Thermal erosion of cratonic lithosphere as a potential trigger for mass-extinction

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The temporal coincidence between large igneous provinces (LIPs) and mass extinctions has led many to pose a causal relationship between the two. However, there is still no consensus on a mechanistic model that explains how magmatism leads to the turnover of terrestrial and marine plants, invertebrates and vertebrates. Here we present a synthesis of ammonite biostratigraphy, isotopic data and high precision U-Pb zircon dates from the Triassic-Jurassic (T-J) and Pliensbachian-Toarcian (Pl-To) boundaries demonstrating that these biotic crises are both associated with rapid change from an initial cool period to greenhouse conditions. We explain these transitions as a result of changing gas species emitted during the progressive thermal erosion of cratonic lithosphere by plume activity or internal heating of the lithosphere. Our petrological model for LIP magmatism argues that initial gas emission was dominated by sulfur liberated from sulfide-bearing cratonic lithosphere before CO2 became the dominant gas. This model offers an explanation of why LIPs erupted through oceanic lithosphere are not associated with climatic and biotic crises comparable to LIPs emitted through cratonic lithosphere.

There are currently two main hypotheses to explain recurrent catastrophic global climatic change and related mass extinctions in Earth history. The first invokes super-greenhouse conditions due to extreme atmospheric CO2 concentrations1,2. This enrichment is often interpreted as degassing of magmatic CO2 from volcanic basalt provinces1 and/or from the degassing of carbonateous or organic-rich sediments by sill and dyke intrusions3,4. The second scenario invokes a short period of global icehouse conditions caused by degassing of large volumes of volcanic SO2, atmospheric poisoning, cooling, and eustatic regression5,6. Although both hypotheses are compatible with massive volcanic degassing, they must also be able to explain the paleontological record in marine and continental stratigraphic sections. Mass extinction events are recorded in various marine and continental sedimentary sections distributed around the world. One major challenge is to correlate these sections in order to obtain a global “picture” required to understand global climate change associated to mass extinction. Marine versus continental sedimentary sections do not necessarily record the same processes neither the same time interval. In particular, LIPs volcanic activity related to major periods of extinction (Siberian Trap, CAMP, Karoo-Ferrar, Deccan) is restricted to continental settings while key observations to demonstrate global mass extinction is recorded in marine environments. It requires, therefore, precise and accurate time constraints to link volcanic activity with the change in the paleontological record, precision at the 100 ka level, which is only achievable using high precision U/Pb geochronology on zircon8,9. Here, we review data from the stratigraphic record of the Triassic-Jurassic (T-J) and Pliensbachian-Toarcian boundaries combined with geochronological data8-10 in order to establish the sequence of events that initiate two of the major mass extinctions recorded in Earth’s history. Then, the various alternatives to explain the climatic and chemical changes associated to these sequences of events are discussed.

Sequence of events associated to the Triassic-Jurassic boundary

Detailed ammonite biostratigraphy7,11 combined with the carbon and oxygen stable isotope records1,12,13 and zircon geochronology8,9 allows reconstruction of the sequence of events associated with biological crisis observed...
at the T-J boundary (Fig. 1). Figure 1 shows the synchronicity, initially pointed out by Marzoli et al.14, between end-Triassic extinction (ETE) marked by the major extinction of the Triassic ammonoids (indicated by the last occurrence (LO) of Choristoceras crickmayi) and the earliest CAMP volcanism19. The ETE event is characterized by a strong negative excursion of δ13Corg recorded in New York Canyon (Nevada, USA) and worldwide28, correlated to a negative excursion of δ13Cwood measured in fossil leaf and wood from East Greenland14,15 and by a marine regression in the upper Rhaetian of Austria, England and Nevada (Fig. 1). This eustatic regression which predates or is concomitant with environmental changes at the Rhaetian – Hettangian transition is supported by various stratigraphic evidence: (1) At New York Canyon, the end Triassic sediments are characterized by a bed packed with small shallow water bivalves indicating low sea level conditions; (2) In northern Peru (Chilinquito, Ucubamba Valley) an erosional tempestite horizon located just below Odoghertyceras ammonites (early Jurassic) bearing sediments indicates this section was above storm wave base in the topmost Triassic16; (3) A pronounced increase in the proportions of terrestrial versus marine palynomorphs during the end-Triassic interval is observed in various sedimentary sequences from the Alps17–19; (4) In England, wave-ripple structures and mudcracks horizons, evidencing shallowest water depth conditions and sporadic emersions, are observed just few centimeters below the end-Triassic negative δ13C excursion20. This regressive event interpreted as cool climate conditions (Fig. 1) is in agreement with the high δ18O values as measured in Oysters from Lavernock (UK)15. (h) Sea level variations.

