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Emplacement characteristics, time scales, and volcanic gas release rates of continental flood basalt eruptions on Earth

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ABSTRACT

Continental flood basalt provinces are the subaerial expression of large igneous province volcanism. The emplacement of a continental flood basalt is an exceptional volcanic event in the geological history of our planet with the potential to directly impact Earth's atmosphere and environment. Large igneous province volcanism appears to have occurred episodically every 10–30 m.y. through most of Earth history. Most continental flood basalt provinces appear to have formed within 1–3 m.y., and within this period, one or more pulses of great magma production and lava eruption took place. These pulses may have lasted from 1 m.y. to as little as a few hundred thousand years. Within these pulses, tens to hundreds of volumetrically large eruptions took place, each producing 10^3–10^4 km^3 of predominantly pāhoehoe lava and releasing unprecedented amounts of volcanic gases and ash into the atmosphere. The majority of magmatic gas species released had the potential to alter climate and/or atmospheric composition, in particular during violent explosive phases at the eruptive vents when volcanic gases were lofted into the stratosphere. Aside from the direct release of magmatic gases, magma-sediment interactions featured in some continental flood basalt provinces could have released additional carbon, sulfur, and halogen-bearing species into the atmosphere. Despite their potential importance, given the different nature of the country rock associated with each continental flood basalt province, it is difficult to make generalizations about these emissions from one province to another. The coincidence of continental flood basalt volcanism with periods of major biotic change is well substantiated, but the actual mechanisms by which

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the volcanic gases might have perturbed the environment to this extent are currently not well understood, and have been little studied by means of atmospheric modeling. We summarize current, albeit rudimentary, knowledge of continental flood basalt eruption source and emplacement characteristics to define a set of eruption source parameters in terms of magmatic gases that could be used as inputs for Earth system modeling studies. We identify our limited knowledge of the number and length of non-eruptive phases (hiatuses) during continental flood basalt volcanism as a key unknown parameter critical for better constraining the severity and duration of any potential environmental effects caused by continental flood basalt eruptions.

INTRODUCTION

Continental flood basalt provinces are a subset of the broader group of large igneous provinces. The generation of a large igneous province is an exceptional volcanic event in Earth history because of the large total volume of predominantly basaltic magma generated, and lava erupted, over brief periods of geological time (usually less than 1–2 m.y.). Individual continental flood basalt eruptions, of which hundreds to thousands constitute a province, have produced lava volumes on the order of 10^3–10^4 km^3, likely at mean eruption rates of tens up to 10^2 km^3 per year (Self et al., 2006, 2008b; Chenet et al., 2008). By contrast, 30 yr of almost constant volcanic activity at Kīlauea volcano (Hawai`i) from 1983 to 2013 has produced ~4 km^3 of basaltic lava (USGS, 2013), and the largest basaltic eruption of the past ~1000 yr (Eldgjá, Iceland, 934 CE, probably lasting up to 6 yr) produced an eruptive volume of ~20 km^3 (Thordarson et al., 2001). Thus, volumetrically, continental flood basalt eruptions were huge compared to basaltic volcanism on Earth today.

Through time, large igneous province volcanism has led to the construction of extensive lava plateaus, from 1 to 3 km in thickness at any one location on land, and considerably thicker on the seafloor (Fig. 1). The extrusive and intrusive products of large igneous provinces collectively cover areas in excess of hundreds of thousands of square kilometers (sometimes more than 1 million km^2 [1×10^6 km^2]), and, typically, the aggregate extruded volcanic deposit and lava volumes are greater than 1×10^6 km^3. Research between the late 1980s to the turn of the millennium (summarized by Courtillot and Renne, 2003) showed that during large igneous province volcanism, the climax or peak in terms of erupted lava volume was often much less than 1 m.y. in duration (Rampino and Stothers, 1988; Courtillot, 1999; Chenet et al., 2009).

Large igneous provinces have formed throughout much of Earth's history and are a manifestation of Earth's normal, but in this case episodic, internal processes. The processes of generation and emplacement can be thought of as unusual transient events in Earth's volcanic history when compared with magma production at mid-ocean ridges and subduction zones (for a monograph on large igneous province characteristics, see Mahoney and Coffin, 1997). The most common hypothesis to explain the formation of large igneous provinces invokes decompressional melting of mantle plume heads (Campbell et al., 1990; Ernst and Buchan, 2001; Campbell, 2005). The frequency of large igneous province events since the Archean eon (ca. 2.5 Ga) has been estimated at one every 20 m.y. (Ernst and Buchan, 2001), but when just considering the last 270 m.y. (i.e., including the oceanic large igneous province record, some of which was destroyed by subduction earlier than 270 Ma), the frequency may have been up to one every 10 m.y. (Coffin and Eldholm, 2001). However, Rampino and Prokoph (2013) recently proposed an average frequency of 30–35 m.y. for the past 500 Ma.

Large igneous province volcanism has occurred in two broad compositional varieties: basaltic, which are the most numerous, and silicic (Bryan, 2007), which are few in number and will not be further discussed here. In this paper, we focus on continental flood basalt provinces, which are the subaerial (i.e., on-land) expression of large igneous provinces. Continental flood basalt volcanism is characterized by the combination of large erupted volumes and relatively frequent, huge basaltic eruptions (Coffin and Eldholm, 1994; Bryan and Ernst, 2008). In detail, some continental flood basalts, which are dominated by vast piles of basalt lava flows (as shown on Fig. 2), have silicic igneous rocks amongst their sequences, and vice versa for silicic large igneous provinces.

There is a striking age correlation with mass extinction events for at least four continental flood basalt provinces emplaced in the past 300 m.y. (for reviews, see Officer et al., 1987; Wignall, 2001; Courtillot and Renne, 2003; Kelley, 2007). One of the most famous examples is the mass extinction event at the end-Cretaceous (ca. 66 Ma) and its coincidence with the emplacement of the Deccan Traps continental flood basalt province in India (e.g., Vogt, 1972; Courtillot, 1999; Keller et al., 2008, 2012). Moreover, this is the only well-substantiated case of an asteroid impact coinciding with a continental flood basalt event and a mass extinction event (e.g., Keller, 2014, this volume). Perhaps more strikingly, when the eruptions of the Siberian Traps were first proposed as a trigger for the end-Permian mass extinction (252 Ma), this presented a possible correlation of the emplacement of the largest continental flood basalt province with the greatest loss of floral and faunal diversity in Earth's history (Erwin, 1994; for a review, see Wignall, 2001; Reichow et al., 2009). There has also been important recent work on the possible association between the Central Atlantic magmatic

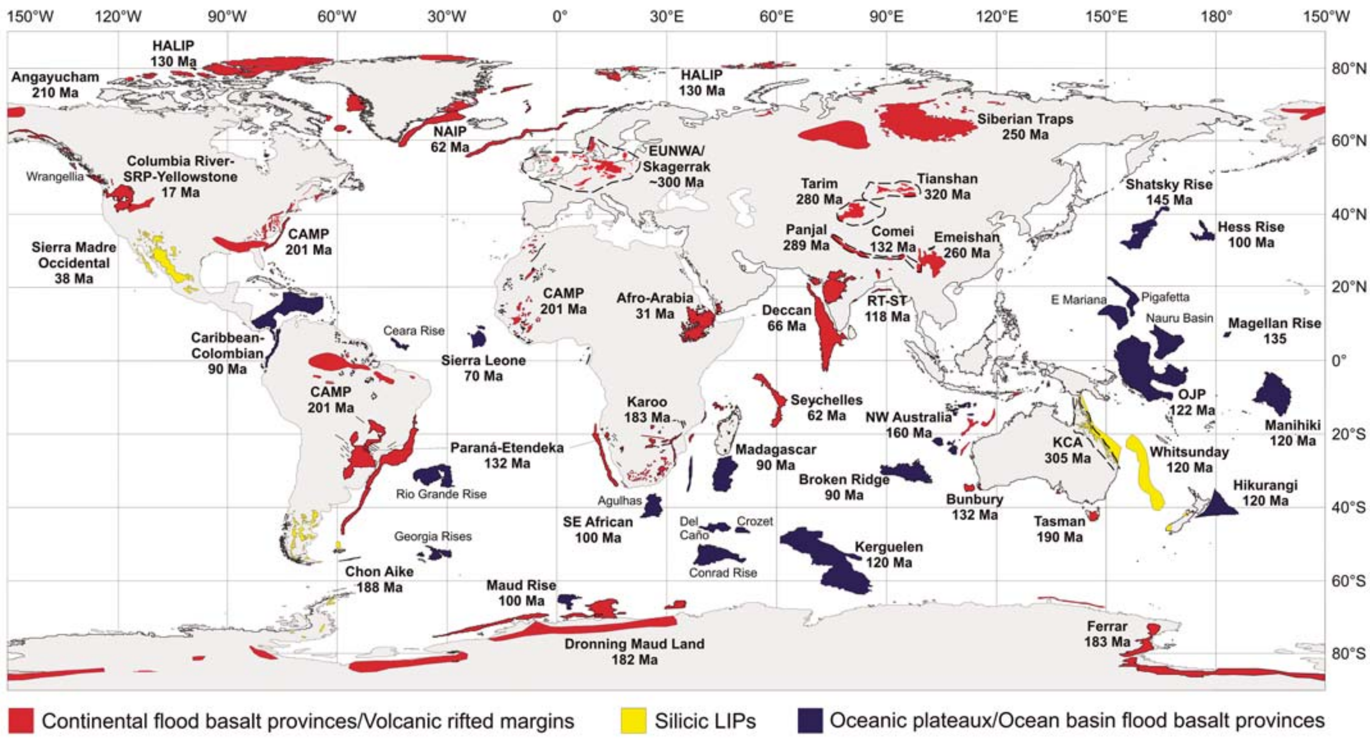

Figure 1. Large igneous provinces of the world, including continental flood basalt provinces, oceanic plateaus, and silicic large igneous provinces (LIPs; after Bryan and Ferrari, 2013). Ages are those of the main phase or pulse of volcanism, according to Bryan and Ferrari (2013). Inferred extent of some provinces shown by dashed lines. Discussion in this paper mainly focuses on the Columbia River Basalt Group and the Deccan Traps, as well as the Siberian Traps and the Emeishan provinces. Other LIPs not mentioned in this chapter; see Bryan and Ferrari, 2013.

