Large Scale Volcanism and the heat-death of terrestrial worlds

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Abstract

Large scale volcanism has played a critical role in the long-term habitability of Earth. Contrary to widely held belief, volcanism rather than impactors have had the greatest influence on, and bear most of the responsibility for, large scale mass extinction events throughout Earth's history. We examine the timing of Large Igneous Provinces (LIPs) through Earth's history to estimate the likelihood of nearly simultaneous events that could drive a planet into an extreme moist or runaway greenhouse, quenching subductive plate tectonics. This would end volatile cycling and may have caused the heat-death of Venus. With a conservative estimate of the rate of simultaneous LIPs, in a random history statistically the same as Earth's, pairs and triplets of LIPs closer in time than 0.1-1 Myrs are likely. This simultaneity threshold is significant to the extent that it is less than the time over which the environmental effects persist.

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Large Scale Volcanism and the heat-death of terrestrial worlds

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Key Points:

- Simultaneous Large Igneous Provinces may yield mass extinctions, drastic climate change, and a runaway greenhouse on Earth and Venus-like worlds.
- Earth's LIPs occur approximately randomly and uniformly over time.
- On average simultaneous LIP pairs and triples are expected over 2,800 Myr, yielding enhanced environmental impacts.

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Abstract

Large scale volcanism has played a critical role in the long-term habitability of Earth. Contrary to widely held belief, volcanism rather than impactors have had the greatest influence on, and bear most of the responsibility for, large scale mass extinction events throughout Earth's history. We examine the timing of Large Igneous Provinces (LIPs) through Earth's history to estimate the likelihood of nearly simultaneous events that could drive a planet into an extreme moist or runaway greenhouse, quenching subductive plate tectonics. This would end volatile cycling and may have caused the heat-death of Venus. With a conservative estimate of the rate of simultaneous LIPs, in a random history statistically the same as Earth's, pairs and triplets of LIPs closer in time than 0.1-1 Myrs are likely. This simultaneity threshold is significant to the extent that it is less than the time over which the environmental effects persist.

1 Introduction

Large igneous provinces (LIPs) on Earth are voluminous ($1x10^5$ to > $1x10^6$ km^3), mainly mafic (-ultramafic) magmatic events of intraplate affinity (based on tectonic setting and/or geochemistry) that occur in both continental and oceanic settings. They are typically either of short duration (<5 Myr; often <2 Myr) or consist of multiple pulses over a maximum of a few tens of Myr (Coffin and Eldholm, 1994; Ernst, 2014, Svensen et al. 2019; Ernst et al. 2021a).

1.1 Terrestrial Large Igneous Provinces (LIPs) and their link to climate change

LIPs have been tied to dramatic climate change resulting in mass extinction events in Earth's history (Wignall, 2001; Bond and Wignall, 2014; Bond and Grasby, 2017; Ernst and Youbi 2017; Ernst et al. 2021a, 2021b) due to the release of toxic (to life) gases and large CO_2 releases possibly heating up the climate, for example in the end Permian (e.g. Reichow et al., 2009; Svensen et al., 2009; Polozov et al., 2016; Burgess et al., 2017; Jurikova et al. 2020). Although recent work by Schobben et al. (2020) indicates that enhanced weathering may have also created anoxic ocean conditions that may have played a key role. Crediting LIPs alone is problematic, given the poor record of large impact events we have to work with (Napier, 2014, see Fig 4) where crater counts beyond 500 Myr old are extremely sparse. However, humans are an innovative species and new craters have been discovered in surprising places in recent years (e.g. Kjær et al., 2018). Although the record of LIP events throughout Earth history is incomplete and more dating accuracy is needed, it is possible to characterize the timing of such events on the continents to at least 2.8 Ga (Ernst, 2014; Ernst et al. 2021b). In recent years a number of works have attempted to find periodicities and related external correlations with LIP events and mass extinction events in general (e.g. Prokoph, Ernst and Buchan 2004, Melott and Bambach, 2013). In general, such studies have found no cycles that have both high intensity and persist throughout. But existence of weak, intermittent periodicities of unknown statistical significance, entertained by some, would only enhance our conclusions reached below, as would any other departure from uniform randomness. Other workers have attempted to look at the possible correlations between deep mantle structures and LIPs over the past few hundred million years (e.g. Doubrovine et al., 2016) in particular Large Low Shear-wave Velocity Provinces (LLSVPs) (McNamara, 2019; Torsvik et al., 2010; Burke and Torsvik, 2004). Yet these are only useful for the past few hundred million years. It is not currently possible to extrapolate LLSVPs to gigayears ago (Ga), although a combined paleomagnetic geochemical approach is suggested in Kastek et al. (2018). Given the relative youth of oceanic crust (being younger than ~250 Myr) any older record of oceanic LIPs will be located as deformed remnants in orogenic belts and will necessarily be incomplete (e.g. Coffin and Eldholm 2001a; Dilek and Ernst 2008; Doucet et al. 2020).