Notes: ETE: End Triassic Extinction. MPT: Early Jurassic major plant turnover1. LO: Last Occurrence. FO: First Occurrence. Neo & Ppl: Neophylites & Psiloceras planorbis ammonite species respectively. (See supplementary information for additional details about the correlation between marine and continental sections).

Sequence of events associated to Pliensbachian-Toarcian boundary

Environmental perturbations related to the early Jurassic Pliensbachian-Toarcian boundary have been associated for some time with the onset of the Karoo-Ferrar large igneous province21. This inference is confirmed by high precision U-Pb dating on zircons20,22 which indicate that major sills intruded into organic-rich sediments in the Karoo basin are correlated with the Toarcian Oceanic Anoxic Event (OAE) recorded in the marine sedimentary section from Peru, dated by ammonites and intercalated zircon bearing ash beds (Fig. 2). The end-Plainsbsbachian extinction, preceding the Toarcian OAE23, is marked by an important diversity drop (disappearance of 90% of the ammonite taxa) associated with a generalized sedimentary gap linked to a marked regression event in NW-Europe and the Pacific area24. This regression may represent a major short-lived glaciation associated to the thermal-erosion of the continental lithosphere following by CO2 degassing associated to CAMP volcanism. This warming potentially associated with large volcanic CO2 emissions from CAMP volcanism (Fig. 1)1,2,12,15. This warming period is associated with an abrupt change in plant diversity observed in Greenland1,15 and with a second negative δ13C recorded in the Hettangian Psiloceras planorbis beds (coeval with P. pacificum) that postdate the ETE (see supplementary information).

Figure 1. Stratigraphic and isotopic correlations for the Triassic-Jurassic boundary. (a) U-Pb ages on zircon from ash beds embedded in marine stratigraphic sections from N. Peru and Nevada30. (b) Standard ammonite zones for the late Triassic-early Jurassic. (c) Duration of CAMP volcanism in North America and Morocco (Argana Basin)9. (z) δ13Corg from New York Canyon (Nevada, USA)30. (f) δ13Corg recorded in stratigraphic sequences from East Greenland and pCO2, estimated for the late Triassic-early Jurassic12,15. (g) δ18O measured on Oysters from Lavernock (UK)15. (h) Sea level variations.

Notes: ETE: End Triassic Extinction. MPT: Early Jurassic major plant turnover1. LO: Last Occurrence. FO: First Occurrence. Neo & Ppl: Neophylites & Psiloceras planorbis ammonite species respectively. (See supplementary information for additional details about the correlation between marine and continental sections).
Pliocene ammonites (Nevada) and below sediments containing Early Toarcian ammonites (Nevada and New Zealand). The cooling model is also supported by recent $\delta^{18}$O data on belemnites.

The regression phase is followed by a worldwide transgression during the Early Toarcian, with the deposition of black shales associated with the Toarcian OAE. This transgression is interpreted as partly linked to glacio-eustatic sea-level rise associated to rapid change from cold to warm climatic conditions. The lower limit of the Toarcian OAE in S. Peru has been dated at 183.22 ± 0.25 Ma, coinciding with the oldest Karoo sill and lava currently dated (granophyre sill intruded in the Tarkastad Formation date of 183.014 ± 0.054 Ma and granophyre in the New Amalfi Sheet date of 183.246 ± 0.045 Ma). The Toarcian OAE is responsible for a second extinction affecting mainly benthic foraminifera populations and brachiopods but the ammonites were only slightly affected, mostly by a moderate drop in diversity.

The stratigraphic and isotopic evidence presented here indicate that initial eustatic regression events predate or are concomitant with evidence of environmental change at the Rhaetian – Hettangian and the Pliensbachian–Toarcian transitions. The major question is: what process(es) could produce these initial regressions? The short duration of these events (<1 Ma) would be difficult to explain with tectonic processes because of the long timescales associated with heat-induced changes in lithospheric buoyancy. Such long-term processes also seem unable to explain the initiation of biological crises. These regressive events are difficult to reconcile either with large initial CO$_2$ degassing associated with LIPs as proposed to explain the T-J and Pl-To mass extinctions or by volatile-release (CO$_2$, CH$_4$, Cl$_2$) from deep sedimentary reservoirs during contact metamorphism associated to dykes and sills intrusion because massive CO$_2$ degassing is expected to produce super greenhouse conditions. An alternative is that volcanic emissions of large igneous provinces would release a sufficiently large volume of sulfur causing global cooling and eustatic regression, which was followed by warming/transgression associated with the progressive increase of CO$_2$ in the atmosphere associated to LIPs emission and metamorphic reactions in sedimentary basins.

