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Volatile fluxes during flood basalt eruptions and potential effects on the global environment: A Deccan perspective

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Abstract

We examine the role that flood basalt eruptions may have played during times of mass extinction through the release of volcanic gases. Continental flood basalt provinces have formed by numerous eruptions over a short period of geologic time, characteristically a few million years. Within this period, a short-lived climactic phase that lasts about 1 Ma typically emplaces a large proportion of the lava volume. This phase consists of a series of huge eruptions, each yielding 10^3–10^4 km^3 of magma. Each eruption lasted on the order of a decade or more, and built an immense pāhoehoe-dominated lava flow field by eruptive activity along fissures tens to hundreds of km long. High fire-fountains, emanating from vents along the fissures, at times sustained eruption columns that lofted gas and ash into the upper troposphere and lower stratosphere while the lava flows covered huge areas. The combination of large eruption magnitudes, maintained high effusion rates during eruptions, and the repeated nature of the characteristic, large-scale eruptive activity occurs in Earth history only during periods of flood basalt volcanism. Based on recent analogs and determination of volatile contents of ancient flood basalt lavas, we estimate that individual eruptions were capable of releasing 10,000 Tg of SO_2, resulting in atmospheric loadings of 1000 Tg a^{-1} during a sustained decade-long eruptive event. We apply this model of flood basalt volcanism to estimate the potential mass of CO_2 and SO_2 released during formation of the ~65 Ma Deccan province. The Deccan lava-pile contains the record of hundreds of enormous pāhoehoe flow-fields erupted within a period of about 1 Ma. Consequently, atmospheric perturbations associated with SO_2 emissions from just one of these long-lasting eruptions were likely to have been severe, and constantly augmented over a decade or longer. By contrast, the amounts of CO_2 released would have been small compared with the mass already present in the atmosphere, and thus much more limited in effect. Individual eruptions were followed by hiatuses of hundreds to thousands of years during which the gas contributions to the atmosphere would be recycled. It is clear that the nature and potential atmospheric impact of a series of huge-volume, repeated, long-term degassing events requires further investigation in conjunction with appropriate climate models.

Keywords: flood basalts; eruptions; Deccan province; sulphur gas; carbon dioxide; Cretaceous–Tertiary boundary

1. Introduction

Extinction events are important factors in the history of life on Earth, and many studies suggest catastrophic causes for at least some major mass extinctions. Two types of catastrophic event have been invoked: major impacts by

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asteroids or comets [1] and episodes of continental flood basalt volcanism [2]. As an example of the first cause, the end-Cretaceous (~65 Myr) mass extinction has been correlated with the impact of a 10-km-diameter asteroid with Earth, e.g. [3], which undoubtedly would have had severe environmental consequences [4]. However, apart from that example, convincing evidence of impacts has yet to be found at the times of other major extinction events [5]. In support of the second cause, the apparent coincidence flood basalts volcanism such as that of the Deccan province (India) with the end-Cretaceous mass extinction, the Siberian flood basalt province with the severe end-Permian extinction at ~250 Ma ago, and the Central Atlantic Magmatic Province with the end-Triassic extinction event [6,7], all suggest that flood basalt eruptions may have significantly contributed to a number of global biotic crises. Several studies have compared the dates of extinction events of various magnitudes with the timing of flood basalt episodes and found strong correlations that support a possible cause-and-effect connection (e.g., [8–10]). Thus, extreme events of both terrestrial and extraterrestrial origin may be responsible for many of the 'punctuation marks' in the history of life on Earth [11–15].

Based on recent analog eruptive activity [16], and determination of volatile contents of ancient flood basalt lavas, it is estimated that individual eruptions were capable of releasing on the order 10,000 Tg of SO_2 [17,18]. This could have resulted in a sustained atmospheric loading of 1000 Tg yr^{-1} over a 10-yr-long eruption duration, assuming constant effusion rates. Such fluxes of S gas are enormous when compared to even the largest historic eruption, and the impact upon the atmosphere and climate are likely to have been significant.

Here we examine the role that flood basalt eruptions might have played during times of mass extinction, highlighting the Deccan volcanism that occurred at the time of the 65 Myr mass extinction event. We restrict this study to subaerial flood basalt eruptions, and consider only the potential amounts of sulphur (S), as its common gas sulphur dioxide (SO_2), and carbon dioxide (CO_2) that would have been released to the atmosphere. Estimates of how flood basalt volcanism might affect the atmosphere, climate, and hence the global environment are presented and these general considerations are applied to the Deccan lava succession. We do not include discussion of any explosive activity that may have accompanied, or was associated with, the eruption of the Deccan lavas (e.g., [19,20]), apart from that which occurred at the vents. Nevertheless, it is clear that such explosive activity could have significantly augmented the delivery of gases and ash to higher levels of the atmosphere. The aim of this work, therefore, is to provide key information and estimates that will better inform modeling of atmospheric effects, and enable the development of improved simulations of the climatic and environmental impact of flood basalt volcanism [21].

2. The extreme nature of continental flood basalt volcanism

The culmination of subaerial flood basalt province formation is unique with respect to all other terrestrial basaltic magmatism because it is characterized by the repeated effusion of huge batches of magma. Individual eruptive events commonly produce lava flow fields with volumes as large as 3×10^3 km^3, exemplified by the flow fields in the Columbia River province [22]. Eruptive events of such magnitude and frequency have not occurred at any other times in Earth history. In fact, the huge volume of magma emitted during individual flood basalt eruptions, the enormous total volumes of lava emplaced during flood basalt province formation (10^5 – >10^6 km^3), and the brief interval of geologic time at the main eruptive phase, [5,9,10], are truly exceptional. Most importantly, these combined factors provide an obvious potential to deliver large masses of volcanic gas into the atmosphere.

It has been long suggested that flood eruptions would have had severe consequences upon the environment (see [5]), and the obvious way in which this could occur is by eruptive degassing. Yet, remarkably, an assessment of the masses of volatiles released, the gas flux during eruptions, gas-release variations over the duration of province formation, and the manner in which gas was introduced into the atmosphere has not been previously attempted. This current work builds on the one published study that provides a gas-release budget for an individual flood basalt event, that of the eruption of the 1300 km^3 Roza flow of the mid-Miocene Columbia River flood basalt province (15 Ma), WA, USA [17].

Over the past few million years, the greatest magnitude of basaltic volcanism has occurred at volcanic centers such as Iceland, and the largest of these eruptions range up to 20–30 km^3 per event. Moreover, modern lava-forming eruptions of the past century have rarely exceeded 1 km^3, with only four greater than that size in the past 120 yrs [23]. By contrast, the formation of a flood basalt province consists of a series of large magnitude eruptions that together produce a thick stack of lava flows. The flows create vast sheets that ultimately combine to cover areas extending to more than a million km^2 and attain aggregate volumes in excess of 10^5 km^3 [24]. Past work suggests that flood basalt provinces are largely composed of pāhoehoe-dominated lava flow fields [25,26] formed by eruptive activity along fissures that were tens to hundreds of km long [27,28].

