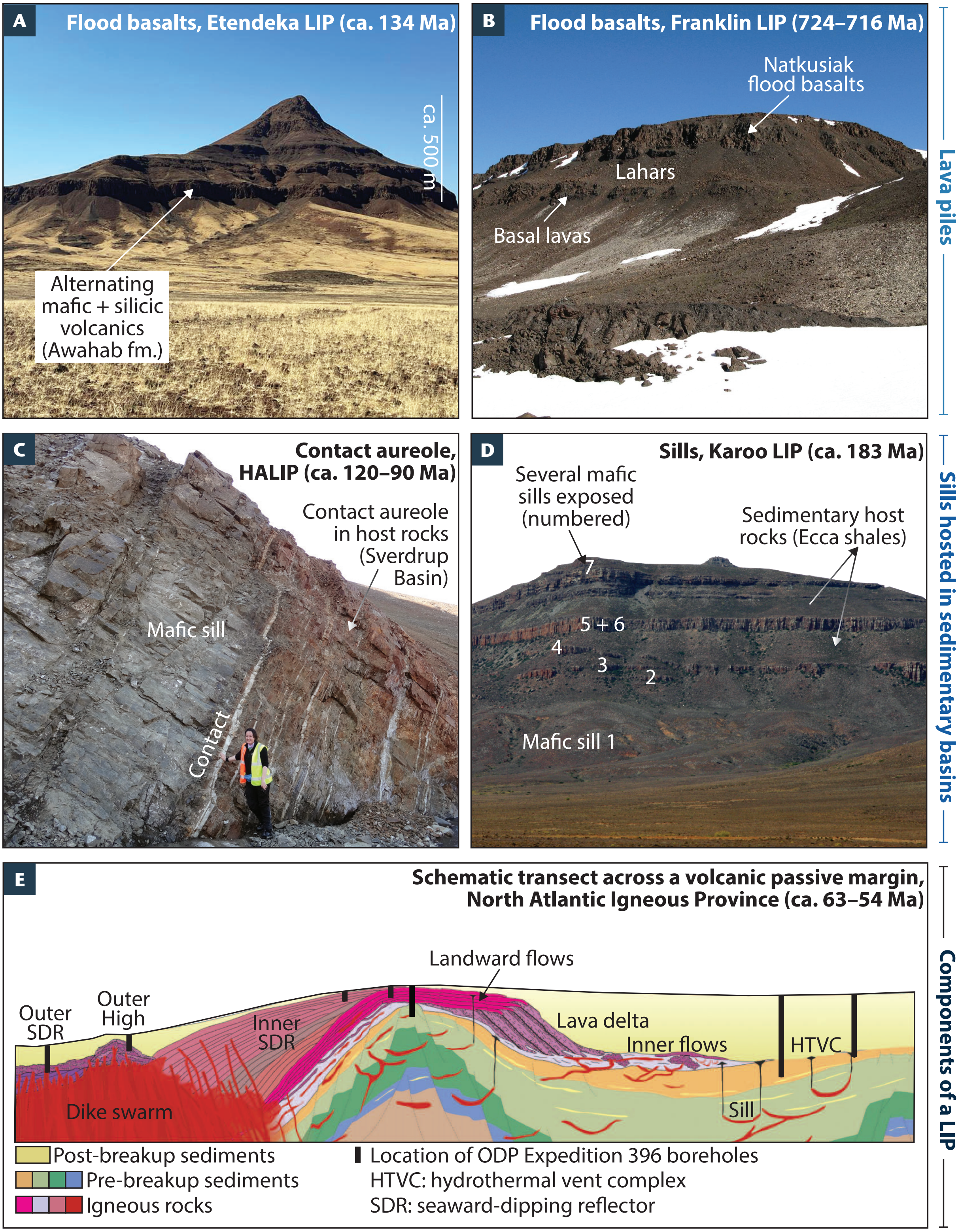


Figure 2 The many faces of LIPs. (**A**) and (**B**) show iconic lava piles from the Early Cretaceous Paraná-Etendeka LIP in Namibia (Roger's Knee Peak) and the Neoproterozoic Franklin LIP in Canada. (**C**) and (**D**) show examples of sills hosted in sedimentary basins from the Cretaceous High Arctic LIP in Canada (F.M. Deegan for scale) and the Early Jurassic Karoo LIP in South Africa. (**E**) Schematic profile across a volcanic margin (NAIP, after Planke et al. 2022) showing various components of LIPs such as sills and hydrothermal vent complexes through which thermogenic gases could have migrated to the surface. Photos: (**A**): S. Callegaro; (**B**) J.H. Bédard; (**C**) V.R. Troll; (**D**) H.H. Svensen.