1.2 Application to Venus

Recently Way and Del Genio (2020) (hereafter WG20) speculated that simultaneous LIPs may have been responsible for the transition from a previously temperate cool Venusian climate to its present runaway hothouse state which we refer to as the "Great Climate Transition" (GCT). We consider this hypothesis by quantifying the randomness of LIPs in Earth's history and the probability for simultaneous LIPs. This analysis also has application to similar terrestrial exoplanetary worlds that we expect to discover in the coming decades.

As outlined below it is reasonable to use the timing of LIP production on Earth to inform studies of that on Venus during its hypothetical habitable period when it may have had plate tectonics - an important consideration when comparing Venus and Earth (Lenardic and Kaula 1994). Venus has a similar size and density compared to Earth (Lodders and Fegley 1998) and is estimated to have a similar geochemistry (e.g., Treiman 2009).

It has been demonstrated to have had abundant mantle plumes generating large intraplate mafic magmatic events (including major volcanic centers and corona) that are considered analogues of terrestrial LIPs (Head and Coffin, 1997; Ernst et al. 1995; Hansen 2007, Ernst et al. 2001, 2007; Gülcher et al. 2020; Buchan and Ernst 2021). The cytheriochronology of such presumptive LIPs is uncharted, and the indirect method of crater counting (e.g. Bottke et al., 2016; McKinnon et al., 1997) is only very approximate given the low counts of impact craters leading to a large range of resurfacing age estimates (150-750 Myr). There is debate on whether the Venusian cratering record indicates a major magmatic overturn event or steady resurfacing over the last 1-2 Ga (Ivanov and Head 2013, 2015, Strom et al. 1994, Hansen and Young 2007). The stratigraphically oldest units on Venus are complexly deformed terrains termed tesserae (e.g. Ivanov and Head 1996; Hansen and Willis, 1998; Gilmore and Head 2018). Recent insights provide some evidence for erosion (both wind and water) in tesserae (Khawja et al. 2020; Byrne et al. 2020). Given this it may be inferred that the age of tesserae (Perkins et al. 2019; Ivanov and Basilevksy 1993), which had been inferred from crater counting to be only slightly older than that of the stratigraphically younger plains volcanism (Basilevsky and Head 2002), is actually artificially young. Preservation of meteorite impacts would begin only once the climate transition had begun due to fluvial erosion shut off (Khawja et al. 2020). Thus, the geological history of tesserae could extend back billions of years in the oldest stratigraphic units. During this time there could have been a robust history of prior LIP volcanism. This earlier LIP flood basalt history may be preserved in tesserae. In some areas curving lineament patterns in tesserae can be correlated with topography variation implying that the lineaments represent shallow-dipping layering that could represent flood basalt sequences (Byrne et al. 2020). This could suggest that tesserae formation may overlap with multiple LIP events (flood basalts), and in this sense be very comparable to the LIP record preserved in basement terranes on Earth. There is also evidence of contemporaneous large scale magmatic events in Venus' recent past (e.g. Robin et al. 2007).