Data from the 1300 km^3 Roza flow field suggest that the duration of emplacement was more than a decade [28]. This would have required an average volumetric eruption rate as high as the peak attained by the 15 km^3 Laki eruption (AD 1783, Iceland [29,30]), which achieved a maximum volume lava flux of $\sim 4\times10^3$ m s^{-1} (i.e. a mass flux of $\sim 1.1\times10^7$ kg s^{-1} at an erupted lava density of 2750 kg m^{-3}). However, lava effusion rates would have fluctuated over the course of a flood basalt eruption as a result of changes in the active fissure segment and the duration of lava release from that segment. At the Laki peak eruptive rate, effusion rates would be ~ 1.5 to 2 m^3 s^{-1} m^{-1}, or 4 to 5.5×10^3 kg s^{-1} m^{-1} (m = meter length of fissure), for a 2- to 3-km-long active fissure segment. To put this in context, this rate per meter length of fissure is approximately five times that of the total average effusion rate of the current Kilauea basaltic eruption, and eruptions at this rate would deliver 2.5 km^3 of lava per week, whereas the Kilauea eruption has produced just over 2 km^3 in more than 20 yrs [31].

Moreover, when the eruption rate is highest, the activity at the vents is also the most explosive [30]. Extensive ash deposits are associated with Icelandic basaltic fissure eruptions such as Eldgjá, AD 934 [32] and Laki, AD 1783, and the occurrence of deposits of spatter, spatter-fed lava, and scoria mounds along Columbia River province eruptive fissures [27,28,33] suggest occasionally violent to mild fire-fountaining during flood basalt eruptions. Calculations show that fountain heights during periods of peak output may have exceeded 1.5 km for magma volatile (assumed to be water) contents of 1–1.5 wt.% (after [34]). The resulting model estimates for the convective plumes rising above these fountains, based on Woods' [35,36] treatment of the rise of basaltic eruption plumes into a moist atmosphere, indicate eruption column heights in excess of 13 km and are similar to those estimated for the Laki eruption [30]. Clearly, flood basalt eruptive activity is capable of lofting gases and fine ash into the atmosphere above the vent system (Fig. 1), and such eruptive clouds could achieve mid- to

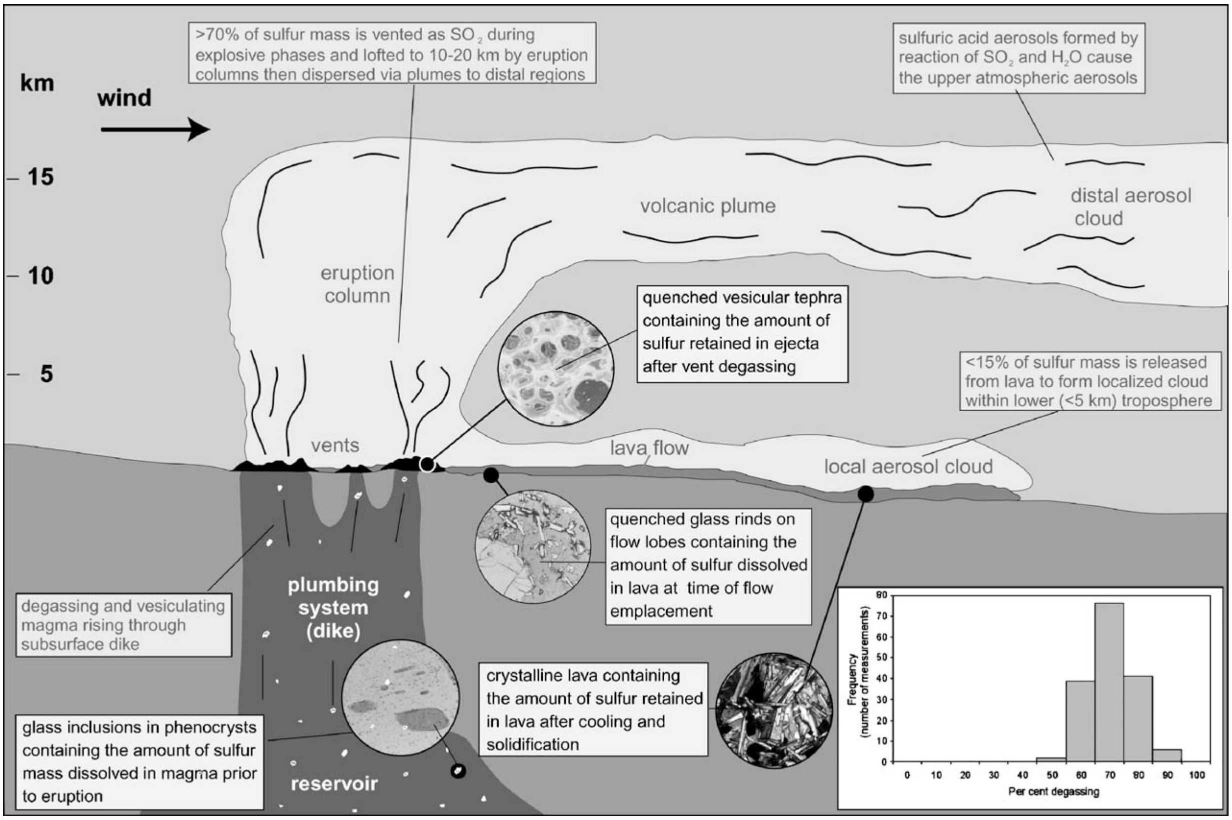

Fig. 1. Schematic illustration showing the key features of two-stage degassing in flood lava eruptions, modified from [18], showing how gas and ash is released and how a sulphate aerosol cloud is generated at two levels and can cover the whole troposphere downwind of the source area. Inset bottom right shows % of magmatic content of dissolved S released at the vents, determined by the difference between the sulfur content of glass inclusions and tephra divided by the sulfur content of glass inclusions), based on 164 pairs of measurements from several Icelandic flood lava eruptions, after [16].

upper-tropospheric altitudes for tropical to mid-latitude eruptions, even reaching the base of the stratosphere for higher-latitude eruptions where the tropopause is lower. It is noted that forest fire plumes can readily achieve stratospheric injection of smoke and gases (e.g., [37]), yet the fires are somewhat cooler than the effusion temperatures of basaltic eruptions. Moreover, flood lava flows also release gas from their surfaces once they begin to move away from the vent system (Fig. 1), creating a low-level atmospheric gas and aerosol cloud above the lava fields and beyond. The combined effects of high and low-level gas releases can have severe local and regional environmental effects, extending across mainland Europe in the case of Laki [21,29,38]. In summary, the release of fire-fountain- and/or lava surface-derived gas would be near-continuous throughout the duration of a flood basalt eruption (i.e., 10–10^2 yrs depending upon the magnitude and effusion rate). The impact of such enormous, long-term degassing events on the environment could have been very severe.