each on the order of 10^2 to 10^3 km^3 of magma (FIG. 2A, 2B; Bryan et al. 2010). However, these outpourings of lavas are only the tip of the iceberg. The intrusive parts of LIPs are envisaged as swarms of sills and dikes that span the entire crustal column. Uncertainties surround the magma volumes generated by LIPs because the extent of LIP intrusive components are not always easy to assess, and extrusive components are frequently heavily eroded, especially where LIPs developed in the tropics. In many cases, intrusions are only poorly exposed (if at all) or covered by thick vegetation. In the case of LIPs emplaced into oceanic crust, their partial subduction can also hinder volume estimates, such as for the Wrangellia LIP or the Greater Ontong Java Plateau. Studying the plumbing systems of LIPs is therefore challenging and often necessitates the use of industry drill cores and geophysical methods, particularly seismic reflection data. Industry data and samples have made it possible to understand the formation and evolution of partly buried provinces such as the CAMP, the Siberian Traps, and the NAIP (e.g., Planke et al. 2005; Marzoli et al., 2018; Callegaro et al. 2021). Some LIPs, however, exhibit exceptional exposure and preservation of their plumbing systems, such as the Franklin LIP on Victoria Island (Canada), the HALIP in the Canadian Arctic Islands, or the Karoo LIP in South Africa (e.g., Bédard et al. 2012, 2023; Saumur et al. 2016; FIG. 2C, 2D). In cases like these, the sill network and dike swarms that supplied melts to the surface can be observed in situ. Importantly, sills in volcanic basins commonly exhibit well-developed contact aureoles. These aureoles testify to throughflow of magma and interaction with the surrounding sedimentary host rocks during magma emplacement and cooling. Contact metamorphism of basin sediments and host rocks and the generation of thermogenic volatiles have therefore become fundamental aspects of relatively recent hypotheses linking LIPs with environmental changes (e.g., Svensen et al. 2004; Ganino and Arndt 2009; FIG. 2E).

WHAT MAKES LIPS SUCH POTENT DRIVERS OF GLOBAL CHANGE?

The question "what makes LIPs such potent drivers of global change" is one that may not have a unique answer, but it motivates much of current LIP research. While a convincing temporal link exists between LIPs and environmental changes, there is apparently no single LIP feature that controls their impacts (see Kasbohm et al. 2021 for discussion). Each LIP formed differently and had the potential to induce various types of change, as the articles in this issue explore. Extrinsic conditions were perhaps more crucial than intrinsic features in determining the impacts of any given LIP. For instance, the pre-existing climate state would have been critically important, as well as the location of the LIP when it developed (e.g., tropical or high latitudes), the prevailing paleogeography (i.e., supercontinent or disaggregated land masses), the extent and efficacy of weathering, the host rocks into which the LIP was emplaced, the magma flux, the potential generation of thermogenic gases, and the ability of these gases to escape to the atmosphere and/or ocean.

The amount and type of gases released by LIPs has long been thought to play a role in the effects that LIPs had on the environment. The sheer scale of LIPs means that they would have emitted vast amounts of mantle-derived carbon and sulfur volatiles. Consider the estimates by Svensen et al. (2009) for the Siberian LIP: the amount of CO_2 released from degassing of Siberian Traps flood lavas is thought to have been ca. 20,000 Gt CO_2, while thermogenic volatile production from the Tunguska Basin into which Siberian sills were injected may have reached 114,000 Gt of equivalent CO_2 (FIG. 1B). This example demonstrates the reason behind the explosion of research concerning thermogenic volatiles in the past 20 years. But what are thermogenic volatiles exactly? In brief, they are gases generated when sills and dikes are emplaced into hydrocarbon accumulations or sedimentary host rocks, such as shales, carbonates, or evaporites. When host rocks are heated by magmatic intrusions, volatiles such as carbon-bearing gases (e.g., CO, CO_2, CH_4) are released through low- to high-temperature contact metamorphic reactions, as well as through short-timescale, high-temperature magma–sediment interactions that can occur during crustal assimilation (Deegan et al. 2022; Svensen et al. 2023 this issue; FIG. 3). These volatiles may then migrate along faults, dikes, or vent structures throughout the crust and eventually reach the atmosphere or ocean (FIG. 2E). In this way, LIPs can mobilize volatile elements that were previously locked up in sedimentary rocks and redistribute them to the surface of the planet on very short timescales.