To summarize, while the earliest interpretation of Magellan Venus radar imaging data suggested short duration resurfacing or mantle overturn events (e.g., Strom et al. 1994), current understanding is consistent with a LIP history of Venus possibly very similar to that of Earth. The Venusian LIP history subsequent to tesserae time could be marked by steady state volcanic resurfacing representing a protracted history of flood basalts extending back billions of years. Hence this inferred Venus LIP distribution could be comparable to the terrestrial distribution of LIPs through time (Ernst et al. 2021b).

In the next section we consider key aspects of the terrestrial LIP record for application to Venus' hypothesized GTC. In Section 2 we discuss the data sources and address the question of whether LIP events are independent. In Section 3 we estimate the potential for simultaneous LIPs, with conclusions in Section 4.

2 Characteristics of Terrestrial LIP Database

2.1 Status of the current LIP database

The raw data in Ernst (2014, Table 1.2), and Ernst (2021b) have been compiled from a variety of sources. The dating of LIP units (including mafic flows, dykes, sills, layered intrusions, and associated felsic magmatism) has been determined in a number of ways. The most accurate approach is U-Pb dating which can provide uncertainties as low as 50,000 years (using the CA-ID TIMS method on zircons (Schoene et al 2019; Kasbohm et al.

2021). However currently most U-Pb ages on LIP units are more approximate, with uncertainties of several Myr. Ar-Ar dating can have high precision (e.g., Sprain et al. 2019) but may be less accurate – i.e. suffer from systematic errors (cf. Schoene et al. 2019; Kasbohm et al. 2021). Other systems such as Sm-Nd can be accurate but with uncertainties of 10s of Myr (e.g. DePaolo 1988). Previously unknown LIP events particularly of Precambrian age are being regularly recognized; indeed about 30% of the known events were only discovered in the past 20 years (cf. Ernst and Buchan, 2001 and Ernst et al. 2021b), and most of these newly discovered events only have a small number of precise age determinations. Some of the newly discovered events are of small extent and are interpreted as LIPs in sensu stricto on the basis of proxy criterion such as average dyke thickness (>10 m) (Ernst 2007).

Another consideration is whether a given LIP is a single short-term pulse (<1 Myr) or several short pulses distributed over a period of up to several 10s of Myr. Both types of events are observed: the 201 Ma CAMP event associated with the opening of the Central Atlantic is an example of the former; the 1115-1090 Ma Keweenawan (Mid-Continent rift) LIP of the Lake Superior region of North America is an example of the latter (Ernst, 2014). Depending on the interpretational context, for such events it may be important to decide which is the most important pulse. In some cases, the first pulse is not necessarily the largest. In general, the first pulse is considered to be plume-related and any additional pulses can be related to delamination or onset of rifting (Ernst 2014). However, sufficient data to discern the pulse structure exist for only a minority of LIP events older than 300 Ma. In cases where multiple pulses are confirmed, each can have a significant environmental effect. For instance, the 55 Ma Paleocene-Eocene Thermal Maximum (Svenson et al. 2004; Stokke et al.

2020) can be linked with the second pulse of the North Atlantic LIP (pulses 62 and 55 Ma). For this reason, all known major pulses are important toward evaluating the climatic effect of terrestrial LIPs. Presently it is difficult to determine which LIP events (and their pulses) have a greater environmental impact. For the initial timing analysis below, it is natural to use the first pulse to mark the fiducial time of the event e.g., associating it with the onset of a putative eruptive event driving the LIP as a whole. For the statistical studies below consistent application of this definition to all LIP events is what is important.

It must be noted that LIP size is not the only determinant of its environmental effect (Wignall 2001; Ch. 14 in Ernst 2014) which strongly depends on other factors. For example, the concentration of CO_2, sulfur and other gases in the volcanic component. There is also thermogenic release from the intrusive sill component emplaced into volatile rich sediments (Svensen et al. 2009), and other factors. The largest recorded LIP, the nearly 80 million km^3 combined Ontong Java – Manihiki, and Hikurangi LIPs had a modest environmental effect (a major anoxia event but no evidence of major extinctions). The result is explained by the emplacement of this oceanic LIP under water where its environmental effects were buffered by seawater.