3. Estimating volatile release from flood basalt eruptions

Flood basalt volcanism may influence the environment in two ways; either by climatic cooling effects caused by increasing atmospheric optical density as a result of SO_2 release and sulphuric acid (sulphate) aerosol formation [14,17,20,21], or by atmospheric warming through the addition of the greenhouse gas, CO_2, e.g., [39,13]. These two apparently conflicting cause-and-effect scenarios are likely to be a simplification of much more complex phenomena within the atmospheric and associated climate systems. For instance, SO_2 may act as a greenhouse gas if present in sufficient concentrations at low altitudes, whereas the formation and spread of stratospheric sulphate aerosols formed by oxidation of the SO_2 would cause cooling. In addition, whilst anthropogenic CO_2 emission is now known to cause measurable global warming, the quantities estimated to be released during flood basalt eruptions are very small when compared with the natural atmospheric reservoir ($\sim 3\times10^{15}$ kg CO_2), with one study predicting little climatic effect [40]. Contrary to Caldeira and Rampino [40], the effects of volcanic CO_2 release have also been modeled during and after flood basalt province formation and indicate, first, a warming, but then followed by cooling due to the effects of CO_2 drawdown caused by weathering of the lavas [41]. Before considering the effects of gas releases from an entire flood basalt province, we first examine potential CO_2 emissions and sulphur gas emissions from individual eruptions.

3.1. Carbon dioxide

Direct determinations of the amounts of CO_2 degassed during eruption of flood basalt magmas 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 [42], whilst recent work on Mexican and Hawaiian basaltic lavas suggests between 0.2 and 0.5 wt.% CO_2 [43]. Lange [44] argues for much higher potential volatile contents ($\sim$2 wt.% CO_2) for Columbia River magmas in order for them to become sufficiently buoyant to rise and erupt; but non-empirical estimates such as these should be treated with caution. Following Self et al. [18], we therefore adopt 0.5 wt.% as a high, but reasonable, value for the pre-eruptive CO_2 content in flood basalt magmas, and consider that magma degassing is highly efficient with most of this gas released at the eruptive vents.

Assuming 100% degassing, and an aphyric magma (a condition commonly met in flood basalts), then the mass of gas released from a magma can be estimated from Eq. (1):

$$M_{CO_2} = M_v\ C_{CO_2} \quad (1)$$

where M_{CO_2} is the mass of CO_2 released from the melt in kg, M_v is the mass of magma in kg, and C_{CO_2} is the concentration of CO_2 in the melt as a mass fraction (0.005). This calculation shows that approximately 1.4×10^{10} kg, or 14 Tg of CO_2, could be released for every 1 km^3 of basaltic lava erupted (assuming a density of 2750 kg m^{-3}), thus the total release from an erupted lava volume of 1000 km^3 would be $\sim 14\times10^3$ Tg CO_2. Whilst this is a very large mass, it should be noted that it represents less than 1/200th of the CO_2 present in the modern atmosphere ($\sim$3 million Tg, or 3×10^{15} kg), and only about 3% of the current annual land–atmosphere CO_2 flux. In effect, even an instantaneous release of this quantity of CO_2 would increase the content of the current atmosphere (i.e. $\sim$365 ppmv) by only 1.7 ppmv. This compares with the current, largely anthropogenic, annual increase of 1 ppmv since 1958.

Since the mass of CO_2 would be released throughout the duration of a flood basalt eruption, the annual fluxes to the atmosphere would actually be considerably smaller than that given above. For example, a more realistic estimate might be to assume an 80% efficient degassing of CO_2 during a 1000 km^3 eruption over a 10 or 50 yrs eruptive period. Under these conditions, an eruption would yield between $\sim$220 and 1100 Tg a^{-1} for the 50 and 10 yr durations, respectively, and produce only a tiny increase in atmospheric CO_2 concentration (*cf.* present anthropogenic production of 6.8×10^3 Tg a^{-1}). Clearly, such annual CO_2 flood basalt eruption fluxes are negligible when compared with the natural atmospheric reservoir, and even doubling or tripling the volume of magma released within these eruptive periods, or considering higher CO_2 concentrations in the melt [45], would make no significant difference to this conclusion.

3.2. Sulphur degassing

Studies of S degassing [18] demonstrate that ~75% of the volatile sulphur in basaltic magma is released, largely as SO_2, into the atmosphere at the vents (Fig. 1). It instantly begins conversion to sulphuric acid (sulphate) aerosols, and continues to do so over periods of days to a month. The Laki eruption released a total of ~120 Tg SO_2, delivered as quasi-continuous emissions with maximum fluxes reaching around 6 Tg day^{-1} (and an average, longer-term flux of 3 Tg day^{-1}). At the highest rate, 3 days of Laki emissions would have released the same amount of SO_2 as the entire Mount Pinatubo 1991 eruption. The contender for the greatest amount of SO_2 emissions from a flood lava eruption in the past few millennia is the Icelandic basaltic fissure of Eldgja, AD 934–940, which contributed ~200–220 Tg [32].

For the purposes of this paper we express the Laki SO_2 emission as the mass of gas released at the vents per cubic kilometer of magma erupted. From petrological and empirical considerations [17,29,46] this can be estimated by:

$$M_{SO_2} = M_v(1 - W_{xls})\, 2\, [C_{inc} - C_{tep}] \quad (2)$$

where M_{SO_2} is the mass of SO_2 released at the vent in kg, M_v is the mass of magma in kg, W_{xls} is the mass fraction of phenocrysts in the magma (assumed not to contribute any gas), C_{inc} and C_{tep} are the concentrations of S in glass inclusions and vent tephra, respectively, and the factor of two accounts for the difference between the atomic masses of S and SO_2. Using a magma density of 2750 kg m^{-3}, $W_{xls}=0.02$, and $C_{inc}-C_{tep}=0.00117$, 1 km^3 of erupted magma can be shown to have released an average of 6.3×10^9 kg (6.3 Tg) of SO_2 at the vents.

Sulphur gas releases from ancient flood basalt eruptions are more challenging to determine because the lavas have typically been affected by weathering or ground-