**Cratonic lithosphere as a potential sulfur reservoir**

Petrolological constraints on primary magmas indicate that the mantle is hotter and melts more extensively to produce LIP lavas or continental flood basalts (CFB) than for current oceanic islands basalts. The melting of garnet-bearing peridotitic sources at high pressures (5–6 GPa) and anomalously high mantle potential temperatures ($T_p$) of >1,600 °C (Fig. 3) are required to generate the parental melts of high-Mg meimechites from the Karoo–Ferrar province while lower $T_p$ (1450 °C ± 50 °C) and lower pressures of melting (>2 GPa) were
estimated for tholeiitic lavas from CAMP and Ferrar large igneous province49. Available data suggest that the Karoo-Ferrar and CAMP have been emitted on top of thick lithosphere50. First, the eastern and the southern extents of the CAMP were located on top of Archean and Proterozoic cratons, while the Karoo LIP was erupted on and around the Kaapvaal craton. Shear wave velocities (V_s), suggest that the Karoo and CAMP areas were underlain by thick lithosphere (>200 km) prior to continental break up51–53, which postdates the LIP emplacement54. The thin lithosphere on both margins of the CAMP area (east coast of North America and north-west coast of Africa) is the consequence of stretching and thinning before seafloor spreading55. A thick lithosphere exceeding 200 km beneath the Kaapvaal craton is also documented by kimberlite-borne mantle xenoliths56. The thickness of the lithosphere beneath the Ferrar LIP is probably similar, given that the Ferrar LIP emission was linked to the Wilkes Land craton57. Taking into account estimates of the thickness of continental lithosphere beneath Karoo-Ferrar and the CAMP area, the melting conditions estimated for LIP's meimechites and tholeiitic lavas48,49 point out the fundamental role of the lithospheric mantle to produce these lavas. Various geochemical and isotopic studies on CAMP58–60 and Karoo-Ferrar magmas61–65 indicate that continental lithospheric mantle is a major geochemical component involved in the petrogenesis of these lavas. Two different hypotheses could explain the melting of the lithospheric mantle65: the arrival of a thermal plume initiating heating and subsequent partial melting of the subcontinental lithosphere3, or internal heat production of mantle insulated by continental lithosphere allowing for partial melting of the upper asthenospheric and continental lithospheric mantle to produce LIPs magma63,64–68. This initial step of thermal erosion/thermal heating of the cratonic lithosphere is critical to understand the volatile budget associated with LIPs while studies of the composition of the Kaapvaal craton have shown that sulfide minerals are enclosed in the basal part of the cratonic lithosphere69 (Fig. 4a). The formation of these sulfide minerals are linked to multiple refertilization/metasomatic events, which affected the base of the subcontinental lithospheric mantle from the Archean to the Proterozoic69.

Figure 4 illustrates how thermal erosion of the lithosphere associated with the rising of a thermal plume or internal heating of the subcontinental mantle could release sulfur from the cratonic roots. (I) Low degree melts from the base of the lithosphere may rise and initiate the thermal erosion of the cratonic lithosphere (Fig. 4a,d). According to the low solidus temperature of sulfides relative to dry peridotite70 (Fig. 3), the sulfide-enriched lithologies will be remobilized by the progressive percolation of low degree melts from the subcontinental lithosphere. In a runaway process, the S-rich melts/liquids released from the base of the cratonic lithosphere do not directly reach the surface, but enrich progressively shallower levels of the lithospheric mantle, levels which could be remobilized sequentially during the thermal erosion of the lithosphere (Fig. 4a,d); (II) If lithospheric erosion is sufficiently shallow, scavenging of sulfur-rich melts/liquids could either reach the surface and release significant amounts of sulfur to the atmosphere or be mixed with the first CFB magma pulses producing initial high SO2 flux to the atmosphere (Fig. 4b,e). The former process could be linked to the emission of small volumes of alkaline lavas and carbonatites associated with translithospheric fracturing as observed in various LIP areas71; (III) The last stage (Fig. 4c,f) corresponds to an advanced degree of thermal erosion of the lithosphere, sufficient to lead to significant melting and extrusion of the lavas observed in the Karoo-Ferrar area and in the CAMP. The injection of large volumes of magma into sedimentary basins releases additional sediment-derived greenhouse gases (CO2, CH4, ...) produced during contact metamorphism4,5. These models are in agreement with geochemical data.

