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The effects of large igneous provinces on the global carbon and sulphur cycles

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ABSTRACT

The correlation between large igneous provinces (LIPs), extinction events, and rapid climate change suggests that volcanism can have a detrimental impact on Earth surface conditions. Changes in atmospheric and ocean chemistry, particularly the climate-sensitive carbon and sulphur cycles, are among the most probable processes for inducing global environmental stress. However, the interactions and feedbacks between volcanism and these cycles are numerous and complex, making the characterisation of the response to a LIP challenging. Here we summarise the sources and sinks of carbon and sulphur from large scale volcanism and magmatism using information from modern and ancient systems. For the sources, we review the current understanding of volcanic emissions, and explore the relative contributions and importance of magma-derived degassing versus volatile release from sediments affected by igneous intrusions and lava. In addition, we explore the various ways in which LIPs can reduce atmospheric concentrations of these same elements. The relative influences of each source and sink are in part determined by the mode of LIP emplacement and eruption style, along with the subsequent timescales of such effects. We focus on a few key examples, including the Siberian Traps, the Paraná-Etendeka, and the Central Atlantic Magmatic Province (CAMP), to demonstrate how the environmental impact can vary considerably with differing modes of emplacement, LIP duration, and eruption styles. In particular, we show that the host rocks can have a dominant role as a source or sink of emissions, depending on the lithologies affected by the LIP emplacement.

1. Introduction

There have been periods during Earth's history when huge volumes of magma have been produced and erupted over a wide area in a short period of time, driven by large mantle-derived thermal and material fluxes into the shallow crust. Such events are termed Large Igneous Provinces (LIPs) and their occurrence appears independent of regional plate tectonics prior to emplacement (e.g. Coffin and Eldholm, 1994). LIPs are characterised by pulses of activity during a short timeframe (10^4–10^6 years) that erupt the bulk of the total LIP volume (e.g. Bryan et al., 2002, 2010; Knight et al., 2004; Chenet et al., 2007). Their present day geographical extents can exceed 10^5 km^2 and reconstructed maximum extents could have exceeded 10^7 km^2 (e.g. McHone, 2003; Bryan and Ernst, 2008). The emplacement style and surface expression of a LIP can vary considerably, based primarily on the lithosphere present above the rising magma (e.g. Jerram et al., 2016). In continental settings, LIPs form flood basalt provinces (Jerram and Widdowson, 2005) coupled with sizeable intrusive complexes (e.g. Svensen et al., 2004; Polteau et al., 2008) that can be intricately linked with volcanic passive margins (Planke et al., 2000). In marine settings, they form oceanic plateaus, marine basin flood basalts and hyaloclastites, seamount groups, and submarine ridges (e.g. Neal et al., 1997; Greene et al., 2008). There have been numerous LIPs throughout the Phanerozoic and likely the Proterozoic and Archean as well, with many examples partially exposed at the Earth's surface (Fig. 1).

A correlation exists between LIPs, extinction events, and rapid climate change during Earth's history (Fig. 2), suggesting that large scale volcanism can have a detrimental impact on conditions suitable for life (e.g. Stothers, 1993; Courtillot, 1999; Wignall, 2001; Bond and Wignall, 2014). Specifically, alterations to the climate-sensitive carbon and sulphur cycles are among the most probable causes of ecosystem stress. The interactions and feedbacks between volcanism and these cycles are numerous and complex, making it difficult to characterise the climatic response to each LIP emplacement. Here we review the potential sources and sinks of carbon and sulphur from LIPs. We explore the current scientific understanding of volcanic emissions, and consider the relative importance of mantle-derived degassing versus degassing from sediments heated or incorporated by igneous intrusions and

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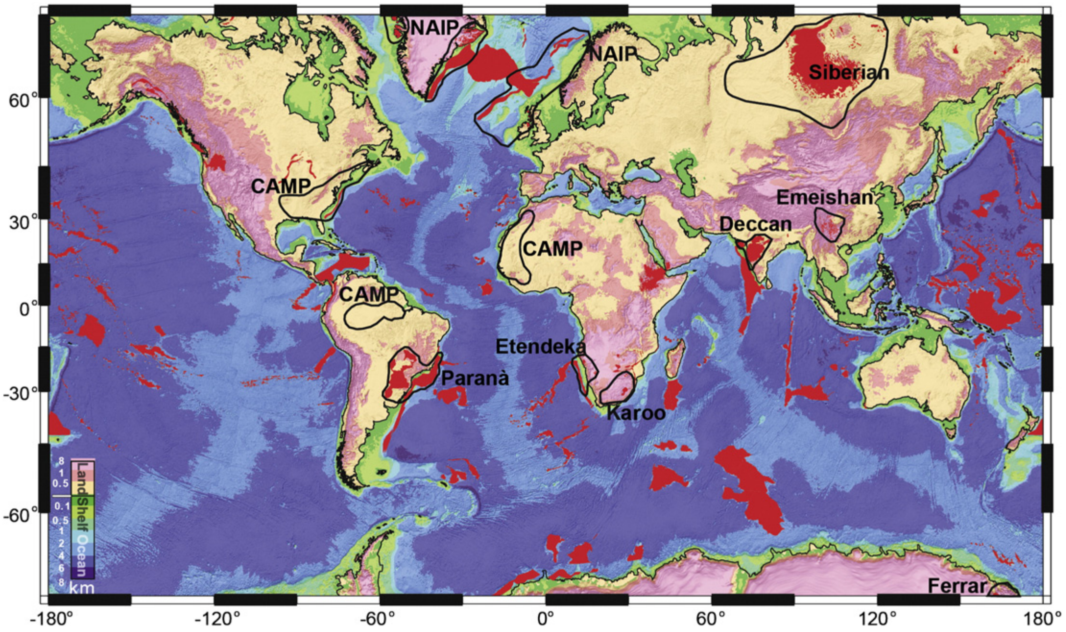

