Arc eruptions deliver ‘first blow’ in the pulsed end-Permian mass extinction

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Abstract

Brief pulses of intense magmatic activity (flare-ups) along convergent margins represent drivers for climatic excursions that can lead to major extinction events. However, correlating volcanic outpouring to environmental crises in the geological past is often difficult due to poor preservation of volcanic sequences. Herein, we present a high-fidelity, CA-TIMS U–Pb zircon record of an end-Permian flare-up event in Eastern Australia, that involved the eruption of >39,000–150,000 km3 of silicic magma in c. 4.21 million years. A correlated high-resolution tephra record (c. 260–249 Ma) in the proximal sedimentary basins suggests recurrence of eruptions from the volcanic field in intervals of ~51,000–145,000 years. Peak eruption activity at 253 Ma is chronologically associated with the pulsed stages of the Permian mass extinction event. The ferocity of the 253 Ma eruption cycle in Eastern Australia is identified as a driver of greenhouse crises and ecosystem stress that led to the reduction in diversity of genera and the demise of the Glossopteris Forests. Simultaneous global continental margin arc flare-up events could thus present an additional agent to trigger greenhouse warming and ecosystem stress that preceded the catastrophic eruption of the Siberian Traps.

Full Text

Extinction events in Earth’s history are associated with perturbations in climate. The triggers are typically related to bolide impacts or vast outpouring from large igneous provinces\(^1\)-\(^3\). The largest extinction at the end of the Permian Period, accounting for the loss of up to 85–90% of marine invertebrates and 75% of terrestrial species, is inferred to be caused by the eruption of the Siberian Traps\(^2\)-\(^5\). Although, additional drivers including methane release from clathrates, hypercapnia, oceanic anoxia and acidification have been suggested as causative to the end-Permian extinction event (see discussion in\(^4\)). Coincidental periods of heightened arc volcanism can also lead to significant greenhouse aerosol emission (H\(_2\)O, CO\(_2\), and CH\(_4\): Fig. 1) that are often greater than basaltic eruptions due to interactions with crust rich in carbonate and carbonaceous material\(^6\)-\(^10\). The resulting climatic variability could feasibly contribute to extinction events locally or globally, depending on the scale of the eruptions\(^7\).

Despite continuous and long-lived subduction, the volumetric input of magma into volcanic arcs is highly episodic\(^7\),\(^1\)\(^1\). Magmatic flare-up events of c. 2 to 20 million years are interspersed by longer periods of relative quiescence (spanning ~30–70 million years)\(^1\)\(^2\). These flare-up periods can be a global phenomenon (Fig. 1)\(^6\). The magmatic addition in a flare-up can be as much as 10 to 1000 times greater than in a steady-state (per km length of arc every million years)\(^1\)\(^3\). It is less clear how these volumetric addition rates correlate to the volcanic record, where preservation is poor. Studies from young volcanic arcs suggest cycles of large outbursts of silicic eruptions occur with shorter periodicities (Kyr to a few Myr) within these broader flare-up periods\(^1\)\(^4\),\(^1\)\(^5\).

Relatively few volcanic arcs preserve direct evidence linking eruptions to particular flare-up cycles\(^1\)\(^6\), let alone to periods of climatic perturbations or extinction\(^6\),\(^7\). As volcanic arcs account for most
silicic eruptions on the planet and can attribute appreciable outpouring of gases (CO$_2$, H$_2$O and CH$_4$)$^{6,7,9}$, understanding their periodicity and eruption volume is of crucial importance. This is particularly so during periods of global climatic and environmental instability, such as at the end of the Permian.

**Eastern Australia Permian flare-up**

A high-fidelity record of arc magmatism is presented from the Permian to Triassic margin in Eastern Australia (Figs 1 & 2). New high-precision Chemical Abrasion Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-TIMS) U–Pb zircon ages were measured on nine volcanic deposits and three representative coeval granites. The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ CA-TIMS dates were obtained from analyses composed of populations of single zircon grains, initially screened using cathodoluminescence imaging for magmatic grains that lack inherited cores. The results are combined with published CA-TIMS ages on 73 tephra in adjacent sedimentary basins and 128 SHRIMP/LA-ICPMS ages on granites of the New England Batholith$^{17}$. The age systematics are compiled with geological mapping$^{18-20}$ and estimates of crustal thickness based on Sr/Y trends to quantify the scale of magmatism for the first time.