One aspect of heterogeneity and uncertainty in LIP dating is recognized from the data themselves - namely apparent rounding of the reported values (e.g., to the nearest 5 Myr or 10 Myr). An effect of such rounding on our conclusions is demonstrated in Figure 1 below, with further details in SI.

2.2 Simultaneous but independent LIPs

A main objective of this work is to quantify the rate of occurrence of what we call "simultaneous LIPs" based on the timing of LIPs in the Earth's record. By this term we mean LIPs -- presumably causally independent of each other (see Figure 1 in the next Section 2.4 and SI) -- occurring close enough in time that their effects add up to yield more significant geological or atmospheric effects than ensue from individual events. Pragmatically this means two or more concurrent events that are geographically separate, thus presumably driven by causally separated events. This analysis is in pursuit of the ultimate goal of extending the results to Venus in order to elucidate the possible importance of such events for the history of that planet. As shown in Ernst and Buchan (2002) and Bryan and Ferrari (2013) there are numerous events that occur at approximately the same time but are widely separated geographically and thus are unlikely to be linked to the same source. An example are events at 66 and 62 Ma: the former is the Deccan LIP of India and the latter the North Atlantic LIP of NW Europe with locations about 10,000 km apart. Another example from 95-90 Ma includes the second pulse of High Arctic, Caribbean-Colombian, and Madagascar LIPs. Given their spatial separation these are likely independently derived from separate plumes. The only basis for possible linkages would be if the source is from mantle plumes originating at the core-mantle boundary where their triggering is linked to cooling episodes in the core. Such coeval but widely separated LIPs can best be recognized in the younger Phanerozoic record. They are more difficult to recognize in the Precambrian record, given the ambiguity of whether coeval events on different crustal blocks can be reconstructed into a single event or must represent coeval but spatially separated independent events. For much of Precambrian time distinguishing these cases will await better defined paleo-continental reconstructions.

2.3 Are LIP Events Independent of each other or are they Causally Related?

We now assess evidence for randomness (in time) of these events. A simple approach is to compare the distribution of the time differences between successive LIPs with that expected under the assumption of independence, as shown in the top panel in Figure 1. The dotted line is the cumulative distribution function (CDF) of the raw age data from Ernst (2014, 2021b). Formally the cumulative distribution function *CDF*(*x*) is the fraction of data values less than or equal to *x*. The CDF can be derived with no binning of the data, since it is just a curve that starts at zero and jumps by 1/N discontinuously at each of the ordered data values. It is zero below the smallest value, rising in equal steps to a maximum of 1 at and above the largest value. The thin black curve is the theoretical CDF for ages distributed randomly and uniformly over the total 2,800 Myr interval. That this curve does not well match the distribution of the actual data is largely due to the effects of rounding discussed in the SI. This assertion is supported by the much closer match with the curve adjusted for rounding (thick black line), as detailed in the SI. Note that the excess of very small intervals, expected as a consequence of rounding, is nicely nullified by this procedure. The raw data contain 92 intervals <= 1 Myr (CDF = .343 as in the Figure), while Equation (2) below predicts 24.6 for the same parameters. Rounding has enhanced the number of such intervals by nearly a factor of 4 (92/24.6=3.74).

Given the rather small, necessarily incomplete data set, with random and possibly systematic measurement errors and the uncertainty in the actual rounding of the data, this agreement is rather strong evidence for random LIP occurrence. Further statistical evidence concerning randomness is presented in SI.