Figure 3. Pressure-Temperature diagrams for the condition of melting of dry-peridotite compared to the thickness of the lithosphere before thermal erosion (>200 – 230 km4,69). The adiabat temperatures for CAMP and Karoo-Ferrar CFB are estimated by Herzberg and Gazel47 based on petrological constraints. *The red and orange zones indicate the conditions of formation estimated for Vestfjalla meimechites48 and CAMP tholeiites49 respectively. **The continuous black and yellow lines show the solidus for dry peridotite81 and mono-sulfide solutions70, respectively. This latter solidus was determined only to 3.7 GPa, the yellow dashed line indicates extrapolation to higher P-T conditions (See supplementary information for details about the melting conditions in an upwelling plume).
emphasizing an important role of the lithospheric mantle in the petrogenesis of Karoo-Ferrar and CAMP LIPs, but also suggest that a precursor magmatic phase predates the main phase of LIPs emission. The existence of a precursor phase of magmatism associated to the Karoo-Ferrar LIP is supported by recent mercury data determined in marine sediments \(^72\) (Fig. 2g). The high Hg concentrations and Hg/TOC (TOC: Total Organic Carbon) ratios correlated with the negative carbon-isotope anomalies associated with the Pliensbachian-Toarcian boundary and Toarcian OAE observed in Peniche, Arroyo Lapa, Mochras and Bornholm sections are indicators for two distinct episodes of Hg release to the atmosphere by volcanic activity \(^72\) in line with our sequence of two distinct magmatic events.

To estimate the potential amount of S released to the atmosphere during the initial phase of lithosphere thermal erosion/heating, we have calculated the amount of sulfur present in the lower 25 km of the lithosphere and assuming a surface equivalent to half the area covered by Karoo-Ferrar or CAMP LIPs. Based on garnet chemistry from Kimberlite xenoliths, the basal part of southern African lithospheric mantle includes significant proportions of melt metasomatized peridotite \(^56\). Assuming that the basal part of the lithosphere was composed of 40% depleted peridotite (119 ppm S), 55% metasomatized peridotite (300 ppm S) and 5% pyroxenite (800 ppm S), we obtain a potential sulfur content that could be released to the atmosphere (calculated in equivalent SO\(_2\)) of ~45,000 Gt and ~210,000 Gt of SO\(_2\) for the case of the Karoo-Ferrar and CAMP, respectively (see supplementary information for details). Our estimates for potential sulfur release from the lithospheric mantle are 5 orders of magnitude higher than the mass estimated for Laki (~122 MT SO\(_2\)) or Pinatubo (~20 Mt SO\(_2\)) eruptions.

Figure 4. Schematic sections illustrating heating of the lithospheric mantle associated to the arrival of a thermal plume beneath a thick cratonic lithosphere (panels (a–c)) or linked to the increase of mantle temperature through supercontinent thermal insulation (panels (d,e)). The basal part of the lithosphere is composed of melt-metasomatized peridotite \(^69\). Panels (a,d) illustrate the initial step of melting, panels (b,e), the precursor step of magmatism suggested by Ernst and Bell \(^71\) while panels (c,f) show schematic sections of cratonic lithosphere during the generation of large volume of CFB. These latter sections are based on a model suggested by Heinonen et al. \(^65\) for the magma generation of Karoo-Ferrar CFB.
Assuming that only a small proportion of this sulfur is effectively released to the atmosphere, it could still have a significant impact on climate and environment.