Figure 2. A stack of lava flows, typical of the "trap" or stepped topography characteristic of flood basalt lavas, exposed along the Grande Ronde River in Washington State (USA). The >600-m-thick pile of lavas seen here is part of the Columbia River Basalt Group.

province and the extinction events at the Triassic-Jurassic boundary (e.g., Whiteside et al., 2007; Blackburn et al., 2013). Overall, however, there is still debate about whether and how continental flood basalt volcanism is causally linked to periods of biotic crisis throughout geologic time. Recent comprehensive reviews of large igneous province volcanism can be found in Bryan and Ferrari (2013) and Bryan et al. (2010). The topic of large igneous province volcanism and mass extinctions is discussed extensively in Courtillot (1999) and Wignall (2001), and the age dating of continental flood basalt provinces and mass extinctions events has been discussed in detail elsewhere (e.g., Courtillot and Renne, 2003), including meteorite impact events (Kelley, 2007).

In this paper, we review emplacement characteristics, time scales, and gas release rates of continental flood basalt eruptions. One of our aims is to compile a set of eruption source parameters for continental flood basalt eruptions. These eruption source parameters could be used as inputs for atmospheric modeling efforts to test whether, and to what degree, continental flood basalt eruptions could have caused or triggered environmental changes in the geological past. By necessity, we use information from those continental flood basalt provinces for which some geological evidence exists with regard to the size, duration, and style of the eruptions—that is the Columbia River Basalt Group and the Deccan Traps in particular. We focus on the gases released directly from erupted lavas (for which more information is available in the literature and where conclusions from one continental flood basalt province are more likely to be applicable to others), although we also briefly review other emissions sources associated with magma–country-rock (sediment) interactions. We aim to highlight areas of uncertainty that currently limit our abilities to gain a better understanding of the Earth system impacts of continental flood basalt volcanism. Because continental flood basalt provinces consist of distinct but volumetrically significant lava flow units, it is important to consider both the emplacement characteristics of the province as a whole, but also of the individual lava flow units, as discussed in the following two sections of this paper. In the final three sections of the paper, we discuss what we know about volcanic gas emissions and their potential environmental impacts, and we compile a set of eruption source parameters for typical magmatic sulfur releases from such events.

EMPLACEMENT CHARACTERISTICS OF CONTINENTAL FLOOD BASALT PROVINCES

Emplacement characteristics are key factors for understanding gas release from continental flood basalt provinces, both in terms of magma emplacement rates (and hence gas release rates) and also in terms of the duration of pulses of activity and the intervening hiatuses. A feature of all large igneous provinces is the high magma emplacement rates (e.g., Storey et al., 2007; Svensen et al., 2012), with aggregate extruded lava volumes of 1×10^6 km^3 or more erupted over periods of one to a few million years, corresponding to a time-averaged lava emplacement volume of at least 1 km^3/yr. The Siberian Traps formed ca. 250 Ma (e.g., Reichow et al., 2005, 2009) and they represent volumetrically the largest continental flood basalt province. The Siberian Trap province covers about 5×10^6 km^2 and totals about 4×10^6 km^3 of mainly basaltic lava and associated volcanic rocks, which erupted over a period of ~1 m.y. (Kamo et al., 2003). This province also has voluminous intrusive rocks (e.g., Svensen et al., 2009), as well as lava types that are not strictly basalt (Sobolev et al., 2011; for a recent review see Black et al., 2012).

Recent studies have shown that the bulk erupted lava volumes from continental flood basalt provinces only give us part of the story, because continental flood basalt volcanism is highly pulsed (i.e., alternating phases of activity and non-activity) over the time scale of the emplacement of the province as a whole. Understanding the timing, duration, and intensity as well as the length of episodes of activity and episodes of non-activity is a key requirement for the assessment of any potential environmental effects caused by continental flood basalt volcanism. Studies using the ^{40}Ar/^{39}Ar geochronological method (Courtillot and Renne, 2003), and, to a lesser extent, uranium-lead (U-Pb) age determinations, have shown that many continental flood basalt provinces erupted over quite brief periods of geologic time (for a review, see Kelley, 2007), which is especially true for the main pulse of lava production.

The best-understood and age-dated continental flood basalt province, the Columbia River Basalt Group (Fig. 3), consists of a total extrusive volume of 250,000 km^3, erupted between 17 and 10 Ma (Miocene), with minor volumes of lava erupted to as young as 6 Ma. However, as shown in Figure 3, a volume of ~150,000 km^3 (or 72% of the total volume) was emplaced over ~400,000 yr (Barry et al., 2010, 2013) at ca. 16 Ma in the Grande Ronde Basalt Formation (it should be remembered that this time interval is predicated upon the errors of the ^{40}Ar/^{39}Ar ages). For another example, the Deccan Traps flood basalts were previously believed to have erupted over a period of ~5 m.y., based on the large range of early age determinations (see Vandamme et al., 1991). Redating of the basalts using refined Ar/Ar techniques, combined with paleomagnetic studies of the lavas, however, indicates that much of the Deccan lavas were erupted over a period of only ~500,000–800,000 yr (Chenet et al., 2009). The entire duration of Deccan volcanism may have been ~3 m.y., although this still remains to be thoroughly documented. Some continental flood basalt provinces may show evidence of two or more peaks in magma output; it has been suggested that the Deccan had three pulses, with the main pulse emplacing a considerable portion of the total volume in as little as 500,000 yr or less (Chenet et al., 2009; Keller et al., 2008, 2012).

Constraining the temporal occurrence and exact duration of the main activity phases for all continental flood basalt provinces is difficult because of the precision of geochronological determinations. Volumetrically larger continental flood basalt provinces, such as the Siberian Traps, originally contained in total twenty times as much lava as the Columbia River Basalt Group, but little robustly supported detail is known about when the major pulses of volcanism occurred in the Siberian Traps. The volcanism seems to have occurred over a 2-m.y.-long period from 252 to 250 Ma. Most of the lava ages seem to fall within a 1-m.y.-long period (Kamo et al., 2003; Reichow et al., 2009), but large parts of the province remain relatively unstudied.

In summary, we stress again that the acme or main pulse(s) of volcanism in a continental flood basalt province is a very important parameter when considering environmental effects of flood basalt eruptions. Only two continental flood basalt provinces are presently well enough studied to say where in the lava pile, and when geochronologically, these main volumetric pulses of lava production might have occurred: the Columbia River Basalt Group province and the Deccan Traps province. It is not even certain yet that the Deccan's main volumetric pulse came late (i.e., at the time of the extinction peak) in the eruptive history of the province (Self et al., 2006; Chenet et al., 2007, 2009). Generalizing from these two relatively well-constrained examples, continental flood basalt volcanism appears to last for 1–3 m.y., with the pulse or pulses of main lava-volume emplacement being as brief as a few hundred thousand years. Not every continental flood basalt province may have followed this model of formation; therefore, caution is needed where part of a continental flood basalt province is poorly known and/or spatially very widespread and buried (e.g., the Siberian Traps; Reichow et al., 2005, 2009).

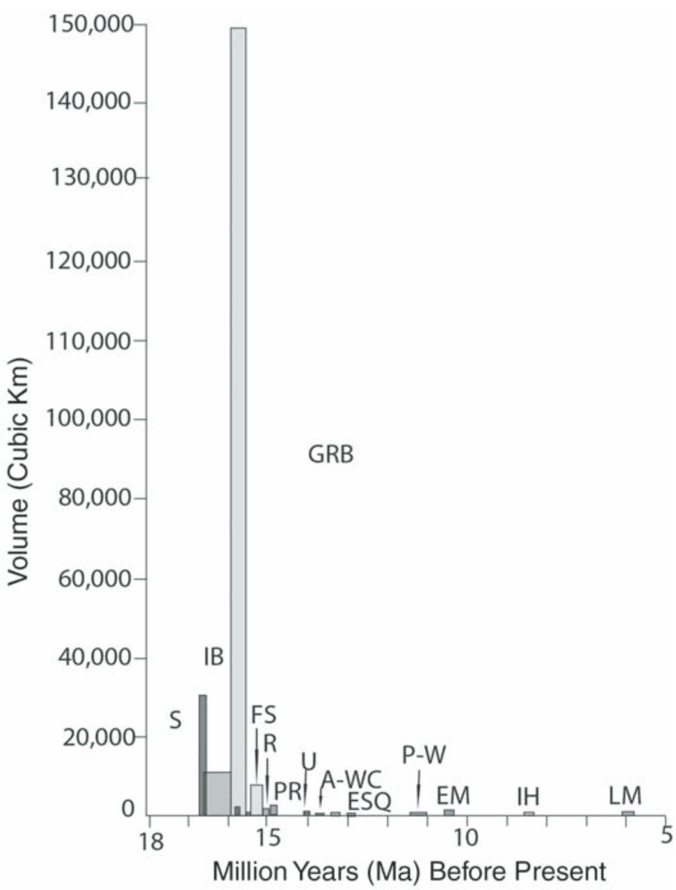

Figure 3. Volume of lava plotted against time (based on latest $^{40}Ar/^{39}Ar$ age dates; after Barry et al., 2013) for the Columbia River Basalt Group, showing the large "spike" of the main pulse of volcanism, the Grande Ronde Basalt Formation (GRB). Other formations of Columbia River lavas are identified by the initials in Barry et al. (2013) and are not mentioned in this chapter.