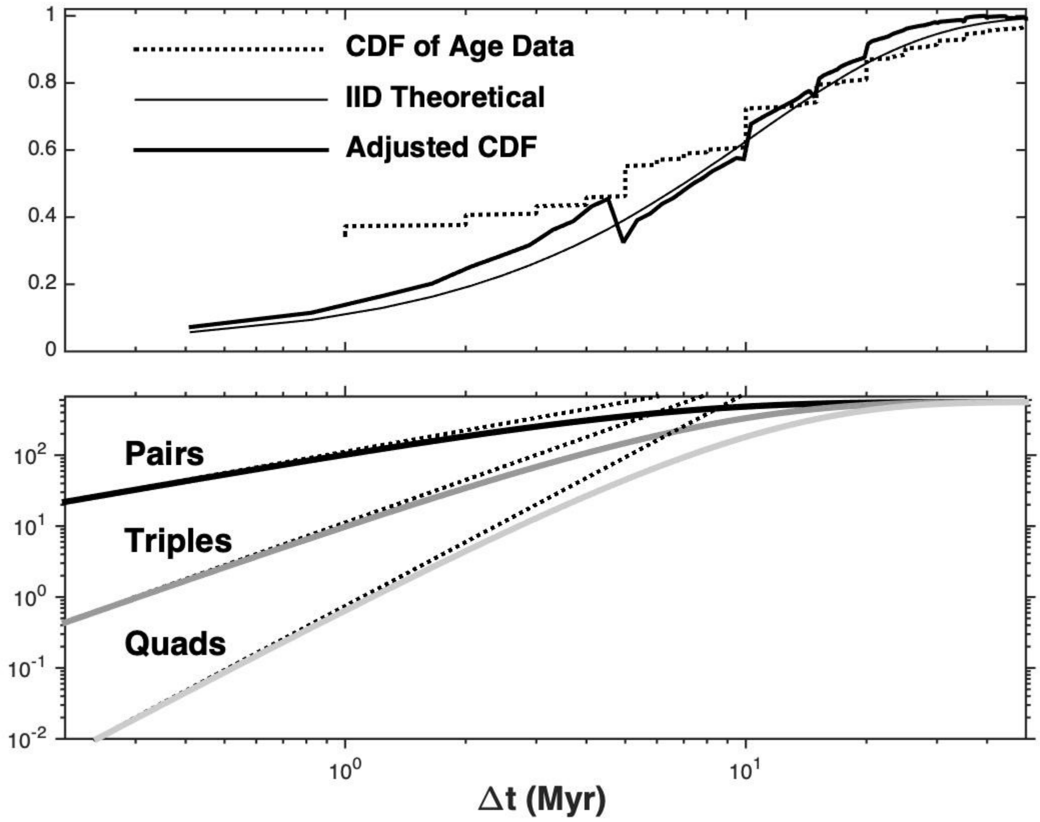

Figure 1: **Top:** Cumulative distributions (CDFs) of time intervals *between consecutive events*. Dotted line: the raw *LIP* age data. Thick black line: *LIP* age data adjusted for rounding as discussed in the *SI*. Thin black line: theoretical CDF for purely random (i.e., identically and independently distributed) data.

Bottom: Expected number of LIP clusters simultaneous to within time $\Delta t \in Myr$ – i.e., N_0 times the Erlang probability distribution. The exact form in Eq. (3) is shown with solid lines (black for pairs, medium grey for triples, and light grey for quadruplets) and the straight-line approximations from Eq. (4) with dotted lines. The exact forms asymptote to the total number of events, namely N_0 = 560 = the fiducial event rate λ_0 = 0.2 times record length 2,800. E.g. for Δt = 1 Myr, read approximately 100, 10 and 0.6 as the expected number of pairs, triplets and quadruplets, respectively (cf. Table 1). Results for other values of these parameters can be scaled as described in Section 3.

