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Research paper

Periodicities in the emplacement of large igneous provinces through the Phanerozoic: Relations to ocean chemistry and marine biodiversity evolution

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ABSTRACT

Large igneous provinces (LIPs) are considered a relevant cause for mass extinctions of marine life throughout Earth's history. Their flood basalts and associated intrusions can cause significant release of SO_4 and CO_2 and consequently, cause major environmental disruptions. Here, we reconstruct the long-term periodic pattern of LIP emplacement and its impact on ocean chemistry and biodiversity from $\delta^{34}S_{sulfate}$ of the last 520 Ma under particular consideration of the preservation limits of LIP records. A combination of cross-wavelet and other time-series analysis methods has been applied to quantify a potential chain of linkage between LIP emplacement periodicity, geochemical changes and the Phanerozoic marine genera record. We suggest a mantle plume cyclicity represented by LIP volumes (V) of $V = -(350\text{–}770) \times 10^3\ \text{km}^3 \sin(2\pi t/170\ \text{Ma}) + (300\text{–}650) \times 10^3\ \text{km}^3 \sin(2\pi t/64.5\ \text{Ma} + 2.3)$ for t = time in Ma. A shift from the 64.5 Ma to a weaker ~28–35 Ma LIP cyclicity during the Jurassic contributes together with probably independent changes in the marine sulfur cycle to less ocean anoxia, and a general stabilization of ocean chemistry and increasing marine biodiversity throughout the last ~135 Ma. The LIP cycle pattern is coherent with marine biodiversity fluctuations corresponding to a reduction of marine biodiversity of ~120 genera/Ma at ~600×10^3 km^3 LIP eruption volume. The 62–65 Ma LIP cycle pattern as well as excursion in $\delta^{34}S_{sulfate}$ and marine genera reduction suggest a not-yet identified found LIP event at ~440–450 Ma.

1. Introduction

Flood basalts and their associated plumbing systems represent large igneous provinces (LIPs) and are typically linked to mantle plumes that originate from deep in the mantle (e.g., Coffin and Eldholm, 1994; Ernst and Buchan, 2001; Courtillot et al., 2003) triggering large volume gas release in the ocean-atmospheric systems. Numerous studies have attempted to explore the links between the type, duration and magnitude of specific LIPs and temporally associated environmental perturbations (e.g., Caldeira and Rampino, 1993; Wignall, 2001; Berner, 2002; Svensen et al., 2009). In addition, there have also been evaluation of a long-term statistical link between the cycle of LIPs, ocean chemistry and biodiversity over the last 230 Ma and purely based on coeval timing of events (e.g., Caldeira and Rampino, 1993). A timing link between LIPs and mass extinctions has been discussed for several decades (e.g., Wignall, 2001; Courtillot and Renne, 2003), with ongoing high-resolution studies complementing this relationship (e.g., Isozaki, 2009; Saunders and Reichow, 2009). A recently discovered ~62 Ma and ~140 Ma cyclicity in the complete Phanerozoic marine fossil record (Rhode and Muller, 2005) has re-ignited the quest for primary and secondary geological factors might have caused these repeated fluctuations. For example, the ~62 Ma cyclicity in LIP, $^{87}Sr/^{86}Sr$ and $\delta^{34}S_{sulfate}$ records detected in independent studies (Prokoph et al., 2004a, 2008) have been merged to explain such patterns and possible relationships between these cycles (Melott et al., 2012).

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Here we attempt to reconstruct potential links between large-scale magmatism, ocean chemistry and biological evolution based on new databases and, for the first time, using cross-wavelet analysis to trace the cycles and their coherency though time and detect abrupt and gradual change. We used marine isotope records of sulfur and strontium as potentially continuous proxies for variability of igneous magmatism, in particular mantle plume related LIP eruptions. Moreover we used LIP volumes to better quantify magnitude relationships between LIP, oceanic chemistry and marine biodiversity evolution. The main challenging feature of the LIP record is its incompleteness. The LIP database is frequently updated with new LIPs being recognized as well as improvements in the ages, areal and volume extent of known LIPs (e.g., Torsvik et al., 2008; Reichow et al., 2009; Bryan et al., 2010; Ernst and Bleeker, 2010). However, the best dated and defined group of LIPs called "A10" (Ernst and Buchan, 2001) through the last 520 Ma have not changed or amended except for an increase in the ages of some LIPs dated only by the Ar/Ar method. The astronomical cycle based calibration of Fish Canyon sanidine reduced the ^{40}Ar/^{39}Ar method's absolute uncertainty from ∼2.5% to 0.25%, and more importantly increased the absolute age of ^{40}Ar/^{39}Ar-based dates by ∼0.6% (Kuiper et al., 2008). In this way, the age-determination issues around the Permian–Triassic boundary are an exception. Considering the age uncertainties mentioned above and the biostratigraphic resolution to which fossil and geochemical records are fitted (e.g., Prokoph et al., 2008) the LIP records can be used for statistical robust comparison with other long-term geological records at ±2 Ma resolution. However, the A10-record does not include information on the size of the LIP, thus cannot provide a link between the magnitudes of an LIP and environmental changes.