EMPLACEMENT CHARACTERISTICS OF INDIVIDUAL CONTINENTAL FLOOD BASALT ERUPTIONS

Eruption characteristics and style of individual eruptions are further important considerations when attempting to constrain the flux of volcanic gases from continental flood basalt provinces. By building up databases concerning these individual eruptive units, we will understand more in terms of the degree to which we can generalize from one eruption to another (both within the same provinces and between different provinces). This is important regarding generalizing their typical volumes, durations, and intensities, but also in order to allow us to make the most appropriate decisions regarding the heights of injection into the atmosphere to choose as model inputs.

During the emplacement of continental flood basalt provinces, hundreds to possibly thousands of eruptions produce immense lava flow fields, each the product of a single or cluster of vents, or a group of vents along a fissure (i.e., a line of volcanic vents; Self et al., 1997, 1998). Consequently, all flood basalt lava fields are dominated by basaltic lava flows (see Fig. 2), and, perhaps rather surprisingly, all continental flood basalt provinces examined in detail are dominated by compound pāhoehoe lava flow fields (e.g., White et al., 2009; Bryan et al., 2010). The term lava flow field designates the entire lava products of one prolonged eruption. Overall, this is a reflection of similar eruption conditions and magma types in most provinces. A certain amount of volcanological knowledge exists about the subaerial volcanism that occurred in continental flood basalt provinces (e.g., the Deccan province; Bondre et al., 2004), but this does not extend to the intrusive components, except in a couple of cases, i.e., the Karoo-Ferrar province (Svensen et al., 2012; Moulin et al., 2011; Elliot et al., 1999) and the Siberian province (e.g., Svensen et al., 2009; Sobolev et al., 2011).

For the purposes of estimating the gas output of a flood basalt eruption, it is desirable to break a province down to its individual eruptive units. Therefore, in the next two subsections, we discuss the general characteristics of individual flood basalt lava flow fields (see also Bryan et al., 2010), and the challenges of determining the timing and volumes produced by a main pulse of magma effusion during emplacement of a province. Resolving the duration of individual eruptions within continental flood basalt provinces is an even greater challenge. Only for the Roza flow field (1300 km^3 of basalt lava) of the Columbia River Basalt Group has an independent, first-order estimate been made based on the characteristics of the fissure-fed pāhoehoe lava flows that inflate during emplacement, which constrains the eruptive phase to have lasted a minimum of ~15 yr (Thordarson and Self, 1998).

In terms of understanding the impacts of continental flood basalt province emplacement on our planet, constraining the timing and length of hiatus periods within an eruption sequence is as important as knowing the durations of eruptions. For the Grande Ronde Formation of the Columbia River Basalt Group, there were ~100 separate eruptions within ~400,000 yr or less (Reidel and Tolan, 2013), but both of these values still have quite a degree of uncertainty. In the Columbia River Basalt Group case, the average hiatus was 3900 yr if we assume that each eruption lasted 100 yr, but in reality, this average hiatus may not be typical of the durations between eruptions.

Unfortunately, our understanding of most other continental flood basalt provinces is poorer by far than our knowledge about the Columbia River Basalt Group (Reidel et al., 2013). We have little to guide us when interpreting any eruption scenarios based on eruption frequency and hiatus length between eruptions, due the present inability of radiometric age-dating methods applied to basalts to be more accurate than about ±0.1 Ma at tens of millions of years, and about ±0.5–1.0 Ma at fifty to hundreds of millions of years. Some studies have attempted to define groups of lavas erupted over shorter periods of time; these are discussed later.

Eruption Products and Eruption Style

Flood basalt eruptions simply make pāhoehoe lavas, which are the smooth, ropey-surfaced flows that are common on all Hawaiian volcanoes, and are Earth's most common eruptive product (Self et al., 1998). All continental flood basalt provinces, from the very ancient geologic eras to the youngest on Earth (i.e., the Columbia River Basalt Group), consist almost entirely of pāhoehoe lavas. Vents for the lavas are rarely preserved, but the vent system for the Roza flow field of the Columbia River Basalt Group was discovered in 1975 and has recently been restudied (Swanson et al., 1975; Brown et al., 2014). The proximal vent facies show evidence of periodic explosive (fire-fountain) activity (Self et al., 2005) recurring many times during the eruption; thus, the style of activity was somewhat like Hawaiian effusions with accompanying fire-fountain activity, but the volumes of lava produced were magnified many times in scale, and the resulting flow fields are extensive and voluminous.

Flow fields are composed of thousands of lava sheet lobes (Fig. 4). Sheet lobes, and innumerable smaller lobes, stacked and superposed in some places and laterally arranged in others, make up whole flood basalt provinces. Evidence of hiatuses between the eruptions is presented by weathered surfaces on tops of lava flow fields, such as the red boles of the Deccan Traps (Widdowson et al., 1997), but we must remember that flow fields, per se, cannot be recognized in many continental flood basalt provinces, where only subvertical sections through the lavas are exposed. Difficulties in correlating individual lava flows between outcrops (e.g., Jay et al., 2009) presently preclude the recognition of the geographic extent of single flow fields in provinces such as the Deccan Traps.

Emplacement Rates and Lava Volumes

Insights on the lava volume produced and duration of individual eruptions can be gained by studying the physical characteristics of their deposits. Flow fields are composed of many lava flows, which never form a single stretch of lava but consist of a succession of lobes that represent the sequential emplacement of the lava flow (Fig. 4; see Hon et al., 1994; Self et al., 1998). These lava lobes can occur on several scales. For instance, kilometer-scale lobes can be found to include centimeter- to meter-scale lava lobes in the field. One common type in flood basalt provinces is sheet lobes, which are typically several kilometers in lateral dimensions and tens of meters thick. The sheet lobes inflate to a considerable thicknesses during the time that they reach their great extent (Self et al., 1997; Vye-Brown et al., 2013). This suggests a relatively gradual emplacement of the flows over a period of time, most likely years to decades (Thordarson and Self, 1998; Jerram and Widdowson, 2005). Yet, the average lava output rates during an individual continental flood basalt eruption must still have been higher than in any historic eruption except perhaps the extremes of some Icelandic lava outpourings. For example, the time required to emplace a 1000–2000 km^3 lava flow field at the range of peak output rates of the Laki eruption (2000–4000 m^3/s; Thordarson and Self, 2003) would be ~10–20 yr. If the eruptions were much faster (higher magma output rates), then there would be different types of lava in the flow fields, such as ʻaʻā (lava characterized by a rough or rubbly surface), and channeled flows with evidence of thermal erosion at the base of flows (Keszthelyi and Self, 1998; Greeley et al., 1998); if eruptions were much slower, then there would be insufficient time to accommodate the number of lava-producing eruptions, and hiatuses between eruptions, during the geochronologically constrained duration of a main continental flood basalt pulse.

Despite the minimum volumes of individual eruptive units being known for parts of the Columbia River Basalt Group, it is only recently that some understanding has been gained on the possible eruptive volume or mass of flood basalt eruptions from other continental flood basalt provinces, mainly the Deccan Traps of India (e.g., Chenet et al., 2008; Self et al., 2008a). Assumptions about typical flow thicknesses can also give us insights into potential flow volumes. For the Deccan example, if areas from 70,000 to 175,000 km^2 were covered by pāhoehoe lava flow fields during emplacement of some formations in the Wai Subgroup (Self et al., 2006, 2008a), then adopting a range of flow-field thicknesses from 30 to 50 m (Jay et al., 2009) indicates eruptive volumes in the range 2100–8750 km^3. Further, the Mesozoic to Cenozoic continental flood basalt provinces are the best studied and preserved, and the information is biased toward the younger examples. Constraints on the dimensions of almost all eruptive lava flow field units in continental flood basalt provinces are hampered by the effects of burial, tectonism, and erosion since emplacement.

One thing that seems to be exceptional about basaltic large igneous provinces is that most individual eruptions in continental

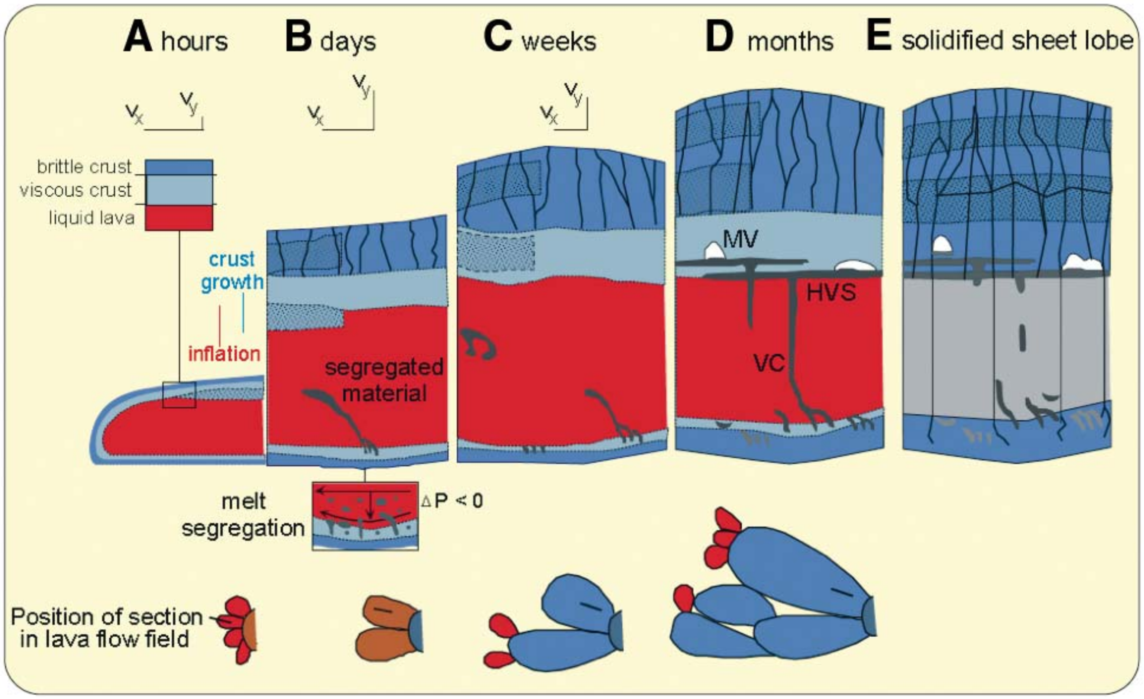

Figure 4. Cartoon showing the development of a pāhoehoe basalt lava flow field over time as the lava sheet lobes grow outward and downslope by advance. Lobes also coalesce and thicken by inflation. Vx and Vy show proportions of lateral and vertical expansion of flow lobe. Inset shows localized separation of flow lines leading to drops in internal pressure (P) and vesiculation at the basal crust-core boundary. Schematic plan view of growing lava flow field is given beneath each stage. MV—megavesicles; HVS—horizontal vesicular sheets; VC—vesicle cylinders. This scheme applies to flood basalt lava flow fields (after Thordarson and Self, 1998).