Fig. 1. The worldwide distribution of LIPs and associated volcanic basins (after Svensen et al., 2015). Red outcrops denote LIP products at the surface, while black filled circles and heavy outlined lines show locations of selected LIPs discussed in this paper.

lava. In addition, we consider the various ways in which the emplacement of LIPs can sequester these same elements. The relative contributions of each source and sink are in part determined by the mode of LIP emplacement, the host lithologies of intruded and extruded material and eruption style, along with the subsequent timescales of such effects. Therefore, we explore how the environmental impact can vary considerably depending on these variables.

1.1. The emplacement of a LIP

Large igneous provinces can be broadly grouped into volcanic and sub-volcanic domains. Volcanic domains include volcanoes, lava flows, and ashes from eruptions, while sub-volcanic domains comprise plutons, sills, and dikes emplaced in sedimentary basins or other shallow parts of the crust (e.g. Jerram and Bryan, 2015). Chemically, LIPs can be made up of predominantly mafic, mixed mafic and silicic, or primarily silicic material, depending in part on the geotectonic setting and the prevalence of partial melting of surrounding material (Bryan et al., 2002; Bryan, 2007). Mafic-dominated LIPs are the more common variety found (e.g. Jerram, 2002), especially when emplaced into ocean crust. In continental settings LIPs can be predominantly mafic, but have varying proportions of a silicic component in their melt generations, reflecting the variety of inclusion and melting of crustal material, remelting of underplated material, and fractional crystallisation processes. In rare occurrences this silicic component comprises a substantial fraction of the total melt generated (>10^4 km^3), particularly during the peak and final stages of flood volcanism (Peate, 1997; Marsh et al., 2001; Jerram and Widdowson, 2005; Ukstins Peate et al., 2005). Instances where the LIP is predominantly silicic have been termed 'silicic large igneous provinces' (SLIPs; e.g. Bryan et al., 2002).

The most common volcanic product is mixed volumes and styles of tholeiitic basalts. These form compound-braided, tabular-sheet flows, or hyaloclastites, in the order of 1 to 1000's km^3 in volume (Jerram, 2002; Bryan et al., 2010). In subaerial settings the larger sheet flows

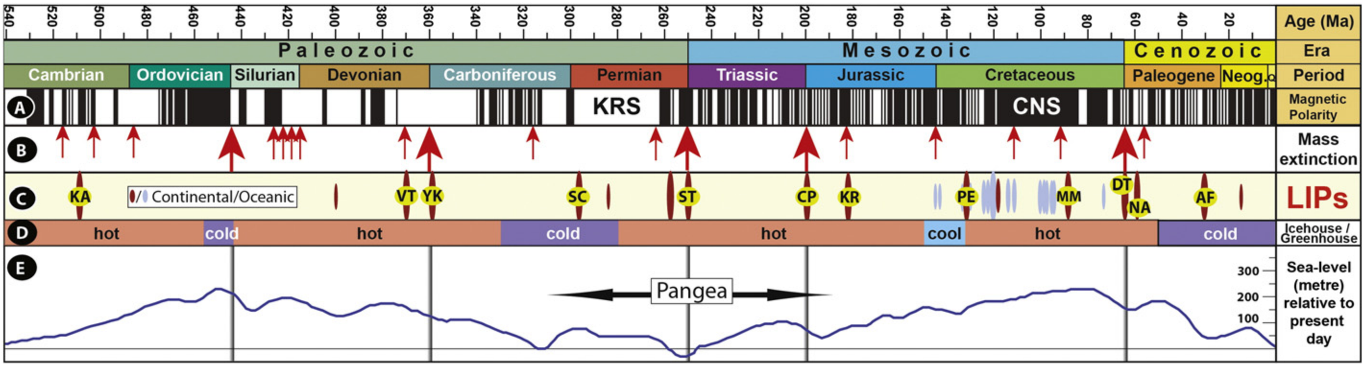

Fig. 2. The main identified mass extinction events and large igneous province emplacements during the Phanerozoic. Row (A) shows magnetic polarity (Eide and Torsvik, 1996; Gee and Kent, 2007), where KRS = Kiaman Reverse Superchron and CNS = Cretaceous Normal Superchron. Row (B) shows red arrows marking mass extinctions, with 5 major events marked by larger arrows. Row (C) shows known LIP events (Torsvik et al., 2008), red for continental flood basalts and grey for oceanic plateaus. LIPs: KA = Kalkarindji, VT = Viluy Traps (Ricci et al., 2013), YK = Yakutsk, SC = Skagerrak, ST = Siberian Traps, CP = Central Atlantic Magmatic Province, KR = Karoo-Ferrar, PE = Paraná-Etendeka, DT = Deccan Traps, NA = North Atlantic Igneous Province, AF = Afar. Note that the existence of oceanic plateaus pre-Jurassic period is very poorly constrained. Row (E) denotes known fluctuations between Icehouse (cold) and Greenhouse (hot) conditions. Row (F) displays sea-level variations (Haq and Al-Qahtani, 2005; Haq and Shutter, 2008). Figure courtesy of Trond Torsvik.