2.4 Missing terrestrial Oceanic LIP record

As shown in Dilek and Ernst (2008); Coffin and Eldholm (2001b) modern oceanic crust is present back to about 200 Ma, and the preserved oceanic LIP record (i.e., LIPs emplaced onto oceanic crust) for this period can be compared with the continental LIP record for the same time period. In this period the rate of LIPs averages one per 20-30 Myr, and the oceanic LIP record over this time period is similar. This estimate could suggest that the combined continental and oceanic LIP record back through time could equal twice the continental LIP record. In Dilek and Ernst (2008) it was suggested that the number of missing LIPs back to 2.5 Ga is about 100. There is currently significant effort to try to identify this missing oceanic LIP record in orogenic belts (e.g., Ch 2 Ernst 2014; Doucet et al. 2020). On Earth the climatic impact of oceanic LIPs is typically less significant because of the buffering effect of overlying ocean water. At this point it is important to make a distinction between LIPs emplaced onto oceanic crust vs LIPs emplaced underwater. Generally, LIPs emplaced onto oceanic crust are also emplaced underwater and hence the overlying seawater can buffer the environmental effect.[1] While LIPs emplaced onto continental crust are typically emplaced above water, there are periods in Earth history where freeboard was lower and major expanses of continental crust were underwater (e.g., Korenaga et al. 2017). This may particularly apply in the Archean as indicated by flood basalts emplaced on continents (linked to LIPs) as pillow basalts; these would therefore be interpreted continental LIPs emplaced underwater.

Another important point is the following: On Earth, given the strong independence of LIPs from plate tectonic processes and that a plume originating in the deep mantle near the boundary with the core does not "know" whether it is arriving under continental or oceanic crust (e.g., Section 14.3 in Arndt et al., 2008; Section 2.2.5 in Ernst, 2014) and hence whether an oceanic or continental LIP is produced is essentially random. One could

[1] Aquatic life forms may not agree with this assessment.

entertain approximately doubling the known continental LIP rate based on an inferred missing oceanic LIP record, with a similar situation for ancient Venus.

2.5 Relevance to Venus of terrestrial oceanic LIP record

The hypothesized LIP influenced GCT can be divided into three periods: pre-warming, syn-warming and post-warming. In the pre-warming time inferred oceans could mute the climatic effects of any LIPs emplaced beneath these oceans, by analogy with the situation of LIPs (continental or oceanic) on Earth. Therefore, during this pre-warming time LIP simultaneity should be calculated using the timing based on continental and oceanic LIPs regardless of whether they are emplaced under water or not.

However, if the ocean depths were shallower than present day Earth's then underwater LIPs could interact with the atmosphere more easily and contribute CO_2 to the climate transition. In addition, we remain ignorant about the topography, land/sea mask and bathymetry of a pre-GCT Venus. WG20 present a limited number of possibilities: everything from a land planet with limited surface water reservoirs, to a full-blown aquaplanet completely covered in water. Most WG20 topographies used modern Venus while another used modern Earth. In the former the land-sea ratio was ~40-60, while on modern Earth it is presently ~30-70. Certainly, if more land is exposed then there are likely to be fewer underwater LIPs. During the GCT, as the oceans become shallower, underwater LIPs could have more direct access to the atmosphere. This suggests that, where possible, the application of the terrestrial record to Venus should include both that from continental and combined continental plus oceanic LIP record in order to bracket the range of possibilities on Venus. However, it should be noted that it is difficult to quantify a number of related things: 1.) We do not know what the land/sea mask might have been in the pre-surfacing period (Strom et al. 1994); 2.) We do not know the baythmetry of any hypothetical ocean, nor do we have any constraints on the land topography: The pre-resurfacing hyposometry of Venus remains a mystery to us; 3.) We do not know with any precision what the water inventory of the pre-resurfacing period was beyond very rough constraints provided by the D/H ratio from the Pioneer Venus Large Probe Neutral Mass Spectrometer (Donahue et al. 1982; Donahue and Hodges 1992). Regardless, we can place an upper limit by assuming the rate of oceanic to continental LIPs are equal based on Ernst et al. (2004) who found such a rate on Earth over the past 200 Myr. As mentioned previously we cannot go farther back in time because there is little preserved oceanic crust older than 200 Myr.