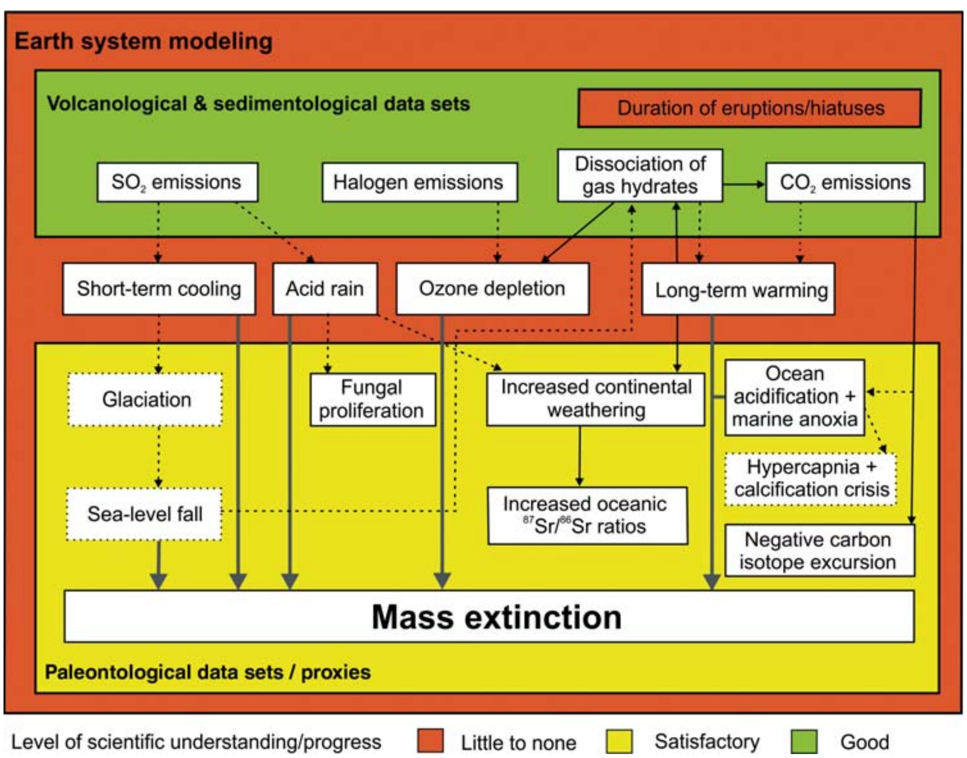

Figure 5. Schematic illustrating some of the proposed environmental effects and Earth system feedbacks of continental flood basalt (CFB) volcanism (adapted from Wignall [2001, 2007], who summarized the chain of feedbacks for the Siberian Traps). Not all volcanic gas emissions and therefore feedbacks shown here are applicable to all continental flood basalt provinces. Dashed lines and box outlines indicate effects and feedbacks that are possible in theory but have not yet been fully quantified or are still debated in the authors' opinion. Light gray arrows indicate main mechanisms thought to cause a mass extinction (either terrestrial or marine or both). The colors indicate the level of scientific understanding and progress of each discipline, illustrating that while the quantification of gas fluxes from continental flood basalt volcanism and paleontological proxies are available (green and yellow), some key mechanistic understanding that links the two is missing (orange). For example, lack of knowledge of the magnitude of short-term cooling from volcanic sulfur, or the amount of acid deposition of volcanic sulfur species, means that some of the proposed cause-and-effect relationships are weak and speculative. Earth system modeling is one of the means by which to quantify these linkages, but there is little scientific progress to date.

flood basalt provinces yielded a huge mass or volume; with a limit of 1×10^{15} kg for a super-eruption (Self, 2006), this is equivalent to ~360 km^3 of basaltic lava, and only a few of the smallest of the Columbia River Basalt Group units may fall below this class. Thus, it seems that when continental flood basalt provinces were forming, they did so by a series of basaltic super-eruptions, each one far exceeding the lower limit of this class (see Bryan et al., 2010, their table 2). However, even though these were huge eruptions volumetrically, in terms of the volcanic explosivity index (VEI; Newhall and Self, 1982), the majority of eruptions may have been VEI 3–4, with occasional explosive (intense fire-fountaining) phases of VEI 5–6 magnitude, analogous to the violent Strombolian and sub-Plinian phases of the Laki eruption (Thordarson and Self, 1993; Woods, 1993).

GAS RELEASE FROM CONTINENTAL FLOOD BASALT ERUPTIONS

One of the main ways in which volcanism impacts our atmosphere and environment is via the release of volcanic gases. Figure 5 summarizes some of the ways in which these gases may have affected the atmosphere and the environment in the geological past, including feedbacks that have been proposed to lead to sufficient ecosystem stress to cause a mass extinction.

In general, water vapor (H_2O) is the most abundant volatile species released during an eruption (contributing between 50% and 90% by volume of the gas phase) followed by carbon dioxide (CO_2), which contributes between 1% and 40% by volume (Gerlach, 2004). Halogens are released in minor quantities, mainly in the form of hydrogen chloride, hydrogen fluoride, and, with even lower abundance, hydrogen bromide and hydrogen iodide (Pyle and Mather, 2009). Despite their low abundance compared with other species, halogens play an important role in volcanic plume chemistry (von Glasow, 2010). Halogens efficiently destroy ozone; however, under low stratospheric chlorine loadings, an eruption must deliver sufficient chlorine directly into the stratosphere for heterogeneous reactions that promote chlorine activation on liquid sulfate aerosol to take place (Solomon et al., 1998). Whether or not volcanic eruptions can deliver sufficient halogens to stratospheric altitudes is, however, still a matter of debate (e.g., Tabazadeh and Turco, 1993; Kutterolf et al., 2013). To date, sulfur dioxide (SO_2) is the sole volatile species released during volcanic eruptions that, following conversion to sulfate aerosol, has been shown to alter the radiative balance of the atmosphere to a measurable extent (e.g., Robock, 2000). Sulfur (S) species contribute between 2% and 35% by volume of the gas phase, and SO_2 and hydrogen sulfide (H_2S) are most abundant (Gerlach, 2004; Textor et al., 2003, 2004).

Estimates of the volatile content of magmas from past eruptions usually come from melt (now glass) inclusions trapped within crystals, which is feasible but challenging for continental flood basalt volcanism, because both crystals and preserved degassed matrix glass are rare in continental flood basalt lavas, and both crystals and glassy lava are often (but not always) altered due to the great age of many continental flood basalt lavas (e.g., Blake et al., 2010). In Table 1, we have compiled published estimates of the amount of gases released by continental flood basalt eruptions and compared these estimates to those for explosive volcanism and flood basalt eruptions in historic times. Basaltic magmas, including those that form flood basalts, are usually rich in dissolved sulfur (commonly with sulfur concentrations of ≥1500 ppm; Wallace, 2005; Black et al., 2012; Zhang et al., 2013). Therefore, the release of sulfur-rich gases from a large basaltic eruption can be much greater than that from an explosive silicic eruption of equal volume. Not all volatile emissions from continental flood basalt provinces may come from the basalts. Minor volatile emissions may arise from silicic volcanism associated with continental flood basalt provinces (Scaillet and Macdonald, 2006; Bryan et al., 2010; Bryan and Ferrari, 2013). Recent evidence, especially from the Siberian Traps, has also highlighted the potentially important role of gas released via interactions between the magma and country rock (Ganino and Arndt, 2009; Svensen et al., 2009). These will be discussed further later herein.

Although data are still sparse (Table 1), comparisons can be made in terms of the gas release budgets from the magmas associated with different continental flood basalt provinces. Self et al. (2008b) measured major-element and volatile composition of melt inclusions and groundmass glass in the quenched products of the Deccan Trap lavas and estimated that individual decade-long continental flood basalt eruptions could have released up to 5000 Mt of SO_2, which equates to a total SO_2 release of up to 6.5×10^6 Mt estimated for the Deccan Trap province as a whole. Within the Columbia River Basalt Group, the Roza flow released ~1200 Mt of SO_2 per year for a decade or longer (Thordarson and Self, 1996), and the Grande Ronde Basalts appear to have released ~10^6 Mt SO_2 in intermittent bursts of <1000–30,000 Mt, separated by long-lasting non-eruptive intervals represented by thick soil horizons in the lava sequence (Blake et al., 2010). Estimates of the total SO_2 emission from the Siberian Traps are in the range 10–20 × 10^6 Mt SO_2 (Black et al., 2012). Typically, for every 1 km^3 of basaltic magma emplaced during a continental flood basalt eruption, 3.5–6.5 Mt of SO_2 will be released (Self et al., 2005; Blake et al., 2010). For context, studies of the Laki lava flows and ash indicate that the magma originally contained ~1700 ppm of sulfur, and that the eruption could have released ~120 Mt of SO_2 from the vent and lava flows (~15 km^3 in volume) over the course of 8 mo (two-thirds of which were released during the first 2 mo of intense activity; Thordarson and Self, 1993; Thordarson et al., 1996). The 1991 Mount Pinatubo eruption (Philippines) was the largest explosive volcanic eruption since 1912 and released ~20 Mt of SO_2 into the stratosphere. For context, the anthropogenic SO_2 flux to the atmosphere in 2005 was ~118 Mt (Smith et al., 2011).