Two major flare-up cycles are identified along the arc at c. 290–280 Ma (30 km$^3$/my per km) and c. 260–245 Ma (63 km$^3$/my per km) that punctuate the background low-volume magmatism along the margin (5–10 km$^3$/my per km: Fig. 3)$^{21}$. The c. 290–280 Ma peak is related to back-arc extension and crustal reworking$^{22}$. The Permian–Triassic event is associated with increasing mantle input to form the prominent batholith$^{23}$. A voluminous sequence (Fig 3) of silicic ignimbrite sheets totalling thicknesses of 6.5–8 km is also preserved at this time over a broad surface expression supporting the estimated high magma fluxes$^{18-20}$. The deposits are consistent with a ratio of volcanic to plutonic material of 1:1 to 1:14. It is less clear how representative the higher than typical ratios observed in arcs (1:2 to 1:30)$^{12}$ are in the context of preservation of igneous rock. However, the ratios are consistent with inferences from modern extending arcs$^{14}$ that preserve thick piles of volcanic strata in a setting similar to that of Eastern Australia in the Permian (Fig. 3a).

The volcanic field preserves 4–8 distinct calderas which span an eruption period of c. 257.54 to 253.34 Ma (Fig. 2). The thickness of each volcanic member varies between 500–4000 m based on mapped relationships or geophysical observations$^{18-20}$. The distribution is consistent with the eruption of at least 39,000 km$^3$ from three centres that migrated over time (Fig. 2). Initial volcanism occurred in the Western Belt involving ~22,750 km$^3$ of caldera infill over c. 2.06 Myr (c. 257.54–255.48 Ma), before tracking to the Southern Belt to erupt ~3,250 km$^3$ over c. 1.12 Myr (c. 255.7–254.58 Ma), and then further to the northeast (Eastern Belt) where multiple large eruptions (~13,000 km$^3$) occurred over the shortest interval of c. 0.49 Myr (c. 253.59–253.1 Ma). Voluminous granitic magmatism follows a similar spatial and temporal trend and persisted in the region until c. 242 Ma$^{17,22}$, including as resurgent feeder dykes that define the calderas (Fig. 2)$^{18}$. 
The structural relationships of the ignimbrite sequence (Fig. 2) are consistent with it being draped over an undulating topography, with erosion of the pile or the volcanic detritus occurring between individual eruptions\(^{18,19}\). Most of the overburden to the youngest volcanic end-members appears to have been lost, consistent with predictions of \(\sim 3–4\) km of denudation on the New England Tablelands in the last 100 million-years\(^{24}\). The volcanic deposits are also truncated in their original extent in all cardinal directions by dissection of the New England Tableland, particularly along the Great Escarpment to the east and the Peel Fault to the south and west (Fig. 2)\(^{22}\). Together these relationships suggest that the preserved volcanic material only records part of the duration of volcanism and is a minimum estimate for the eruption volume. Based solely on the preserved aerial extent of deposits across the entire volcanic field, the eruption volume of the Wandsworth Volcanic Group is 150,000 km\(^3\) (Fig. 2a). Although, this estimate does not account for the \(\sim 3–4\) km of erosion and the amount of ash or other eruptive material that was not preserved near the primary volcanic centres, or in the adjacent Permian basins.

Sedimentary basins proximal to the volcanic field preserve up to 250 tephra spanning the c. 260–247 Ma time frame supporting extensive volcanic outburst during the flare-up event (Figs 2 & 4)\(^{25-29}\). The compilation of tephra intervals in the Sydney, Gunnedah, Bowen, and Galilee Basins are consistent with the recurrence of eruptions every \(\sim 51,000–145,000\) years with an increase in activity at c. 253 Ma (Figs 3b & 4). The total volumetric output from the tephra is less certain, but high-density layers at c. 254–252 Ma have total thicknesses of \(>100\) m across the entire Sydney and Bowen Basin (60,000–64,000 km\(^2\) each)\(^{25,27}\). Geochemical fingerprints of these events are consistent with contiguous and prolonged volcanism from the same, or similar rhyodacite to rhyolite sources that match those identified in the New England region\(^{30,31}\). The large dispersive extent of tephra and their general thicknesses is consistent with super-eruptions blanketing the majority of Eastern Australia in ash-fall and debris over an area of at least 950,000 km\(^2\) consistent with eruptions volumes of \(>150,000\) km\(^3\) (Fig. 2).