2.6 Defining simultaneity of LIPs in terms of superimposed environmental impact

One of the major motivations for our analysis of geographically separate but temporally overlapping LIPs (Section 3) relates to the environmental effect of LIP CO_2 outgassing. Specifically, we wish to investigate the possibility of separate LIPs overlapping in time such that the CO_2 effect of each would superimpose and potentially lead to a runaway greenhouse effect. The average residence time in the atmosphere for an individual CO_2 molecule is <100 years, but a pulse of elevated CO_2 levels in the atmosphere can take much longer to return to an original value. As noted in Archer (2005, 2009) while much of the extra CO_2 added to the atmosphere is removed within a few years, there can be a long tail of remaining residence that can be removed by through silicate weathering. Assuming a 400,000-year time constant for the silicate-weathering feedback would result in mean CO_2 lifetimes of ~45 thousand years. Figure 1 in Archer et al. (2009) illustrates the rapid initial decrease of CO_2 and the long tail that decreases slowly and should have 10-30% of the CO_2 remaining after 100,000 years and perhaps much longer. So, it would seem that the spacing of LIPs to have a superimposed CO_2 effect could be as little as 100,000 years and perhaps as much as 1 Myr.

The analysis by Archer et al. (2009) is model based, but a similar story is revealed by the measured δ13C_{carb} variation at the Permian Triassic boundary (Burgess et al. 2014) caused by the Siberian Traps event (Burgess and Bowring 2015). There is a sharp negative δ13C_{carb} excursion associated with the short LIP pulse at the “Extinction Interval" in Burgess et al. (2014; Figure 1). After an initial sharp negative and then positive δ13C_{carb} excursion there is a much slower decrease for ~300,000 years (associated with continued pulses of the Siberian Traps LIP) followed by a gradual increase in δ13C_{carb} toward the original level of +4 δ13C_{carb} over a period of at least 200,000 years as magmatism waned based on the available dating of Fig. 2 in Burgess et al. (2017).

The modelling and actual data from the Siberian Traps LIP confirms that the pulse of CO_2 from a LIP can in many cases persist for hundreds of thousands of years. As we will discover below, this is well within our estimates of likely LIP simultaneity.

2.7 Relevance of ambient temperature and pressure at the time of LIP emplacement

A number of publications (e.g., Tarese et al. 2017; Robert and Chaussidon 2006) have demonstrated that the ambient temperature of the Earth may have exhibited substantial variation through time. If this conclusion is correct, the ocean temperature may have reached 60-75C between 1.9 and 3.5 Ga. Under such thermodynamic conditions only a small temperature increase due to LIPs could almost boil the oceans. Furthermore, there is evidence that the atmospheric pressure in the Archean could have been as low as 0.25 bar (e.g., Som et al. 2012, 2016). This is an important point, since Gaillard and Scaillet (2014) have shown that volcanic degassing chemistry is dependent upon atmospheric pressure. These works demonstrate that the exact conditions for producing a runaway will require more sophisticated modelling that is outside the scope of the present work.

3 Potentiality for Simultaneous LIPs?

The top panel in Figure 1 and the SI material give compelling evidence that LIPs are identically and independently distributed -- i.e. occurring at a constant rate $\boldsymbol{\lambda}$ (events per unit time) with no influence on each other. In other words they are a *Poisson process*, the most basic and well-studied[2] of all stochastic point processes (Papoulis 1965, Billingsley 1986). The following analysis is based solely on this idealized but accurate model, and is independent of details of the terrestrial LIP record and its sampling.