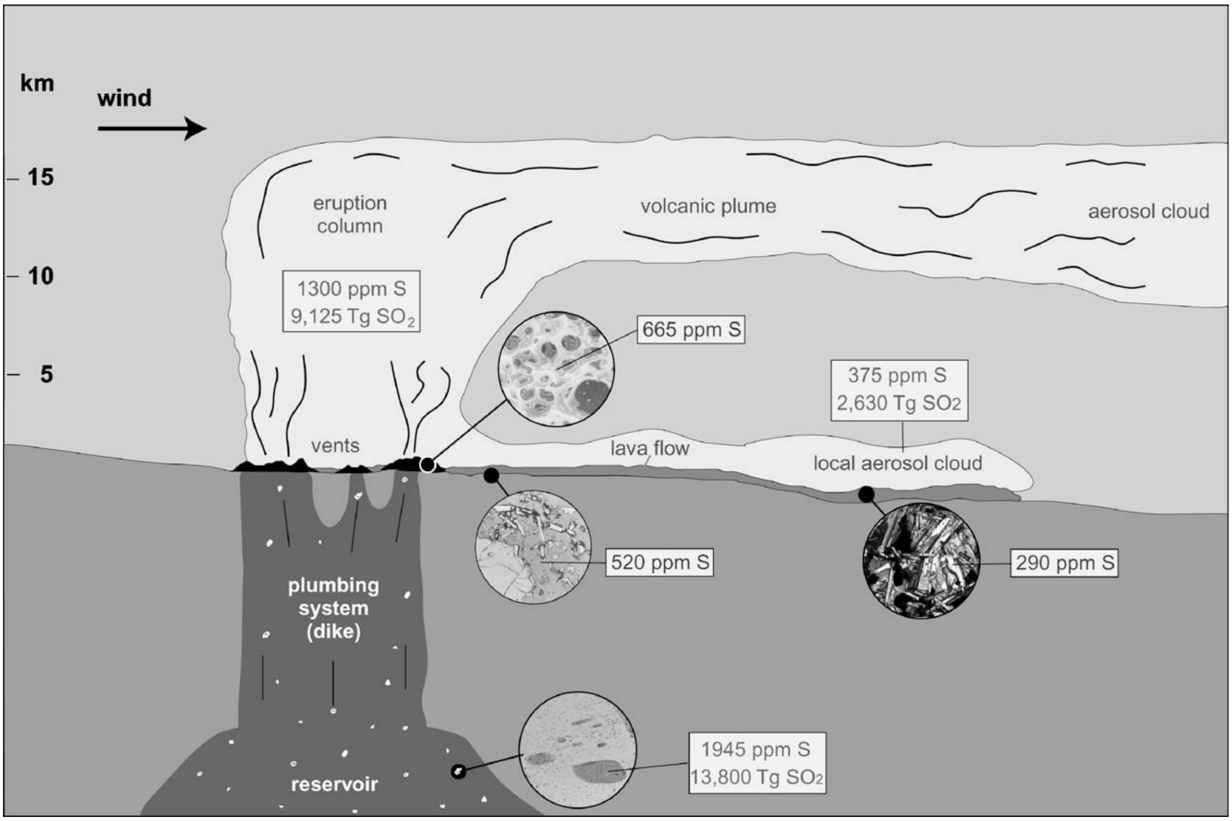

Fig. 2. Concentrations of S (in ppm) in different eruptive products and estimated masses of SO_2 degassing (following scheme in Fig. 1) obtained from a study of 1300 km^3 Roza lava flow field of Columbia River flood basalt province, after [17].

water alteration which can lead to the removal of the mobile or volatile constituents. In addition, petrologic methods of determination require the occurrence of phenocrysts containing glass (melt) inclusions since these reveal the volatile concentrations in the magma chamber. However, flood basalt provinces are dominated by very crystal-poor flows. Nevertheless, the well-preserved and porphyritic Roza lava is one case where the S gas release during eruption can be estimated (Fig. 2) and determinations indicate that S concentrations in the pre-eruption magma were similar to that of Laki. Using Eq. (2), and substituting values for the Roza lava [17], it may be shown that eruption of 1 km^3 of magma released an average of 7.3 Tg of SO_2. The eruption of the entire 1300 km^3 flow field is thus estimated to have released ~9500 Tg at the vents, and another 2.5×10^3 Tg from the lava flow surface, giving a total release of ~12,000 Tg of SO_2, along with significant amounts of HF and HCl. Further, if eruption of the Roza flow field had a duration on the order of 10 yrs [28], then the annual average SO_2 burden added to the atmosphere could have been as much as 1200 Tg a^{-1}, with a portion injected into the lower stratosphere (assuming a 12- to 14-km-high tropopause, appropriate for that latitude) by fire fountains and the associated ~15-km-high convective columns. Over a decade, the total release would have been ~3 Tg of SO_2 per day at a daily average lava effusion rate of ~0.35 km^3, a value similar to the longer-term S emission rate maintained at Laki over several weeks. Such values are very large when compared with the background amount of S in the atmosphere, which is low (<1 Tg).

For crystal-poor basalt lavas, or in cases where alteration of the lava makes the petrologic method unusable (e.g., for most Deccan province lavas), a chemical ratio proxy can be used to obtain approximate estimates of the original S content of the lavas [18]. This is based upon the relationship between the composition (i.e., FeO content) of recent and historically erupted tholeiitic basalt lavas and their observed S content. The relationship may be derived either by direct degassing measurement, or from glass inclusion data, and can be expressed by the TiO_2/FeO ratio of bulk lava, vent tephra, and glass inclusions (Fig. 3). The data from inclusions indicates the potential amount of S dissolved in the melts before eruption, whilst the tephra and lava data reveal the concentrations remaining in these products after eruption. The difference in S concentration at the measured TiO_2/FeO ratio indicates the degree of S degassing during eruption of ancient tholeiitic and related basaltic lavas. In the next section we adopt this approach in order to quantify S gas releases during the formation of the Deccan province.

4. Assessing amounts of sulphur volatiles released during flood basalt province formation

Except for the Columbia River flood basalt province ([22] and references therein), details of lava volumes

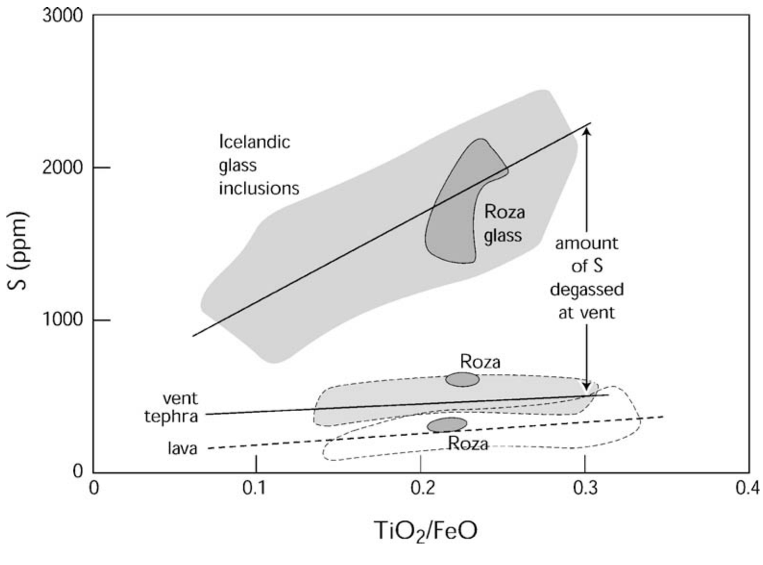

Fig. 3. Fields of measured S concentration vs. TiO_2/FeO in glass inclusions from individual volcanic systems, after [16]. All data are from electron microprobe analyses; best fit line through data derived from glass inclusions in crystals indicate average pre-eruption S concentrations in the magma. At bottom plot the fields of degassed vent tephra and lava flows for same Icelandic and Roza eruption products. Difference between these two fields may represent amount (in ppm) of S degassed during basaltic lava-forming eruptions, as a function of TiO_2/FeO ratio.

emitted during the individual eruptive events that comprise a whole province remain undetermined. Such details, together with an understanding of the variation in output during the period of flood volcanism, are essential before a realistic estimate of volatile release from ancient flood basalt events can be attempted. In this section we discuss what is currently known, and what has yet to be accomplished, in order to assess gas releases during flood basalt volcanism. Beginning with volumes and rates of eruption, Fig. 4a shows the number of $^{40}Ar/^{39}Ar$ age dates available for the Columbia River province [47,48] plotted against the age range using 1σ errors (see also [49]), and a plot of the volume of lava erupted versus time (Fig. 4b) based on data from [22]. Previous compilations of flood basalt age data used to examine the pattern of lava emission (e.g., [9,10]) have not considered variation in the output of erupted material, but in the case of the Columbia River province a distinct peak in lava production is seen at 16–15 Ma. We now attempt to reconstruct a similar volume versus time