Estimates of the halogen content of continental flood basalt magmas are more sparse than for sulfur. In some cases, the halogens appear to stay in the melt phase of the magma, suggesting limited degassing during eruption. This is probably controlled by details of the oxidation and degassing history as the magmas rise.

TABLE 1. SUMMARY OF PUBLISHED ERUPTION SOURCE PARAMETERS FOR DIFFERENT ERUPTION TYPES AND ERUPTION STYLES

Mode	Age of activity	Duration total	Estimate of total subaerial gases released (Mt)				Height of injection	References
			SO_2	CO_2	HCl	HF		
Present-day persistent emissions (Mt/yr)	Present day	Continuous	13 ± 5	65–540	4.3 ± 1	0.5 ± 0.2	Passive emissions vary with volcano summit height (most >1 km). In terms of SO_2: ~10 Mt/yr passive to troposphere, ~1–4 Mt/yr on average to stratosphere from "large" eruptions and rest from sporadic "small" eruptions to troposphere.	Pyle and Mather (2009); Stoiber et al. (1987); Andres and Kasgnoc (1998); Halmer et al. (2002); Pyle and Mather (2003); Mather et al. (2003); Burton et al. (2013); Graf et al. (1997).
Pinatubo (largest eruption of the satellite era)	1991	5 h (climactic phase)	12–26*	42	3–4.5		>30	Krueger et al. (1995); McCormick et al. (1995); Westrich and Gerlach (1992); Gerlach et al. (1996)
Tambora (largest historic eruption)	1815	5–6 d (climax ~24 h)	20–200	Not estimated	100		43	Oppenheimer (2003)
Youngest Toba Tuff (largest Quaternary eruption)	ca. 74 ka	9–14 d	25–3300	Not estimated	1000	1000	32–40	Oppenheimer (2002); Chesner and Luhr (2010)
Continental flood basalt volcanism (limited to cases where magmatic gas fluxes are published)								
Columbia River Basalt Group (CRBG, ca. 17–6 Ma)†								
Grande Ronde Basalts (CRBG)	ca. 16–15.6 Ma	0.4 m.y.	1×10^{6}§	Not estimated	Not estimated	Not estimated		Blake et al. (2010)
Roza Member (CRBG)	ca. 14.7 Ma	~10 yr	~12,420	Not estimated	~710	~1780	~9620 Mt SO_2, ~400 Mt HCl, and ~1450 Mt HF released at vents into 7–13 km altitude.	Thordarson and Self (1996)
Deccan Traps#	ca. 67–63 Ma	4 m.y. period, with most activity within a 1 m.y. period. Pulses of tens–thousands years with hiatuses of 10^3–10^4 yr.	3.5–6.5 × 10^{6}**	1.4×10^{7}††	1×10^6	Not estimated	Volatiles released from vents to altitudes between 7–15 km.	Self et al. (2006, 2008b)
Paraná-Etendeka Province§§	ca. 132 Ma	~1 m.y.	6.2–10.8 × 10^{6}##	Not estimated	7.2–48 × 10^4	6.3–12.6 × 10^5		Marks et al. (2014)
Siberian Traps***	ca. 252–248 Ma	Bulk of the eruption occurred during <1 m.y. period.	~12.6–15.6 × 10^{6}†††	Not estimated§§§	~3.4–8.7 × 10^6	~7.1–13.6 × 10^6	Uncertain but injection into the stratosphere is likely during more violent explosive phases. Early fragmental deposits of uncertain eruptive style.	Black et al. (2012, 2013)
Emeishan province###	ca. 262–256 Ma		1.5 × 10^{6}****	16.8 × 10^{6}††††	Not estimated	Not estimated	Volatiles released from vents into altitudes between 7–15 km. Violent phreatomagmatic phases at the onset of activity might have injected volatiles to altitudes >15 km.	Zhang et al. (2013); Wignall et al. (2009); Ganino and Arndt (2009)
Laki	June 1783 to February 1784 CE	8 mo	122§§§§	304	~7	~15	6–13 km emitting ~95 Tg Mt SO_2, ~3.5 Mt HCl, and 8.3 Tg Mt HF at the vents to the upper troposphere/lower stratosphere.	Thordarson and Self (2003); Thordarson et al. (1996); Hartley et al. (2014)

Note: Estimates of continental flood basalt ages, durations, and paleolatitude are from Kelley (2007), Rampino and Self (2000), and sources therein. Estimates of the nature of associated country rock are from Ganino and Arndt (2009).

*20 usually accepted value.

†Total volume ~0.25 × 10^6 km^3 with a duration of the peak pulse ≤0.5 m.y. (for 72%). Its paleolatitude was 45°N. Associated country rock thought to be granitoid/gneiss, sandstone/conglomerate, and shale/silt.

§Delivered in intermittent bursts of <1 to 30 Gt separated by long noneruptive intervals.

#Total volume >1.3 × 10^6 km^3 with a duration of the peak pulse ≤1 m.y. Its paleolatitude was ~20°S. Associated country rock is granitoid/gneiss, sandstone/conglomerate, and shale/silt.

**This is based on an estimate of 10^6 km^3 of lava for the Deccan Trap province. Evidence suggests that fluxes of 10^2–10^3 Mt of SO_2 per year might have been sustained during eruptive phases for a decade.

††Based on Self et al. (2006), who estimated for 10^3 km^3 and scaled up for 10^6 km^3. They estimated 220–1100 Mt/yr for 10–50 yr pulses of 10^3 km^3 of lava.

§§Its paleolatitude was 40°S. Associated country rock thought to be granitoid/gneiss, sandstone/conglomerate and shale/silt.

##Based on a volume of extruded magma in the province of 2.2 to 2.35 × 10^6 km^3 and previously published degassing efficiencies. Scaillet and Macdonald (2006) suggest a further 9.2 × 10^3 Mt SO_2 for the metaluminous silicic magmas associated with the flood basalts.

***Total volume >2 × 10^6 km^3 with a duration of the peak pulse ≤1 m.y. Its paleolatitude was 60–65°N. Associated country rock thought to be limestone, coal, shale/silt, and evaporite.

†††Based on an estimate of 4 × 10^6 km^3 of lava for the Siberian Trap province.

§§§Estimates of up to >100,000 Gt CO_2 from metamorphism of organic matter and petroleum (Svensen et al., 2009) as well as large quantities of CH_4 (from organic-rich shale and coal) and CH_3Cl (from limestones and rock salt) (Aarnes et al., 2011).

###Total volume ~0.4 × 10^6 km^3 with a duration of the peak pulse 1–2 m.y. Its paleolatitude was 25°N. Associated country rock thought to be limestone, dolomite, sandstone/conglomerate, and shale/silt.

****Based on a total lava volume of ~0.3 × 10^6 km^3 (Zhang et al., 2013, and references therein).

††††Estimates of additional CO_2 emissions of 61,600–145,600 Gt from contact aureoles with country rock sediments.

§§§§Based on an estimate of 14.7 ± 1.0 km^3 of lava (Thordarson and Self, 1993).

However, estimates for the Deccan Traps and the Siberian Traps suggest that emissions of chlorine and fluorine might be of the same order of magnitude as those of sulfur (Table 1; Self et al., 2008b; Black et al., 2012), or possibly higher (Sobolev et al., 2011). Further, there has been speculation that chlorine emissions from the Deccan Traps might account for a Cl-rich layer of sediments identified in France and Italy (Font et al., 2011). Volcanic bromine has greater potential ozone depletion efficiency than other volcanic halogen species; however, due to its low concentrations in the melt and analytical challenges, our understanding of volcanic bromine release is in its relative infancy (Pyle and Mather, 2009; Mather et al., 2012). A recent study by Kutterolf et al. (2013) suggested that new techniques such as synchrotron radiation might one day hold promise for studying bromine emissions from continental flood basalt volcanism.

Direct determinations of the amounts of CO_2 that might be degassed from flood basalt magmas upon eruption are not available. However, it is known that CO_2 is relatively insoluble in basaltic melts and that the mantle is undersaturated with respect to CO_2. Self et al. (2006) adopted 0.5 wt% as a high, but reasonable, value for pre-eruptive CO_2 concentration in flood basalt magmas and considered that magma degassing is a highly efficient process, with 70%–80% of the gas released at the eruptive vents (Thordarson et al., 2003). Self et al. (2006) estimated that ~1.4×10^{10} kg, or 14 Mt of CO_2, could be released for every 1 km^3 of basaltic lava erupted (assuming a density of 2750 kg m^{-3}). Therefore, the total release from an erupted lava volume of 1000 km^3 (the approximate volume for one eruption in the Deccan Traps) might be ~14×10^3 Mt of CO_2 (or 1.4×10^7 Mt CO_2 from the emplacement of the entire Deccan Traps). Ganino and Arndt (2009) used similar reasoning to estimate an emission of 16.8×10^6 Mt magmatic CO_2 for the Emeishan Province. These are the only estimates of CO_2 released from a continental flood basalt province that we are aware of to date (Table 1). While the emission from a single Deccan eruption is a very large mass, it should be noted that it represents less than 1/200th of the amount of CO_2 present in the modern atmosphere (~3×10^6 Mt, or 3×10^{15} kg). For comparison, the current anthropogenic emissions of CO_2 to the atmosphere are ~35 Gt/yr (Le Quéré et al., 2013). Thus, the annual CO_2 flux from a single Deccan eruption equates to only 40% of the current anthropogenic CO_2 flux under the assumption that all 14 Gt of magmatic CO_2 is emitted in an unrealistically short period of a year. If released over a more realistic decade time scale, these volcanic emissions represent ~4% of the current anthropogenic flux only. However, CO_2 has long atmospheric residence times, and the weathering of huge areas of basaltic rock could also have affected atmospheric CO_2 concentrations (Dessert et al., 2001) and/or ocean acidity, which could be tested in the future using state-of-the-art carbon cycle models that account for the "long tail" of CO_2 emissions.