A key result is the statistical distribution of the times between events. Let

$$\mathbf{s} = \mathbf{t(n+k) - t(n)} \qquad (1)$$

denote such a time interval, corresponding to a *cluster* of **k+1** consecutive LIPs with total duration **s**. For example, **k** = 1 corresponds to two successive events separated by **t(n+1) – t(n).** Similarly, **k** = 2 refers to a triplet, and so on. The frequency of such clusters obeys the *gamma probability density* (also known as the *Erlang distribution*):

[2] We make use of the exhaustive mathematical development of the statistics of temporal clustering of such events, under the name of *queueing theory* – e.g., to study arrival of telephone calls at a switchboard and many other applications.

$$p(s) = \lambda^{k} s^{k-1} \exp(-\lambda s) / \Gamma(k) \quad , \qquad (2)$$

where **$\Gamma(k) = (k-1)!$** is the gamma function. This gives the probability for a given LIP to be followed in succession by **k** more, the last of which is time **s** later. Of more interest is the likelihood of finding a **k**-cluster of a specific duration or less, in terms of the *(lower) incomplete gamma function* γ:

$$P(s <= \Delta t) = \int_{0}^{\Delta t} p(s)\,ds = \text{¿¿}\ \gamma(\lambda\Delta t, k) \qquad (3)$$

with an approximation

$$\approx (\lambda\Delta t)^{k} / k! \qquad (4)$$

that for k <= 3 is accurate to 10% for λ = 0.2 per Myr and Δt = 1 Myr and to better than a factor of 2 for all values of these parameters. The takeaway from these plots is: In a LIP record like the Earth's, pairs and triplets of LIPs simultaneous – at the level of ~1 Myr separation -- are very common. In a nutshell: many pairs are expected, at least one triplet is virtually certain, while quadruplets are unlikely. Further summary statistics are given in Table 1 -- for two choices Δt = 0.1 and 1.0 Myr defining simultaneity. Column (1) is the expected number of **k**-clusters; (2) is the corresponding rate at which such **k**-clusters occur over time relative to the LIP rate itself; (3) is the waiting time between **k**-clusters; and (4) is the probability of one or more **k**-clusters. The entries in column (4) are easily computed as 1 minus the probability that no event starts a cluster; since these failures have probability 1 – p, with p from Equation (2), the net result is $1 - (1 - p)^{N}$. Note that these statistics are a function of the dimensionless ratio **λ** Δt, so the two cases can also be considered rate differences by a factor of 10.

multiplicity	(1) N(k)	(2) cluster rate (relative to LIP rate)	(3) Wait time (Myr)	(4) Prob at least one
pair Δt = 0.1	11	2.0%	252	0.9999…
Δt = 1	101.5	18.1%	28	0.9999…
triple Δt = 0.1	0.11	.02%	25,345	0.1046
Δt = 1	9.8	1.7%	285	0.9999
quad Δt = 0.1	.0007	.0001%	3,800,660	0.0007
Δt = 1	0.64	0.11%	4354	0.4746

Table 1: Summary statistics of LIP **k**-clusters for the fiducial Earth record. With oceanic LIPs included: **N** = 560 LIPs over **T** = 2,800 Myr, giving **λ** = **N/T = 0.2**. In each box the first entry is for Δt = 100,000 years. The second entry is for Δt = 1 Myr that yields many more coincidences than Δt = 100,000 years because of the wider window of opportunity.

4 Conclusions

The occurrence of terrestrial LIPs over time is well described as a uniform, independently distributed random process, thus enabling an exact statistical description of temporal clustering. For example, in the 2,800 Myr long terrestrial LIP record one expects ~100 LIP pairs and 10 triplets within 1 Myrs of each other. These results are scalable to other cases using their dependence on the dimensionless parameter **λ** Δt. This result is quite conservative: any departure from uniform randomness (e.g., periodicities) would only increase LIP rates and enhance our conclusion. Multiple simultaneous LIPs may be important drivers of the transition from a serene habitable surface to a hot-house state for terrestrial worlds assuming they have similar geochemistries and mantle convection dynamics in comparison to Earth. This work provides support for the hypothesis of enhanced environmental impacts of near simultaneous LIPs playing an important role in Venus' Great Climate Transition. More work on exactly how such a transition can take place will have to be modeled with modern planetary General Circulation Models. The data and code utilized here are included in "SI.

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