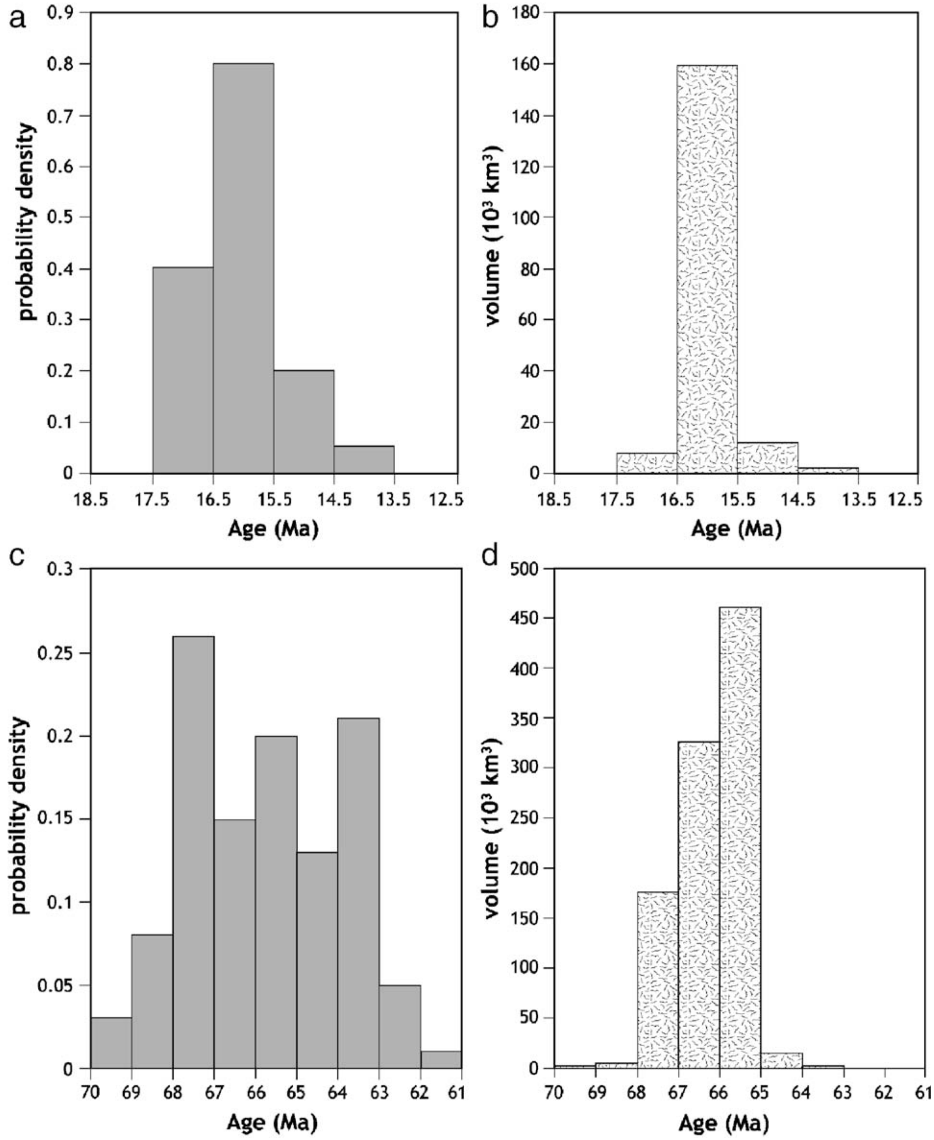

Fig. 4. (a) Ar/Ar age ranges vs. number of age determinations expressed as a percentage of the total number of ages; (b) volumes of lava flows vs. Ar/Ar ages for the Columbia River Basalt Group (after data compiled by [22]); (c) Ar/Ar age ranges vs. number of age determinations expressed as a percentage of the total number of ages for the Deccan flood basalt lavas (after references given in text); (d) Assigned volumes of lava in Deccan lava formations vs. Ar/Ar ages for these formations plotted in 1 Ma intervals (from data compiled in Table 1). Plots (a) and (c) are from data collected by M. R. Rampino, personal communication, 2002; see also [49]).

relationship for the Deccan province and then examine S gas emissions during the emplacement of the Deccan lavas.

4.1. Deccan stratigraphy and lava volumes erupted

Several Deccan dating studies show that volcanism occurred between 68 and <64 Ma (see summary in [10]) but was centered at ~66 Ma (Table 1). The $^{40}Ar/^{39}Ar$ age spectrum (e.g., [50–54]) (Fig. 4c) can now be translated into a volume versus time plot (Fig. 4d) based on stratigraphic information and maps of the extent of the Deccan lava formations [55,56]. The values in Table 1, on which the volume plot in Fig. 4d is based, were obtained by assuming that Deccan volcanism originally erupted ~1 million km^3 of lava; this is a conservative estimate within the currently proposed original range of ~750,000 km^3 to ~2×10^6 km^3 [57]. From this, we consider the likely total magma volumes and time intervals over which the Deccan lavas might have been erupted.

First, the geochemically-based stratigraphy of the main part of the Deccan Basalt Group consists of 3 sub-groups and 12 formations [58–62]. Accordingly, by using (i) the extent of known maximum thickness of individual formations to estimate each of their erupted volumes as low-angle cones, and (ii) sub-dividing the assigned 1 million km^3 by the characteristic thicknesses of the lavas, a first-order apportionment of the volumes of each of the formations may be determined (Table 1). Second, age ranges may then be assigned to each formation using the existing $^{40}Ar/^{39}Ar$ data. From this exercise, it can be shown that the Wai Sub-group, which includes the very widespread Poladpur, Ambenali and Mahabaleshwar formations (estimated age 66.0–65.0 Ma), contain approximately half of the entire Deccan lava volume. The volume versus time plot (Fig. 4d) is presented at 1 Ma intervals, and shows a distinct peak in the 67–65 Ma period. Indeed, much of the lava pile appears to fall within the 800-kyr-long paleomagnetic Chron 29R [52,10], see Table 1, implying that the main period of lava production was even shorter than indicated by the radiometric age data. This supports the previously proposed idea that the main part of the Deccan series was erupted in less than 1 Ma [2,50,52]. A further useful comparison, indicated by this treatment, is that a single large-volume Deccan formation such as the Ambenali originally had a volume similar to the entire Columbia River Basalt Group (~230,000 km^3 [63]), and that several Deccan formations (e.g., Jawhar, Thakurvadi and Poladpur) are each equivalent in volume to the entire main phase lavas (Grande Ronde Formation) of the Columbia River province (~150,000 km^3).