As mentioned already, the volatile load carried by the basalts might only account for part of the release of gases to the atmosphere associated with continental flood basalt volcanism. Recent studies have suggested that gases released from nonmagmatic sources may make an important additional contribution to the gas release budget of continental flood basalt volcanism or indeed might dominate. For example, Ganino and Arndt (2009) have correlated the degree of environmental stress caused by continental flood basalt volcanism with the types of sediments beneath the lavas and estimated that emission of CO_2 from contact aureoles with the sedimentary country rock could have been 4–9 times larger than that released from the magma for the Emeishan Traps. In the case of the Siberian Traps, it has been suggested that magma-sediment interactions could dissociate vast quantities of hydrocarbons and halocarbons such as methane from heating of organic-rich shale and petroleum-bearing evaporates (basin-scale gas production potential estimates suggest that metamorphism of organic matter and petroleum could have generated >100,000 Gt CO_2), resulting in global warming and ozone depletion (Aarnes et al., 2011; Svensen et al., 2009). The suggested mechanism of gas release is through hydrothermal vent complexes, which are now being recognized as a characteristic component of large igneous provinces (for a review, see Svensen and Jamtveit, 2010). Iacono-Marziano et al. (2012a, 2012b) suggested that the release of vast amounts of reduced gases due to magma intrusion in the coaliferous sediments beneath the Siberian province contributed to global warming and to the negative carbon isotopic shift observed at the end-Permian. Grasby et al. (2011) suggested that deposition of coal fly-ash generated by magma-coal pyrometamorphism in the Siberian province resulted in toxic marine conditions. Black et al. (2013) presented modeling to suggest that the halocarbon release from crustal reservoirs associated with Siberian Traps volcanism (Aarnes et al., 2011) could have had significant effects on stratospheric ozone levels. It should be noted that the tropospheric lifetime of halocarbons such as CH_3Cl is sufficiently long (>1 yr) that even those released in the lower troposphere reach the stratosphere, reducing the sensitivity of their environmental effects to atmospheric injection.

GAS INJECTION HEIGHTS OF FLOOD BASALT ERUPTIONS

Basaltic eruptions are commonly more effusive (i.e., lava producing) in character, last much longer, and are much less explosive than silicic eruptions of comparable volume. Basaltic eruptions are also commonly considered to be much less effective in lofting gases into the stratosphere, where gas and aerosol particle lifetimes are longer than in the troposphere. Observations and plume model simulations (Woods, 1993; see Self et al., 2005) suggest, however, that the high eruption rates during the CE 1783–1784 Laki eruption in Iceland produced tall fire-fountains (600–1450 m), so that the convective plume rising above the fountains could have attained altitudes of up to 15 km above sea level (Thordarson et al., 1996; see Fig. 6), which is above the Icelandic tropopause during the summer months. By analogy, at the maximum eruption rates for Laki, the Roza flow eruption of the Columbia River Basalt Group would have produced lava fountains more than 1.5 km in height and may have created a convective column rising ~13–15 km above the volcanic vents (Table 1; Self et al., 2005; Brown et al., 2014).

Extensive ash deposits are associated with Icelandic basaltic fissure eruptions, such as Eldgjá, and the occurrences of deposits of spatter, spatter-fed lava, and scoria mounds along Columbia River Basalt Group eruptive fissures suggest violent to sometimes mild fire-fountaining during flood basalt eruptions. In support of this, observations of a widespread sulfurous haze over Europe in 1783 (Thordarson and Self, 2003; Witham and Oppenheimer, 2005; Schmidt et al., 2011), as well as a sulfuric acidity peak in Greenland ice in 1783 suggest that the Laki eruption column reached the lower stratosphere. For the much larger-volume lava flows typical of continental flood basalt eruptions, the models of convective plume height also indicate that sulfur-rich eruption plumes could reach the lower stratosphere by direct injection in an eruption column (Stothers et al., 1986; Thordarson and Self, 1996), or by injection within a volcanic plume helped by convection above a large, active lava field (Kaminski et al., 2011), or perhaps by a lofting of gases into the lower stratosphere in deep convective systems (e.g., Bourassa et al., 2012). Future efforts in this area should also account for paleo-atmospheric temperatures and composition when using plume rise models because the tropopause height is likely to differ significantly compared to the present day in, for example, a much warmer Late Cretaceous atmosphere.

POTENTIAL ENVIRONMENTAL EFFECTS OF CONTINENTAL FLOOD BASALT VOLCANISM

Evidence of the environmental impacts of continental flood basalt volcanism and the processes leading to these effects comes mainly from three sources: (1) direct evidence from the proxy record, (2) historical records of the effects of large-scale volcanic activity such as the Laki flood basalt eruption in 1783 CE, and (3) by scaling up from observations and measurements of the environmental impacts of present-day volcanism, which not only is on a different scale in terms of the mass eruption rate compared with continental flood basalt volcanism but also often differs fundamentally in terms of eruption style. Figure 5 summarizes the processes and feedbacks that have been proposed to have led to severe environmental changes at the time of continental flood basalt volcanism. The details of these processes are reviewed elsewhere (e.g., Officer et al., 1987; Wignall, 2001, 2007). Proposed cause-and-effect mechanisms include, among others, a short-term cooling effect from sulfate aerosol lasting years to decades and the deposition of sulfur species leading to acidification of

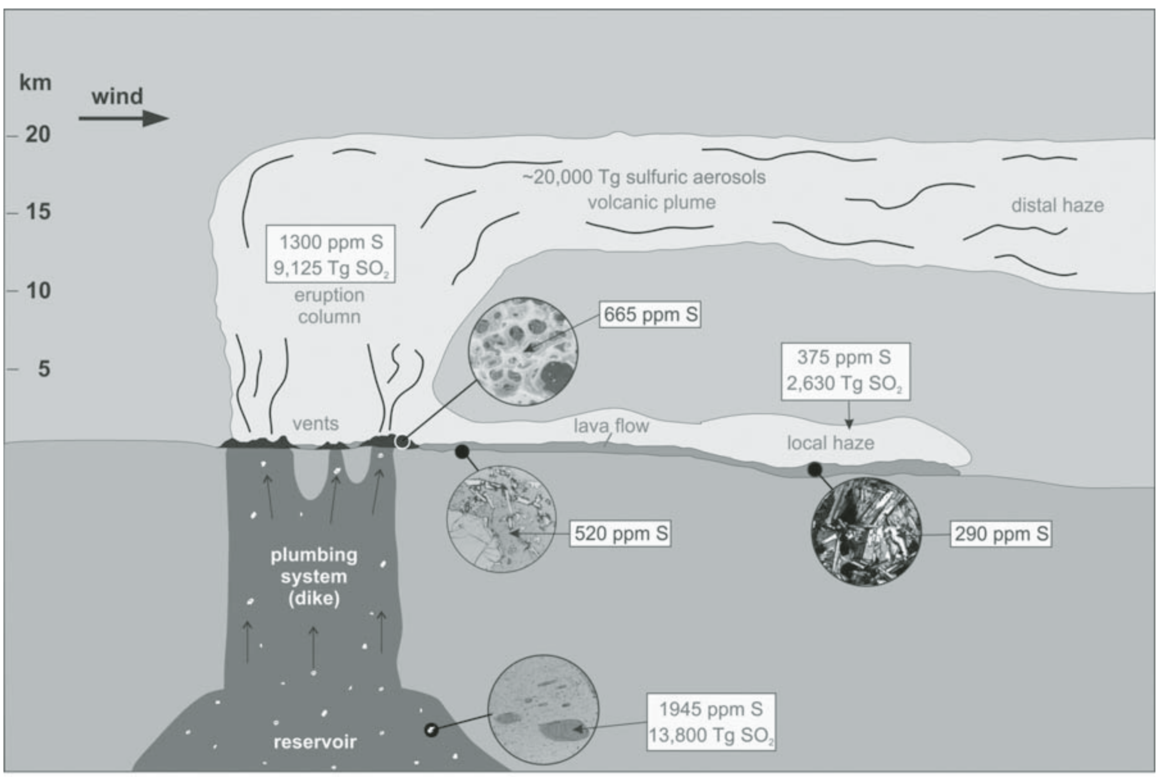

Figure 6. Cartoon showing generalized eruptive style and atmospheric dispersal of gas and aerosol particles (with minor ash) associated with basaltic fissure eruptive activity such as a flood basalt eruption, based on studies of the Roza eruption of the Columbia River Basalt province, Washington, USA (after Thordarson et al., 2009; for a more detailed explanation, see also Self et al., 2005). Tg is terragrams (10^{12} g). Total amount of SO_2 released into the atmosphere is estimated to have been almost 12,000 Tg, ~12 Gt (gigatons), with ~9000 Tg (9 Gt) coming from the vents with the eruption columns.

soils (Black et al., 2013; see the recent review by Bryan and Ferrari, 2013). Proposed long-term effects include global warming from the greenhouse gas forcing of volcanic CO_2 (released by the eruptions) lasting tens to thousands of years (Chenet et al., 2008; Sobolev et al., 2011; Joachimski et al., 2012), which was originally disputed by Caldeira and Rampino (1990) and is still a matter of debate (Self et al., 2006).

The proxy record, including the mass extinction events themselves, clearly suggests significant environmental perturbation around the time of continental flood basalt volcanism (e.g., Li and Keller, 1998; Courtillot and Renne, 2003; Wilf et al., 2003; Visscher et al., 2004; Wignall, 2005; Thibault and Gardin, 2006; Wignall et al., 2009; Keller et al., 2012; Sun et al., 2012; Joachimski et al., 2012; Bryan and Ferrari, 2013). However, one of the challenges that remains is to find a primary marker for the volcanism within these same archives, allowing a clear causal relationship to the environmental perturbation to be developed, rather than purely markers indicating environmental change. Recent efforts in this area have included the use of osmium isotopes (Ravizza and Peucker-Ehrenbrink, 2003; Robinson et al., 2009) and mercury (Sanei et al., 2012; Silva et al., 2014).