Thermomechanical modeling for plume-lithosphere interaction has shown that gas release from plume material could reach the surface prior to the emission of the first lavas, but this model does not take into account the gas released from the cratonic lithosphere. We suggest here that the initial gas release to the atmosphere is not solely composed by gas from the asthenosphere itself (CO$_2$/HCl$^3$), but additional sulfur gases produced from the thermal erosion of the cratonic lithosphere represent a significant portion of emitted gases during this initial period. Studies of recent catastrophic eruptions demonstrate that large SO$_2$ emission affects the climate, but the gas flux, the latitude of the eruption and the maximum altitude reached by the volcanic clouds (troposphere or stratosphere) influences the climatic response (e.g. refs 73,75,76). Models for SO$_2$ release into the atmosphere demonstrate that it is not the magnitude of SO$_2$ emission, which is critical to produce cooling, but the frequency and the duration of SO$_2$ emission$^{38}$. Although we are unable to provide either a quantitative flux estimate or predictions about the heights reached by the volcanic clouds, we provide feasibility tests. Assuming that only 20% of the sulfur from the metasomatized lithospheric mantle is released to the atmosphere during a period of 100,000 years, we obtain a flux between 90 and 410 Mt/yr for the case of Karroo and CAMP, respectively. Timmreck et al. have modeled that sulfur emissions of ~100 times the mass of Pinatubo (corresponding to our estimate of S emitted for a period of 5 to 20 years) creates an average temperature decrease of ~3.5 °K lasting for 9–10 years. Robock hypothesized that a series of volcanic eruptions could initiate a longer-term cooling period. Schmidt et al. support this hypothesis but indicate that SO$_2$ release could cause biotic crisis only if such gas release is high and sustains for several centuries. Multiple SO$_2$ pulses lasting for several thousands of years as suggested here offers a viable hypothesis for the initial cooling required to explain the eustatic regression events and provides stress conditions to initiate biological crises recorded at the end of the Rhaetian (Fig. 1) and of the Pliensbachian (Fig. 2). Nevertheless initial stress conditions do not affect all species in the same manner as illustrated in Figs 1 and 2. For example, if the Plinian–Toarcian boundary is associated to ammonite and planktonic mass extinction, benthic organisms seem less affected (Fig. 2). These observations are in agreement with results from Schmidt et al.$^{38}$ which indicate that the environmental effects of SO$_2$ degassing could be variable depending on the ecosystem and location. Since the residence time of sulfur in the atmosphere is limited$^{6,73,75,77}$, the following effects of CO$_2$, CH$_4$, Cl$_2$ associated to flood basalt volcanism and release from contact metamorphic sediments start to overwhelm the sulfur effect and will be the dominant gas producing greenhouse conditions recorded in the paleontological records. We hypothesize that this last stage is responsible for the second extinction observed at the T-J and Pi-To boundaries. Figures 1 and 2 indicate that the Early Jurassic major plant turnover and the Toarcian OAE slightly postdate the first documented lavas or sills in CAMP and Karoo LIPs, respectively.

The mechanisms and timescales over which sub-lithospheric mantle melts interact with thick Archean or Proterozoic continental lithosphere is therefore a major component in the timing of mass extinction processes for the case of Rhaetian/Hettangian and Pliensbachian/Toarcian boundaries. Figure 5 shows that LIPs emitted on continents have much more severe biotic crises than oceanic LIPs despite their comparable size. This figure also indicates that LIPs emitted on top of Proterozoic to Cenozoic lithosphere have limited effects relative to continental LIPs erupted on cratonic lithosphere such as the Siberian Trap, CAMP, Karoo-Ferrar and Deccan. This indicates that the nature of the underlying lithosphere during large LIP eruption potentially exerts an important control on the consequences on life at the Earth’s surface and is a viable hypothesis in addition to external causes such as asteroid impacts as proposed to explain the Cretaceous-Paleogene crisis$^{59}$. Indeed, higher sulfur
contents in CAMP and Deccan magmas, with respect to the Paraná LIP have been reported\(^{29}\). These higher magmatic sulfur contents were explained by the presence of slab-metasomatized mantle in the source of CAMP and Deccan magmas\(^{29}\). While the CAMP and Deccan LIPs were associated to major extinctions, the emission of the Paraná - Etendeka province was not\(^{29}\). Archaean lithospheric mantle is known to have suffered multiple subduction-related processes, so a difference in the nature of the underlying lithosphere (Archean in the case of CAMP and Deccan traps, Proterozoic for Paraná) provides an alternative explanation for the difference in sulfur content. The proposed mechanism also offers an explanation why large LIPs erupted over oceanic lithosphere, such as the Ontong Java or the Caribbean plateaus, did not cause climatic and biotic crises as large as those of the Karoo-Ferrar or the CAMP despite having erupted similar volumes of basaltic rocks.

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**Author Contributions**

While learning from J.G. about high resolution ammonite stratigraphy and biotic crises, S.P. and O.M proposed to test the hypothesis of atmospheric cooling followed by heating to explain biostratigraphic, absolute age and isotopic data. J.G. and all co-authors (S.P., O.M., A.B., J.S., Bl.S., Br.S. and U.S.) with their specific scientific expertise have been involved in the preparation of Figures 1 and 2 summarizing the sequences of events associated with the T-J and Pl-To boundaries. S.P and O.M. developed the petrological model for thermal erosion of the lithosphere and estimated the amount of S present in the cratonic lithospheric mantle. S.P. prepared the figures. S.P., O.M., J.G., U.S. and Bl.S. wrote the text. All authors reviewed and approved the manuscript.

**Additional Information**

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