Clearly, the main Deccan eruptive phase occurred over a short time-span (66.5–65.5 Ma) during which immense volumes of lava were emplaced (Table 1 and Fig. 4d). From the magmatic output and environmental aspect, the Deccan eruptions would have been characterized by peak gas emissions during early Wai Sub-group times, with a possible earlier peak during early- to mid-Kalsubai Subgroup times. Although details of eruptive volumes and precise dating may change as information becomes available, we believe that this essential picture will not. Some workers have noted that the lower Deccan succession (i.e. Kalsubai Sub-group) has fewer boles (i.e., soils and weathering horizons) compared with the Wai Sub-group succession ([19,64 and references therein]). However, detailed stratigraphic logs of the Neral to the Mahabaleshwar formations [65] provide evidence for hiatuses of various, but unknown, durations throughout the eruption of the Deccan lava pile. It may be that earlier Deccan volcanism featured more-frequent, smaller-volume eruptions with shorter eruptive hiatuses, whereas the later, larger-volume events erupted over longer time intervals but with more lengthy hiatuses between eruptions. Establishing such differences in eruptive tempo will, in future, prove crucial to further assessment of Deccan volcanism and its environmental impact.

Table 1
Stratigraphic sequence of main sub-groups, assigned volumes[a], age ranges[b], and paleomagnetic chrons for the Deccan Basalt Group

Sub-group	Formation	Volume lava[a] ($\times 10^3$ km^3)	Age range[b] (Ma)	P'mag chron
Wai	Desur	10	<64.5	
	Panhala	25	64.5–65	
	Mahabaleshwar	100	65–65.5	29N
	Ambenali	200	65.5–66	29R
	Poladpur	165	65.5–66	
Lonavala	Bushe	100	66–66.5	
	Khandala	40	66–66.5	
Kalsubai	Bhimashankar	10	nc	
	Thakurvadi	150	66–66.5	
	Neral	25	66.5–67	
	Igatpuri	25	67–67.5	
	Jawhar	150	67.5–68	29R?
? Stratigraphic relations				29N?
	Rajpipla/ Narmada	?10	>67	

[a] Assigned assuming a total lava volume of 1 million km^3 and apportioned as described in text.
[b] Assigned age ranges for this study, using Ar/Ar dates from various sources including [54,55]; nc = not considered here. P'mag (paleomagnetic) chrons assigned after [10,50–52].

4.2. Example estimate of sulphur release during a single Deccan eruptive event

Given the geochemical similarity of the Deccan tholeiitic lavas to those of other flood basalt provinces, it is assumed that they had the same potential to release sulphur. Indeed, a compilation of available Deccan analyses [55] reveals that the Fe content and Mg number of the lavas is very similar to that of Icelandic and Columbia River lavas (Fig. 5A), indicating that pre-eruption S concentrations should also be similar (Fig. 5B). In order to assess the likely S gas release during eruption of an individual Deccan lava field, we must first consider the volume of such an eruption. At present this can only be obtained through analogy and by recourse to some basic assumptions. In the Columbia River province, where the lava stratigraphy and flow volumes are best known, lava units thought to be the products of individual eruptions of at least 2–3000 km^3 are

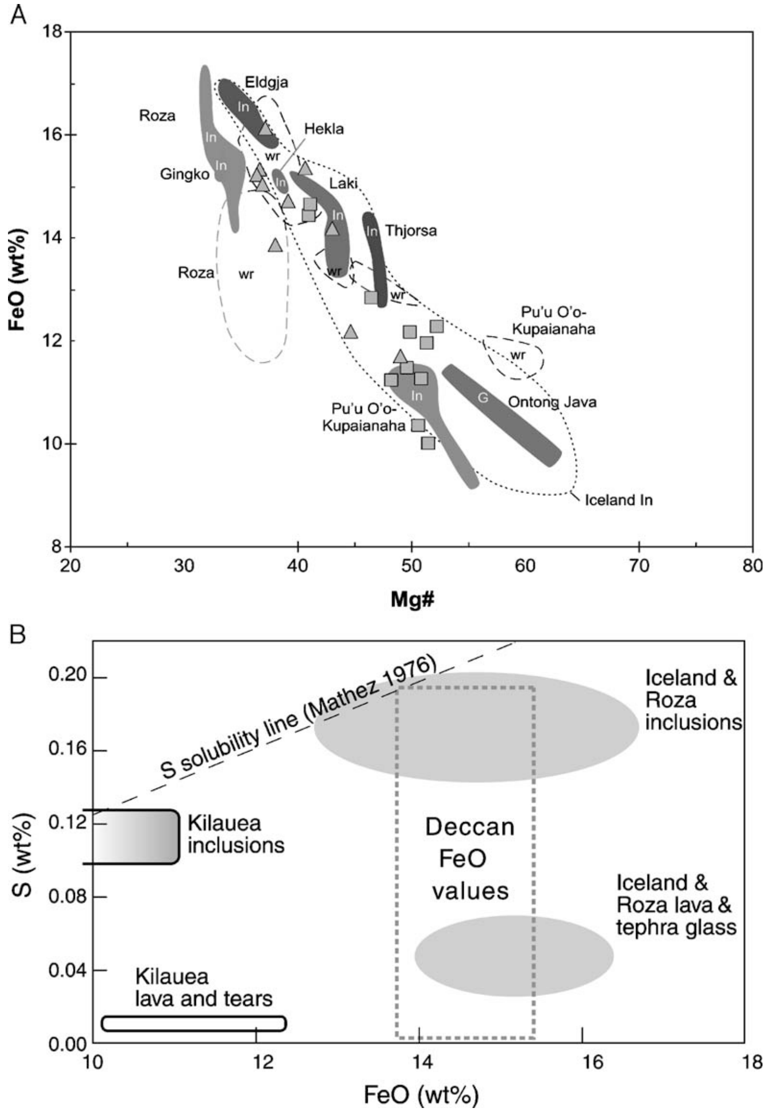

Fig. 5. (A) Fields of data for total Fe as FeO_{total} vs. Mg number for whole rock (wr), melt (glass) inclusions (In) and glass (G) from basaltic lavas from large igneous provinces, showing the similarity of Fe and Mg numbers from Deccan lavas from the Wai Sub-group (squares and triangles, after [55,65]) to those from Columbia River basalts (Roza and Gingko flows) and Iceland (Eldgja, Hekla, Laki); based on data in references given in text and unpublished data in possession of the authors; dashed line is all Icelandic glass inclusions after [16]. (B) Fields of data for FeO vs. S from electron microprobe (EMP) analyses for melt (glass) inclusions in crystals in tholeiitic and related lavas from Iceland (after [16]); Columbia River Roza lava [17] and values of whole rock lava and glassy lava matrix from the on-going Kilauea (Hawai'i) eruption are also plotted (C. R. Thornber, personal communication 2004 and K. Sharma and S. Self, unpublished data). EMP analyses of FeO from Deccan lavas with partially preserved glass are also plotted, with possible projection into the field of inclusion S contents.