The composition of host rocks traversed by LIP plumbing systems is crucial in determining the type of thermogenic volatiles that were generated. For instance, sedimentary basins that contain carbonaceous rocks, such as coal or shale, would have generated various types of carbon volatiles and toxic metals due to devolatilization of organic material in the hosts (FIG. 3A, 3B). Likewise, sedimentary basins that contain evaporitic rocks, such as sulfates and halides, would have generated sulfur-dominated volatiles and associated halogenated compounds (FIG. 3C, 3D). The mass of volatiles released from metamorphic aureoles can be estimated from thermodynamic models and aureole petrology (e.g., Heimdal et al. 2021; Svensen et al. 2023 this issue), while geochemical studies of magmatic rocks and contact aureoles can provide information on how much crust was assimilated by the intruding sills and how volatiles were mobilized in metamorphic aureoles (e.g., Callegaro et al. 2021; Bédard et al. 2023). Furthermore, process-related information about the assimilation and devolatilization of shale in LIP mafic melt has recently been captured in high P–T experiments (Deegan et al. 2022; FIG. 3B). The effects of thermogenic volatiles on the environment range from long-term warming to short-term cooling to ozone depletion, acid rain, and ecosystem poisoning (see Grasby and Bond 2023 this issue; Galloway and Lindström 2023 this issue).

It is important to note that although thermogenic volatiles may represent a powerful factor in determining the lethality of a LIP, this hypothesis rests on the ability for thermogenic volatiles to migrate to the surface. In many cases, proof of volatile expulsion is well documented (e.g., degassing pipe structures in Siberia Traps, the Karoo LIP, and the NAIP; Svensen et al. 2009; Manton et al. 2022). However, in the case of the Canadian HALIP, it was recently suggested that a portion of the thermogenic volatiles generated during sill emplacement into the Sverdrup Basin may have been trapped in the plumbing system and, unable to escape, reacted with the surrounding rocks to produce calcite cements (see discussion in Bédard et al. 2023). Estimating gas fluxes from contact aureoles thus faces several challenges, including the construction of robust basin-scale volume estimates, accurate knowledge of the sedimentary successions at depth, and information regarding the duration and thermal history of each sill–aureole event. The take-away message is that every LIP is unique and requires careful consideration of the factors that could have helped it contribute to contemporaneous environmental crises. These factors range from the produc-