The Laki eruption might serve as a key historical analogue in terms of eruption style, but it was much shorter-lived (8 mo) compared with the average length of a continental flood basalt eruption. Modeling studies have demonstrated that its gas and aerosol clouds dispersed widely across the Northern Hemisphere (Chenet et al., 2005; Stevenson et al., 2003; Highwood and Stevenson, 2003; Oman et al., 2006a, 2006b; Schmidt et al., 2010, 2012). Following Laki, winter temperatures in 1783–1784 dropped up to -0.5 °C below average in central Europe (Thordarson and Self, 2003; Witham and Oppenheimer, 2005; Oman et al., 2006a; Schmidt et al., 2012). Given the difference in eruptive volume, duration, and eruption style, scaling the effects of historical and present-day volcanic activity to continental flood basalt scale may be highly flawed, if not impossible. Both observational evidence and modeling of short-lived explosive eruptions have suggested that a simple scaling between eruption magnitude and climatic impact is unlikely to be valid (Rampino and Self, 1982; Pinto et al., 1989; Timmreck et al., 2010; English et al., 2013).

Based on the estimated SO_2 flux for the Roza flow, Thordarson and Self (1996) were the first to estimate a likely change in aerosol optical depth (AOD) of between 7 and 13. For context, this is at least 2.5 times larger than current climate model estimates for the 74 ka Youngest Toba Tuff eruption (peak global mean AOD of 2.6; English et al., 2013). At the time of their study, Thordarson and Self (1996) assumed that all the SO_2 released forms sulfate aerosol particles of a certain size (i.e., the optimum particle size for scattering incoming solar radiation back to space). However, several modeling studies suggested that when considering aerosol microphysical processes, the impact of explosive volcanism on climate becomes self-limited with increasing SO_2 release, because the coagulation of particles causes particles to grow to large sizes, which have a lower optical depth per unit mass and fall out of the atmosphere faster than smaller particles (Pinto et al., 1989; Timmreck et al., 2010; English et al., 2013). Both Stevenson et al. (2003) and Schmidt et al. (2010) have shown that for a Laki-scale eruption, oxidants are heavily depleted, and so sulfate aerosol yields are lower (range 71–173 Mt of sulfate aerosol) than most previous estimates that assumed all SO_2 released was converted to sulfate aerosol (see tables 1 *in* Oman et al., 2006a and Schmidt et al., 2010).

Given the likely nonlinearities in the Earth system response to a continental flood basalt eruption, modeling studies are one of the key tools to allow us to interrogate the impact of volcanism on the environment. There have only been a handful of modeling studies directly tailored to continental flood basalt volcanism to date. This includes a carbon cycle modeling study, which found a negligible effect of magmatic CO_2 emissions from the Deccan Traps on Late Cretaceous temperatures (Caldeira and Rampino, 1990). Iacono-Marziano et al. (2012b) suggested that magma-sediment interactions during the emplacement of the Siberian Traps released vast amounts of reduced carbon monoxide and methane (CH_4), which resulted in enhanced atmospheric lifetimes of these species and a greenhouse gas forcing of climate on the order of 1.9 W/m^2 to 4.2 W/m^2 for a decade-long eruption. Using a two-dimensional (2-D) chemical transport model, Beerling et al. (2007) suggested that the release of hydrogen chloride and methyl chloride during the Siberian Traps eruptions could have resulted in mutagenic effects on plants through increased ultraviolet B (UV-B) radiation as a result of enhanced ozone depletion. Black et al. (2013) conducted the first three-dimensional (3-D) global climate modeling study of volcanic sulfur and halogen species released by a single magmatic episode of the Siberian Traps and suggested that widespread acid rain and global ozone depletion directly contributed to the end-Permian mass extinction. Dessert et al. (2001) showed, based on modeling seawater strontium isotope ratios, that the emplacement of the Deccan Traps basalts had a significant effect on geochemical cycling of carbon and strontium and atmospheric CO_2 concentrations, and hence climate, although Self et al. (2006) suggested that the model run that showed this was based on implausibly rapid emplacement of the Deccan Traps.

The dashed lines in Figure 5 illustrate that many of the environmental effects and Earth system feedbacks proposed for continental flood basalt volcanism are feasible but have not yet been quantified or are still debated, as is the case for volcanic CO_2 emissions and their impact on Late Cretaceous temperatures (e.g., Caldeira and Rampino, 1990; Chenet et al., 2008). Overall, there is a good to satisfactory level of scientific understanding and progress made by volcanologists estimating the amount of gases released during continental flood basalt volcanism and paleontologists gathering proxy records that clearly imply environmental changes. However, some key mechanistic understanding that links volcanic gas release and environmental effects is still missing. Earth system modeling may be one of the means by which to quantify these linkages, but there is little scientific progress to date. Eruption source parameter scenarios are key to meaningful future modeling efforts. In the next section, we therefore attempt to summarize eruption source parameters based on the currently available data discussed herein, which could be used as inputs for Earth system modeling studies.

Work described here has also highlighted the potential importance of magma–country-rock interactions. While Ganino and Arndt (2009) summarized the broad characteristics of the country rock into which the major known continental flood basalt provinces intruded, we are not yet in a position to generalize from better-studied continental flood basalt provinces to others, and so we do not include these emissions in the source parameters suggested for Earth system modeling detailed in the following section. It is clear, however, from the results of more detailed studies of the Emeishan province (Ganino and Arndt, 2009) and Siberian Traps (e.g., Svensen et al., 2009), that additional detailed work focused on each individual continental flood basalt province will further illuminate these processes and their potential impacts in each case. For example, shale metamorphism in the Karoo has been estimated to have emitted ~27,400 Gt CO_2 through breccia pipes (Svensen et al., 2007). The presence of coal deposits in the Karoo Basin (Cadle et al., 1993) also offers the intriguing possibility of interactions with the intrusive activity in this setting, as well as the Siberian Traps, although further investigation is needed to determine the potential size of this effect (Gröcke et al., 2009).

ERUPTION SOURCE PARAMETERS FOR EARTH SYSTEM MODELING

The Roza lava flow field in the Columbia River Basalt Group is the only individual continental flood basalt eruption for which information about the eruption source parameters is reasonably well constrained based on the geological record (see earlier). At the minimum, information on the volcanic gas flux and the eruption duration is needed as inputs for atmospheric modeling studies. For the majority of continental flood basalt provinces, these eruption source parameters are highly uncertain; yet they are crucial for the assessment of the length and severity of any potential environmental effects and Earth system feedbacks. For instance, if the non-eruptive phases (hiatuses) outlasted the duration of the volcanic sulfate aerosol forcing, then the Earth system would have had ample time to recover after an eruptive phase, which clearly weakens the feedback chain through to mass extinctions in Figure 5. Even hiatuses as short as 50 yr may leave ample time for the Earth system to recover from the cooling of climate caused by volcanic sulfur released during a decade-long continental flood basalt eruption.

Based on published data (Table 1) of the magmatic volatile release per cubic kilometer of lava emplaced (Fig. 7A) and the volume of lava emplaced per year (Fig. 7B), we calculate a mean SO_2 release of ~670 Mt per year for flood basalt eruptions (Fig. 7C). Individual continental flood basalt eruptions could have lasted between 10 and 50 yr (longer eruptions might be possible, but there is no recent analogue or any evidence to make informed estimates). Non-eruptive phases could have lasted many thousands of years, but overall we have little knowledge about their length and frequency. Red boles (soils) that are found sandwiched between the lava flow fields of the Deccan Traps (Widdowson et al., 1997) are thought to form on time scales of several hundreds to thousands of years (Fig. 7D), although in parts of the Deccan lavas, Chenet et al. (2008) made a case for soils forming in much less than 100 yr.

Other parameters needed for a model simulation are the injection height of the gases and the eruption style. The injection height in particular is difficult to constrain directly from the volcanic deposits. However, based on the similarity of the volcanic deposits and the chemical composition of the volcanic products, we can infer that large-scale flood basalt eruptions in historic times such as Laki provide a feasible and well-constrained analogue of the eruption style in the Columbia River Basalt Group and the Deccan Traps (Thordarson et al., 1996); that is a quasi-continuous injection of volcanic gases into the upper troposphere–lower stratosphere.

In summary, based on currently available data, eruption scenarios can be developed with some confidence for the SO_2 released from the Columbia River Basalt Group and the Deccan Traps lavas. By analogy, scenarios for the CO_2 release of the Deccan Traps or the release of halogen species by the Siberian Traps could follow this "template." However, for the Siberian Traps, detailed information on individual eruption volumes is lacking. Based on the volcanic deposits, the eruption type and style of the Columbia River Basalt Group and the Deccan Traps appear to be most commonly associated with emplacement of continental flood basalt provinces. Therefore, the suggested volume of lava emplaced per year and the gas flux per year for the Columbia River Basalt Group and Deccan Traps (Figs. 7B and 7C) may be a reasonable starting point for atmospheric modeling. Other continental flood basalt provinces such as the Siberian Traps may have exhibited large-magnitude explosive phases and also liberated substantial amounts of halogens, both directly via magmatic gases (Sobolev et al., 2011; Black et al., 2012, 2013) and via magma–country-rock interactions (Svensen et al., 2009; Iacono-Marziano et al., 2012a, 2012b; Ganino and Arndt, 2009). Black et al. (2013) addressed these uncertainties by modeling 27 perturbation and recovery scenarios to approximate gas release from plausible magmatic episodes, including a large pyroclastic eruption, metamorphism of hydrocarbon-bearing evaporite salts, and one or more explosive pipes, as well as stratospheric versus tropospheric injection. Overall, there is no simple way to generalize these scenarios for continental flood basalt volcanism as a whole; rather, when it comes to interactions with sedimentary rocks in the crust, we very much need to assess continental flood basalt provinces on a case-by-case basis.