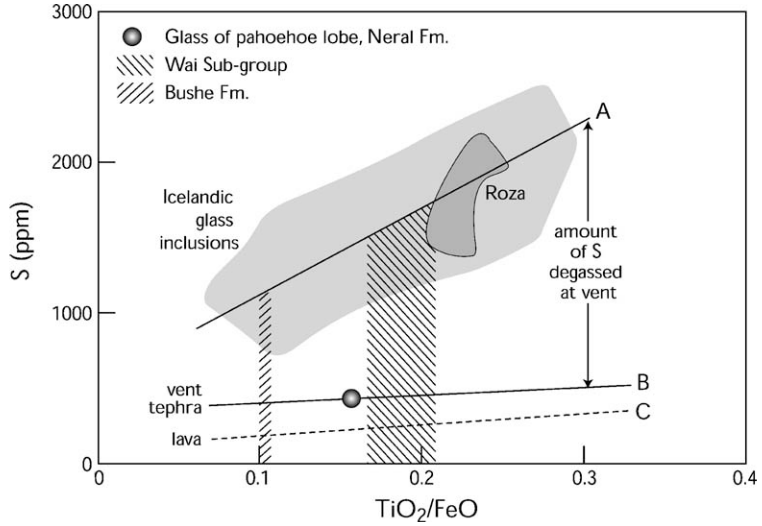

Fig. 6. Same plot as Fig. 3, with ranges of TiO_2/FeO ratios measured in whole rock Deccan lava samples (Wai Sub-group and Bushe Formation; Fe recalculated as FeO) displayed, after data in [55]. Projection of these values into field of inclusion S contents gives a proxy estimate of expected Deccan lava pre-eruptive S contents, which for Wai Sub-group fall within the range 1500–1700 ppm. Also plotted is EMP analysis (average of 3) of a degassed glassy pāhoehoe toe from the Neral formation (Kalsubai Sub-group; Deccan), which plots near the expected position for a degassed lava glass.

known [22,66]. However, in the much larger Deccan province, a flow field covering only one tenth of the estimated 800,000 km^2 area of the province, and having typical observed thicknesses of 20–30 m [65], would represent an eruptive volume of 1600–2400 km^3. Since some individual Deccan formations cover areas considerably larger than this, we therefore assume that the volume of a single Deccan eruptive unit should be equal to, or, more probably, larger than the Columbia River eruptive units. This places likely Deccan eruption volumes within the range 10^3–10^4 km^3.

Based upon the TiO_2/FeO ratio of typical Deccan lava compositions for each of the major sub-groups [55,65], magma S contents of between 1250 and 1750 ppm can be estimated (Fig. 6). In addition, we have made determinations of S concentration in rare occurrences of glassy pāhoehoe lava lobes from the Deccan and obtained 400± 30 ppm, a value similar to those of Roza lava glass selvages. Thus, for the Wai Sub-group lavas we can make a first order estimate that 1200±100 ppm S was degassed from the source vents and active lava fields. Using Eq. (2), the amount of SO_2 released can thus be estimated as 6.5 Tg km^{-3} (lava density 2750 kg m^{-3}; $W_{xls}=0.01$). This value is comparable to that obtained for the Laki eruption. Combining this estimate with the range of likely volumes of individual Deccan eruptions estimated above, average SO_2 emissions of approximately 6500–65,000 Tg per eruption are indicated. Again, this mass would be released at rates between 650 and 6500 Tg a^{-1} for a 10-yr eruption duration with ~75% of this amount emitted at the vents, and the remainder from the surface of the lava flows as they flowed away from the source area.

4.3. Estimates of sulphur gas release over the time span of Deccan volcanism

The stacks of lava flows that comprise each Deccan formation were produced by a limited number of large eruptions. Between these major flow-field-forming eruptions were periods of volcanic quiescence, or minor activity. This is very similar to the picture gained from studies of the Columbia River province, where of the order of 100 major eruptive events occurred during a period of less than 2 Ma [22]. An eruptive climax of this duration would result, on average, in quiescent intervals of 10^3–10^4 yrs between major eruptions, although such eruptive hiatuses must have varied considerably in their actual duration. Such long time intervals would have given biological and environmental systems ample time to recycle emitted CO_2 and to recover from the deleterious effects of volcanic S gas emissions.

In the case of the Deccan, on the order of tens of eruptions are likely to have contributed to each of the stratigraphic formations [65]. One approach to determining how many eruptions formed the Deccan pile would be to consider that if the likely volume of each major eruption was several thousand cubic kilometers, a formation such as the Ambenali (200,000 km^3) could be formed from forty 5000-km^3 events, or a larger number of smaller volume eruptions. Alternatively, since individual Ambenali flow fields are each 20–30 m thick [65], the 450-m thick Ambenali succession (as exposed at its type section of Ambenali Ghat) could be composed of the products of 15–20 large-volume eruptions. The precise number of eruptive events represented in other Wai Sub-group formation sequences (i.e. Poladpur and Mahabaleshwar Formations) is most probably similar to this, but the number involved in emplacement over the whole Deccan province is far from well-understood.

To examine the possible average length of eruptive hiatuses in one formation, we can assume that 20 major eruptions occurred during Ambenali times, and that the total duration required for emplacement of a thick formation such as the Ambenali might be within the range of 160–200 ka. This is based on the observation that much of the Deccan pile falls within the 0.8-Ma-long Chron 29R and that Wai Sub-group lavas occupy about half of the Deccan succession, and that those of the Ambenali Formation occupy between 0.4 and 0.5 of the Wai Sub-group. An estimate can then be made of the average periodicity of eruptions and lengths of the inter-eruption hiatuses. For instance, given that each major flow field was probably generated over a period of 10–100 yrs [28,31], then the cumulative duration of the eruptive activity for 20 events would have been at a minimum only 200 yrs, and at a maximum 2000 yrs, which represents ~1% of the total Ambenali emplacement duration. Conversely, this would mean that on average the hiatuses were about 8000 yrs long, even for the briefest total time span (i.e., 160,000 yrs). Shorter hiatuses between some eruptions are, of course, possible, and are indicated by recent paleomagnetic results [67].

In summary, with an assumed total lava volume of 1×10^6 km^3, Deccan volcanism had the potential to release about 6.5×10^6 Tg of SO_2 into the atmosphere. However, details about the actual size of individual eruptive batches, and associated gas release events, as well as the time elapsing between their eruption, remain unclear. Nevertheless, during Wai Sub-group times, a succession of hundreds of huge lava-field-forming eruptions would each have added 10^2–10^3 of Tg of SO_2 per year to the atmosphere continuously over a decade or more. Moreover, this large mass of gas would be distributed throughout the atmosphere from the near surface to tropopause, or above and, importantly, if the Deccan province originally contained 2 million km^3 of lava, then the above gas flux estimates would double. Each eruption would then be followed by a pause in activity of, on average, a few thousand up to 10,000 yrs. Consequently, the eruptive events that constitute a province such as the Deccan had considerable potential for recurrent or cumulative environmental or climatic deterioration, even if the atmospheric residence time of the gases and aerosols was only of the order of weeks, months or years.