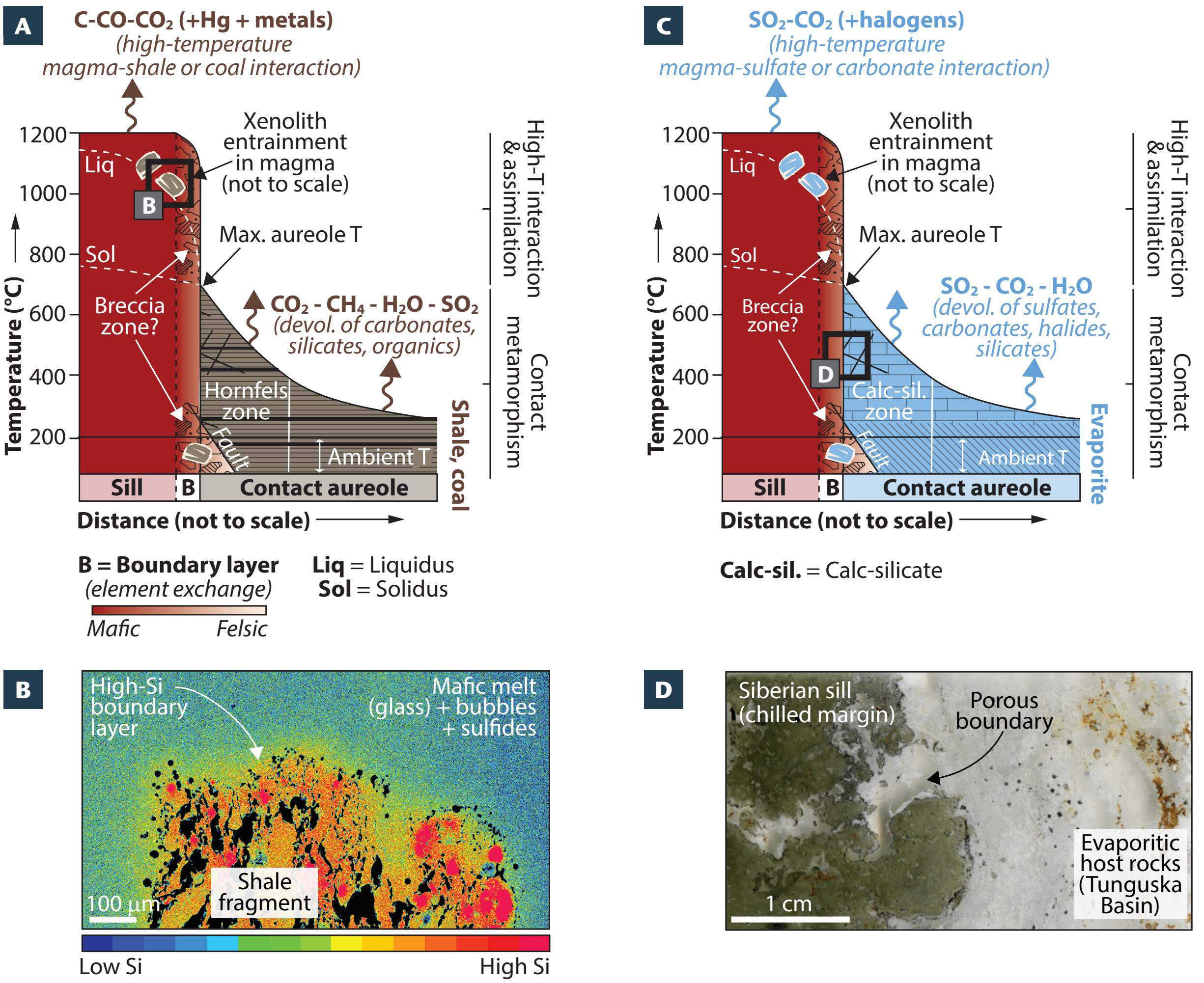


Figure 3 Generalized models of sill–host rock interaction. In scenario (**A**), a mafic sill is emplaced into carbonaceous sedimentary rocks. (**B**) (inset in (**A**)) shows a silica element map of a high *P–T* experiment wherein a shale xenolith is "caught in the act" of dissolving into LIP mafic melt (after Deegan et al. 2022). In scenario (**C**), a mafic sill is emplaced into evaporite and carbonate host rocks. (**D**) (inset in (**C**)) shows a thin section scan of a sill–evaporite contact zone from the Siberian LIP (after Callegaro et al. 2021). Note that the contact aureole temperature (*T*) profile depends on the sill temperature, ambient temperature, sill thickness, and host rock type. See also Svensen et al. (2023 this issue).

tion efficacy of thermogenic volatiles to igneous gas fluxes and LIP weatherability, to coincidence with external factors such as bolide impacts.

TIMING IS EVERYTHING

A challenge with linking LIPs and environmental changes is that evidence for each typically occurs in different areas of the planet. For example, the Siberian Traps erupted in present-day northeastern Russia, but the environmental disturbance associated with this event occurred worldwide, and is recorded in sedimentary rocks as far away as Canada and Australia (e.g., Dal Corso et al. 2022). The best way to verify the LIP-environment connection is to precisely determine the timing of each and demonstrate that they were truly synchronous. Recently, there has been great progress in generating high-resolution proxy reference sections, and in combining traditional carbon isotope analyses with new proxies that record the occurrence of volcanism, such as mercury concentrations normalized to the organic carbon content. These provide a promising tool to correlate events over great distances (see Galloway and Lindström 2023 this issue; Grasby and Bond 2023 this issue; Svensen et al. 2023 this issue). The smoking gun proof of correlation is now considered to be a combination of proxy data and highly precise and accurate radioisotopic ages obtained using either the U-Pb system in zircon or the $^{40}Ar/^{39}Ar$ system in plagioclase. Increasing numbers of studies utilize the U-Pb technique in zircon, retrieving ages from either sills or dikes (see Macdonald and Swanson-Hysell 2023 this issue; Gaynor et al. 2023 this issue), whereas the most common technique for generating ages from lava flows is $^{40}Ar/^{39}Ar$ dating of plagioclase or groundmass (e.g., Marzoli et al. 2018; Antoine et al. 2022).