2. Datasets and their compilation

For our study, we used updated databases of probability-weighted LIP initiation ages and volumes (Ernst and Buchan, 2001; Courtillot and Renne, 2003), $\delta^{34}S_{\text{sulfate}}$ (Kampschulte and Strauss, 2004; Paytan et al., 2004) and $^{87}Sr/^{86}Sr$ (Prokoph et al., 2008), and marine biodiversity (Sepkoski, 2002; Rhode and Muller, 2005) for the last 520 Ma with reference to the GTS2004 time scale (Gradstein et al., 2005). The LIP volume dataset has two versions. Version #1 uses the minimal value for volume ranges and also reduces the estimated oceanic LIP volumes by 50% to remove the amount that is associated with underplating. This results in a better comparison with continental LIPs where the component of underplating is typically not possible to estimate. The version #2 estimate of LIP volumes consists of the maximum LIP volumes including the underplate component for oceanic LIPs. Both LIP volume datasets are restricted to the last 260 Ma due to the availability of reliable volume data.

Each dataset has been Gaussian filtered to equidistant 1 Ma-intervals considering a minimum 2% stratigraphic uncertainty (95% confidence interval of normal distribution). The Gaussian filtering algorithm used is in detail described in Prokoph et al. (2004a). The mean sample age uncertainty is set larger for poorly stratigraphic constraint samples. The Gaussian filtered records for LIP occurrences and volumes are shown in Fig. 1.

3. Data analysis methods

Continuous wavelet transform (CWT) is applied to delineate temporal variations of cycle amplitudes and phase over a 20–500 Ma spectrum for all datasets, whereas cross-wavelet transform (XWT) is used to extract the cross-amplitude and instantaneous time lag (i.e. phase shift) between LIP and other geological records.

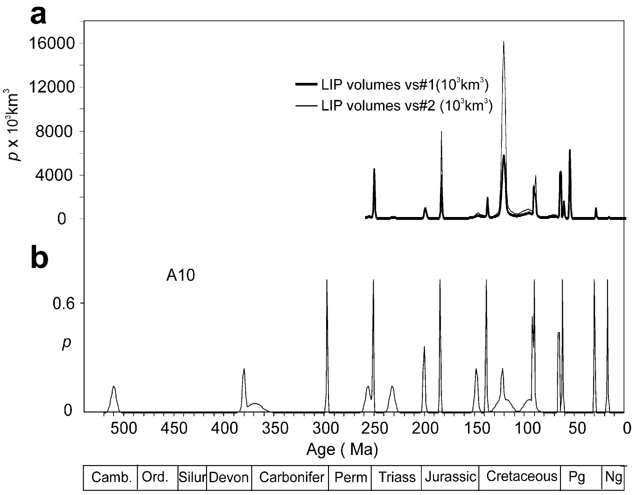

Figure 1. Gaussian filtered LIP volumes for last 260 Ma and A10 occurrences for last 520 Ma. For raw data see Ernst and Buchan (2001) and Table 1, for Gaussian filtered data see Table 2.

Wavelet analysis first emerged as a filtering and data compression method in the 1980s (e.g., Morlet et al., 1982). Wavelet analysis transforms a time-series into a frequency domain; it simultaneously transforms the 'depth' or 'time' domain and the 'scale' or 'frequency' domain by using various shapes and sizes of short filtering functions called wavelets. CWT allows for the

Table 1
LIP volumes.

Age (Ma)	1σ	Rating	Vol-vs.#1 (10^3 km^3)	Vol-vs.#2 (10^3 km^3)	Type	Event ID	Event name
17	0.5	A	175	175	Continental	1	Columbia
30	0.5	A	1200*	1200*	Continental	2	Afar
48	5	B	50$	100$	Oceanic	–	Metchosin (="Coast Range Basalt Province")
56*	0.5	A	7900*	7900*	Continental	5	NAVP
62	0.5	A	2000*	2000*	Continental	5	NAVP
65.5	0.5	A	8600	8600	Continental	6	Deccan
70	1	B	100$	200$	Oceanic	9	Carmacks
73	5	B	600	1200	Oceanic	7	Maud
73	5	B	1250	2500	Oceanic	8	Sierra
90	0.5	A	2250	4500	Oceanic	11	CCCIP
91.6	0.5	A	4400	4400	Continental	10	Madagascar
95	5	A	2000$	2000$	Continental	12	Alpha
96	5	B	750	1500	Oceanic	13	Wallaby
99	7.5	B	4550	9100	Oceanic	14	Hess
101	5	B	600	1200	Oceanic	15	Naturaliste
111	5	B	450	900	Oceanic	19	Nauru
118	5	A	3000*	6000*	Oceanic	18	Kerguelen
122	1.5	A	20,000#	57,000#	Oceanic	20	Ontong
123	5	A	4400	8800	Oceanic	21	Manihiki
123	6.5	B	50$	100$	Oceanic	22	Piñón
136	5	B	800	800	Continental	25	Gascoyne
138	0.5	A	2300	2300	Continental	24	Paraná–Etendeka
145	5	B	900	1800	Oceanic	26	Magellan
147	5	B	1250	2500	Oceanic	27	Shatsky
148	1.5	A	300	600	Oceanic	28	Sorachi
155	5	B	300$	300$	Continental	29	Argo
184	0.5	A	5000#	10,000#	Continental	31	Karoo–Ferrar
200	1	A	2500	2500	Continental	32	CAMP
214	7	B	225$	450$	Oceanic	33	Angayucham (=Ramparts Group volcanics)
232	2.5	A	500	1000	Oceanic	34	Wrangelia
251	0.5	A	5700	5700	Continental	36	Siberian
256	2.5	A	1000	1000	Continental	37	Emeishan

Estimation by Ernst and Buchan (2001) except for * Courtillot and Renne (2003), $ estimates from areal extend, # volume estimates from 5000 to 10,000 × 10^3 km^3.