5. Potential effects of CO_2, SO_2, and sulphuric acid (H_2SO_4) aerosols

As mentioned above, several kinds of environmental effects of flood basalt eruptions have been suggested, including climatic cooling from sulphuric acid aerosols, greenhouse warming from CO_2, and ecosystem damage from acid rain [7,14,68]. Before these potential effects can be properly evaluated, however, the nature of flood basalt volcanism needs to be considered fully. Until this current work, there have been few estimates of the amounts of climatically significant gases these eruptions can release into the atmosphere. Certainly, the effects of CO_2 release during and after a period of flood basalt volcanism require further evaluation since at least one recent study [41] has suggested climate warming following Deccan volcanism but this model requires both a larger mass of gas and a shorter duration of release (100,000 yrs) than we have argued for here. Importantly, in this same study, another model run with a much longer period of gas introduction determined that the warming effect was much smaller [41], yet none of the previous models [40,41] allow for the short-lived CO_2 releases (10–100 yrs) to be followed by lengthy hiatuses (up to 10,000 yrs). During the volcanic hiatuses, the CO_2 introduced during the eruption would be partially removed from the atmosphere by the carbon cycle, some being accounted for by biomass (on the order of 100 yrs), some by drawdown into ocean surface waters (1000 yrs), and some by the onset of weathering of the newly-formed lava fields. The possible cumulative effects of weathering of the newly-formed lava on the longer-term carbon cycle and cooling [41] are important, but would take place over a 10^5–10^6 yr timescale during, and mainly after, the formation of the province. Accordingly, they are beyond the timescales of the effects considered here.

From modern eruptions it is known that significant volcanogenic sulphate aerosols in the stratosphere result in measurable global cooling [69], and similar effects have been postulated for flood basalt eruptions of the British Tertiary igneous province [20]. Volcanic aerosols at all altitudes should cool the Earth's surface if the aerosol size is in the normal range [70], and a maximum cooling effect is achieved by low-level aerosols. Therefore, volcanogenic aerosols in the troposphere could lead to a surface cooling, as well as the stratospheric aerosols. However, in most volcanic eruptions, tropospheric aerosols have a very short lifetime of only about 1 week before they are 'washed out' by natural moisture and rain. The important difference with flood basalt activity is that the supply of SO_2 is semi-continuous and maintained.

The style of eruption of flood basalt lava flows determines the eventual atmospheric and climatic effects of SO_2 and the resulting sulphate aerosols. The volumetric eruption rate in fissure-fed basaltic eruptions helps determine the height of fire fountains over active vents, the convective rise of the volcanic gas plumes in the atmosphere, and hence the climatic effects of an eruption. One major consequence of the conversion of a large mass flux of SO_2 to sulphate aerosols would have been to greatly deplete stratospheric H_2O and OH [71,72], which at present consists of about 1000 Mt globally. However, this depletion may be mitigated during large volcanic eruptions since considerable amounts of water from the moist troposphere may become lofted into the lower stratosphere by the eruption plumes themselves. Moreover, just how the long-lasting sulphate aerosols generated from flood basalt eruptions would have affected atmospheric chemistry and dynamics remains to be determined [73], but will require more than the currently available general circulation models (GCMs) [74].

Another consideration of environmental importance is the geographical location of the flood basalt province during its eruptive climax because this strongly influences the extent of gas and aerosol dispersal within the atmosphere. Paleolatitudes derived from paleomagnetic data and other reconstructions place the Deccan at the time of activity about 20°–25°S of the Equator [52,75]. Given present-day atmospheric circulation patterns, global atmospheric dispersal of aerosols would have been possible from this latitude. Since the Late Cretaceous distribution of the continents was not radically different from that of the present, it is likely that dispersal patterns may have been largely similar to that of modern Earth. For short-lived eruptions, any volcanic aerosol clouds generated at these latitudes would be distributed unevenly into one hemisphere or another, depending upon the season, but for long-lasting flood basalt eruptive events (i.e. emplaced over 10–50 yrs or more), a global distribution of the aerosols becomes likely. Details of these aspects remain to be studied with atmospheric GCMs that replicate the Late Cretaceous conditions [74]. Clearly, many other interesting questions also remain to be studied.

6. Conclusions

Most flood basalt provinces largely consist of tholeiitic basalt, and the work reviewed herein indicates that most tholeiitic fissure basalt eruptions have similar degassing characteristics. We might assume that flood basalt eruptions follow the same degassing pattern, with at least 75% of the burden of dissolved magmatic S and CO_2 released at the vents. In the future it will become increasingly important to determine the volumes erupted in individual flood basalt eruptions if we are to be able to improve on the first-order estimates of gas release outlined here; such information is currently unknown for provinces older than the Columbia River basalts. In this context, knowledge of the length of inter-eruption hiatuses will also become important.

The impact of volcanic S gas release is likely to be profound at times of flood basalt volcanism. By contrast, the masses and rate of release of CO_2 by individual flood basalt eruptions, and especially the resulting predicted increases in atmospheric concentration, are small in comparison to the normal atmospheric reservoir; in effect, a typical flood-basalt event might contribute only 11,100–1400 Tg of CO_2 over a period of decades. Moreover, whilst the amount of CO_2 in atmosphere now is $\sim 3 \times 10^6$ Tg it was perhaps double this amount at the end-Cretaceous, thus making it even less likely that Deccan-derived volcanic CO_2 (or, indeed by other flood basalt provinces erupted during the Phanerozoic) had a direct effect on contemporaneous global warming [40,76]. Furthermore, given that flood basalt eruptions were probably spaced many hundreds (at the very least) to thousands of years apart, there would have been ample time to equilibrate this relatively small extra mass of volcanic CO_2 within natural short term reservoirs. Conversely, biota affected by the deleterious consequences of sulphate aerosols and S deposition may not have been able to fully recover during these hiatuses. Such conclusions conflict with studies that invoke climate change through massive CO_2 release during flood basalt province formation [77,78] and, given the relatively small contribution per eruption to contemporaneous atmospheres, processes other than direct release of volcanogenic CO_2 now need to be sought to explain these observations.

Regarding the S gases emitted, flood basalt magmas appear to be able to release about 5–7 Tg of SO_2 gas per cubic kilometer of lava upon eruption. It is likely during a period of flood basalt volcanism, such as the Deccan, that individual eruptions of ~ 5000 km^3 of lava could release up to 35,000 Tg of SO_2. Such masses would be emitted during decade-long eruptions at rates of 3500 Tg yr^{-1} for a decade, or 350 Tg yr^{-1} over a century. An event like this would be followed by a non-eruptive hiatus, during which biota and climate may begin to recover toward pre-eruptive conditions. Repeated eruptions of this magnitude may well have prevented a complete recovery.

Over the whole period of flood basalt province generation, immense amounts of S gases (mainly as SO_2) and other species (e.g., halogens) will be released to the atmosphere on a geologically frequent, but possibly random, basis. This scenario is incomparable in scale to volcanic gas releases at any other times in Earth history. The SO_2 would have formed considerable amounts of sulphate aerosols that lasted for a long time and certainly, at least as long as the eruptions persisted. Again, the predicted mass of atmospheric aerosols appears to be unprecedented at any other time in Earth history and its effects require testing with climate and atmospheric models appropriate for the geological era during which the flood volcanism was occurring. Many interesting questions remain to be tackled, including issues such as: "Will volcanic plumes rise higher or lower for a given set of paleo-atmospheric conditions?"; and "What would be the fate of SO_2 emissions in a Late Cretaceous atmosphere?" Modelling of dense tropospheric and stratospheric aerosol clouds, and their effects on atmospheric dynamics and chemistry applicable to the scenarios documented in this paper, is now urgently required.

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