Also possible to date are volcanic ash horizons that bracket mass extinction events or major environmental disturbances recorded in the stratigraphic record (e.g., Schoene et al. 2010). Overall, the temporal correlation between LIP emplacement and major climatic disturbance in the Phanerozoic is well established (Kasbohm et al. 2021). However, proof of correlation brings with it more nuanced questions such as:

- Which processes during LIP emplacement are the main drivers of environmental crises?
- How important is the emplacement rate for the environmental impact?

- Are LIPs emplaced continuously—or are stop-start (stochastic) processes important?

The best way to respond to these questions is to precisely determine the timeframe for the emplacement of all the individual building blocks of a LIP and compare this chronology with the timing of changes recorded in the stratigraphic record. However, the questions above will remain outstanding until further accurate and precise dates become available.

In this issue, we outline the current understanding of the timescales of LIP events, what these ages mean, and what is missing (see Gaynor et al. 2023 this issue). It is important to recognize that most of the obtained ages for Phanerozoic LIPs are derived from shallow-level intrusions, rather than from flood basalts or deeper crustal intrusions, which could potentially bias our understanding of the timescales of LIP emplacement. For instance, high-precision dates are available for the ancient Neoproterozoic Franklin LIP, which have proven crucial for determining the relationship between its emplacement and the onset of the Sturtian Snowball Earth event (Macdonald and Swanson-Hysell 2023 this issue). However, there are still many LIP events with sparse or no high-quality age constraints, potentially leading to gaps in our understanding of the environmental impacts induced by LIPs through time (e.g., the Wrangellia LIP). We also stress here that even LIPs that are considered to be well-dated (e.g., the Siberian LIP) contain, at best, a few tens of dated samples over magma volumes on the order of a million km^3 (Kasbohm et al. 2021). High-precision geochronology is costly and time-consuming; nevertheless, future endeavors in obtaining robust age constraints will undoubtedly push forward our knowledge of the timing and tempo of LIP emplacements.

FURTHER READING

Research surrounding LIPs, their magma compositions, plumbing systems, geochronology, links to environmental disasters, and fingerprints in sedimentary records, is currently flourishing. New approaches using state-of-the-art geochemical modeling and experimental approaches, high-precision geochronology, and paleontological and geophysical methods (to name a few) are paving the way for exciting new discoveries. This is great news for LIP-enthusiasts, but it means that we cannot possibly cover all aspects of modern LIP research in one issue of *Elements* for space reasons. A small selection of additional research themes is briefly summarized below.

- The origins of LIPs may be varied (e.g., mantle plumes, melting of fertile mantle lithologies) and remain debated. Geochemistry is a widely used tool for helping to unravel LIP origins and petrogenesis. For an introduction to how trace elements can be used to "fingerprint" LIP provenance, the reader is directed to Pearce et al. (2021).
- LIPs are well-known for their association with magmatic sulfide deposits, the genesis of which in many cases required the availability of crustal sulfur. For an appraisal of how magmatic sulfides are formed and emplaced in LIPs, see Lesher (2019).
- This issue of *Elements* focuses on continental LIPs, but there are many examples of LIPs emplaced in oceanic crust, including the most voluminous LIP known: the Greater Ontong Java Plateau. The effects of oceanic LIPs on the environment are still uncertain, but for those wishing to explore this topic through the lens of sediment geochemistry, a good overview is provided by Percival et al. (2018).
- While the shallow parts of LIP plumbing systems are the focus of this issue, relatively little is known about their deep crustal structures (i.e. lower crustal bodies). Geophysical studies have been instrumental in illuminating this region, as shown by Abdelmalak et al. (2017).
- The sources of LIPs from the lowermost mantle are enigmatic, but what is certain is that LIPs play an important role in linking the Earth's interior to its surface. A review of lower-mantle LIP sources (i.e., large low shear velocity provinces) and their connections to the planet's crust and atmosphere can be found in Torsvik et al. (2021).
- The Perspective by Lee (2023 this issue) further explores the connections between the solid Earth and the atmosphere, and how interactions between the two have affected the habitability and evolution of life on Earth.
- Finally, LIPs represent planetary phenomena that are not restricted to Earth; for example, massive outpourings of mafic lava on Mars and Venus may be analogous to terrestrial LIPs. For readers interested in magmatism in the inner Solar System, a good starting point is the review by Byrne (2000).

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