SUMMARY

Continental flood basalt provinces are the subaerial expression of large igneous province volcanism, and their emplacements are exceptional volcanic events in the geological history of

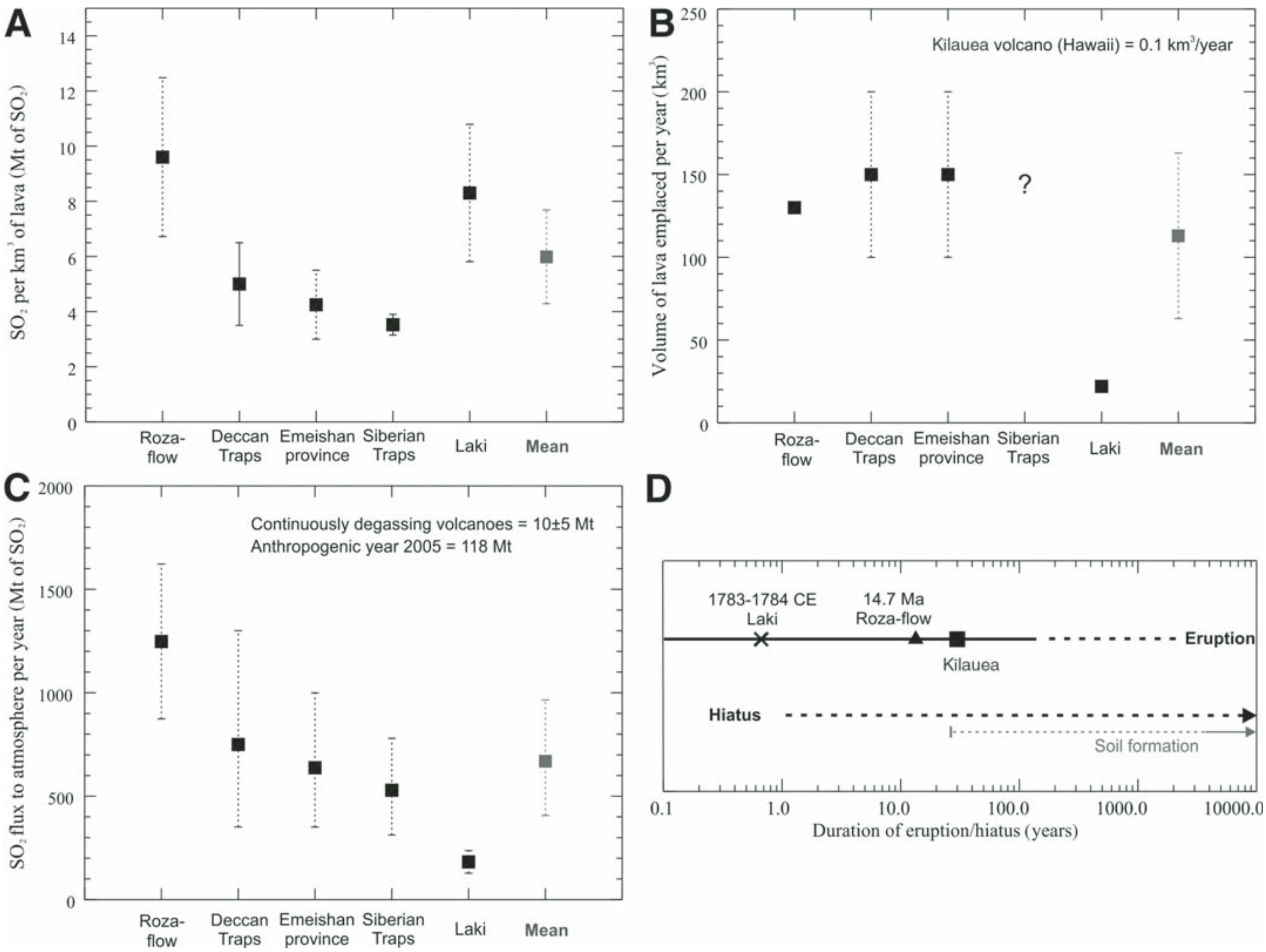

Figure 7. Compilation of eruption source parameters for flood basalt eruptions (see also Table 1 and references listed there), which could be used as inputs for Earth system modeling studies. (A) The amount of sulfur dioxide (SO_2) released per cubic kilometer (km^3) of lava erupted based on measurements of glass inclusions and groundmass glass in the quenched lava products. Dashed error bars indicate that a ±30% uncertainty is assumed, whereas solid error bars represent a reported analytical error. (B) The volume of lava erupted per year during an eruption based on estimates of the volume and duration of an average flow field in each province or, in the case of 1783–1784 CE Laki, a flood basalt eruption in historic times. Dashed error bars indicate that these estimates are highly uncertain. For the Siberian Traps, there is no estimate of the annual lava emplacement rate available as indicated by the question mark. For context, Kīlauea volcano on Hawai`i emplaced ~0.1 km^3 of lava per year averaged over the years 1983–2012 (USGS, 2013). (C) Combining data from (A) and (B), we derived the annual flux of SO_2 to the atmosphere. For context, the annual global mean flux of SO_2 from anthropogenic sources was ~118 Mt of SO_2 in the year 2005 (Smith et al., 2011), and continuously degassing volcanoes release ~10 ± 5 Mt of SO_2 per year (Graf et al., 1997, and references therein). Upper and lower limits shown in (C) are derived by accounting for both the error on the SO_2 measurements as shown in (A) and the error on the emplacement volume of a flow field as shown in (B). The mean is derived by averaging all flood basalt eruptions for which we have data. (D) Estimates of the duration of eruptions and non-eruptive phases for flood basalt volcanism. The latter are highly uncertain as indicated by the dashed lines. Time scales for formation of soils (and/or red boles) on lava flow tops, as observed in the Deccan Traps, have been estimated to be between tens and thousands of years (Chenet et al., 2008; Widdowson et al., 1997).

our planet, forming up to 4×10^6 km^3 of lava flows in as little as 2 m.y. For context, this volume would cover an area the size of the United States of America in 400 m of lava.

Continental flood basalt provinces appear to have formed within 1–3 m.y., and within this period, one or more pulses of great magma production and lava eruption took place, lasting from 1 m.y. to as little as a few hundred thousand years. The frequency and length of these voluminous lava-producing pulses are ill-defined. Each of these pulses featured tens to hundreds of individual eruptions, each producing up to possibly 10,000 km^3, or more usually 1000–5000 km^3, of predominantly pāhoehoe lava. The eruption of the 14.7 Ma Roza flow field of the Columbia

River Basalt Group (the youngest continental flood basalt province on Earth) produced a 1300 km^3 lava flow field and is the only eruptive phase for which a duration of between 10–15 yr has been estimated (Thordarson and Self, 1998). For other continental flood basalt provinces, we can only infer that eruptions lasted decades to probably centuries, based on analogy to the Roza flow and the dominance of pāhoehoe lava flow fields and the similarity of the chemical composition (i.e., tholeiitic melts) of the volcanic products between continental flood basalt provinces.

By measuring major-element and volatile composition of melt inclusions and groundmass glass in the quenched products of the Deccan Trap lavas, Self et al. (2008b) estimated that a decade-long eruption producing a 1000 km^3 lava flow field could have released 5000 Mt of SO_2 into the atmosphere. The Roza flow released ~12,000 Mt of SO_2 over the course of 10–15 yr (Thordarson and Self, 1996). Based on published estimates of the volcanic gas flux, it appears that for every 1 km^3 of basaltic magma emplaced during a continental flood basalt eruption, 6 ± 1.7 Mt of SO_2 could be released (Fig. 7C). Compared to an explosive silicic eruption of equal volume, the typical mass of sulfur-rich gases released from a large basaltic eruption is therefore much greater.

The majority of magmatic gas species released during continental flood basalt volcanism had the potential to alter climate and/or atmospheric composition, in particular during violent explosive phases at the eruptive vents when the gases were lofted into the stratosphere. However, the fate of these gases is more difficult to understand at present. For example, we have little knowledge about the atmospheric burdens, the atmospheric lifetimes, and the climatic impact of the magmatic sulfur- and halogen-bearing species released during a typical continental flood basalt eruption, but recent efforts in this direction include the use of global climate models (Black et al., 2013). Aside from the direct release of magmatic gases, the interaction of magma with the sedimentary bedrock during the emplacement of some continental flood basalt provinces could have released additional carbon and possibly sulfur and halogen-bearing species into the atmosphere (e.g., Svensen et al., 2009; Iacono-Marziano et al., 2012a, 2012b; Ganino and Arndt, 2009). Given the particular nature of these interactions in different provinces, it is difficult to generalize from one province to another, and further work is needed to constrain the magnitude of these emissions on a case-by-case basis.

The general coincidence of continental flood basalt volcanism with times of major biotic change is well substantiated to within the limits of radiometric age determinations; however, the mechanisms by which continental flood basalt volcanism might have perturbed the environment to such a great extent are not well understood. Figure 5 not only summarizes proposed mechanisms by which continental flood basalt volcanism could have triggered biotic crises, but it also gives our opinion concerning the level of current scientific understanding and progress made by specific scientific disciplines. Greater research efforts are to be encouraged in terms of the processes represented throughout Figure 5. Very little scientific progress has been made by means of atmospheric and (paleo-)Earth system modeling, which may help to, for instance, quantify the magnitude of the short-term reduction of temperatures or the effects of acid rain from volcanic sulfur deposition (Black et al., 2013). Given the likely differences in the Earth system response during different periods of Earth history, this is best done for each continental flood basalt province on a case-by-case basis. Notwithstanding the above, our knowledge of the number and length of non-eruptive phases (hiatuses) during continental flood basalt volcanism is far from complete—yet it is critical for quantifying the severity and duration of any environmental effects potentially caused by continental flood basalt volcanism.

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