**Sources of silicic eruptions**

The only prominent local source of silicic ash in Eastern Australia is the temporally correlated Wandsworth Volcanic Group and their spatially associated granites in the southern New England Orogen. Although, along arc extensions in northern Queensland are inferred to be additional contributors, particularly into the Bowen and Galilee basins, they lack prominent exposed volcanic sequences due to partial or complete erosion\(^{32}\). The high proportion of tephra layers at \(\sim 253–254\) Ma corresponds to the vast outpouring of the Eastern Belt. The Dundee Rhyodacite, one of the largest ignimbrite deposits preserved today (\(\sim 918\) km\(^2\)), can be correlated to individual tephra of the thick Awaba Tuff (\(>11\) m thick: c. 253.1 Ma) and its regionally extensive correlatives throughout the other sedimentary basins in eastern Australia\(^{25-27,31}\). The slightly younger Yarrabee Tuff (dated at c. 252.54–253.07 Ma)\(^{25,26,31}\) in the Bowen and Galilee basin and the Garie Tuff in the Sydney basin (c. 247.87 and 248.23) have been linked to the later stages of eruption from the Eastern volcanic belt, but lack an ignimbrite deposit, likely due to subsequent erosion\(^{31}\). The prominence of resurgent granitic magmatism around the Eastern Belt and the
occurrence of thick ignimbrite deposits (Emmaville and Dundee) is consistent with this region representing the key focal point of magmatism that spanned the end-Permian interval (Fig. 2).

A second period of higher-density tephra preservation occurs at 255 and 257 Ma in the surrounding Permian sedimentary basins. These ash layers match the ages of the ignimbrite deposits from the Southern and Western Belt of the Wandsworth Volcanic Group (Fig. 4). The volcanic events are less extensive in the tephra-record and are mostly focused in the Gunnedah, Sydney and southern portions of the Bowen basins suggesting a sustain period (c. 2 Myr) of high-volume eruptions\(^{25,31}\).

Globally, the commonality of arc magmatism at the end of the Permian is consistent with similar eruption-styles occurring concurrently along the margins of the supercontinent Pangea\(^{7,8}\). Synchronous flare-up peaks at c. 255–250 Ma have been identified throughout South America, Antarctica, and China (Fig. 1)\(^{33-36}\). These include the estimated 1.3x10\(^{6}\) km\(^{3}\) of silicic volcanism from the Choiyoi province in South America and Antarctica that is inferred to have contributed to greenhouse warming near the end-Guadalupian event\(^{34}\). Altogether global arc volcanism at the end of the Permian Period would have increased the total volcanic gas output, including the heightened production of greenhouse gasses\(^{7,8}\).

**Super-eruptions and the end-Permian extinction**

The end-Permian mass extinction is inferred to have transpired in several pulses\(^{37-39}\), plausibly initiated by a series of climatic perturbations preceding the actual Permian–Triassic boundary currently dated at 251.90 ± 0.10 Ma (Fig. 4)\(^{40,41}\). The eruption of extensive flood basalts as part of the Siberian Traps is considered to have had the greatest influence on climatic perturbations during the period of c. 252.3–251.9 Ma (Fig. 4)\(^{3,4}\). However, it has been argued that multiple causative agents contributed to the periodic demise of biota and the reduction of diversity from c. 258 until 254 Ma (Fig. 4)\(^{42}\). Particularly since the onset of the late Permian warming (c. 254 Ma) occurred prior to the eruption of the Siberian Traps\(^{38,43-46}\).

Many terrestrial basins in the Southern Hemisphere (c. 252.5 Ma)\(^{47}\), have less severe extinction events before the delineated end Permian extinction horizon (Fig. 4)\(^{28,48-51}\). A series of greenhouse crises have been identified from palynological and geochemical proxies in the high-latitude Sydney Basin, consistent with a period of climatic variability from c. 265 Ma to the beginning of the Triassic (Fig. 4)\(^{48,52,53}\). The Eastern Australia flare-up, and the along-strike extensions throughout Pangea present as compelling agents to some of these cycles of greenhouse conditions\(^{54}\) (Figs 1 & 4). Although, until now the precise timing, vast quantitative scale, and extent of these eruptions in Eastern Australia has remained speculative.

Eruptions in Eastern Australia peaked at c. 254–252.5 Ma, corresponding to a negative excursion in local carbon isotopic ratios (Fig. 4)\(^{25}\). This event marks the initiation of multiple end-Permian greenhouse crises (Fig. 4), involving perturbations in temperature, atmospheric CO\(_2\) and rainfall in eastern
Australia52. The ultra-Plinian (>1000 km3) eruptions of the Emmaville (Fassifern Tuff), Dundee (Awaba Tuff) and the Yarrabee Tuff directly correspond temporally to identified greenhouse crises52,55, all of which pre date the Siberian Traps and the penultimate end Permian extinction. Additional Triassic greenhouse crises correspond to renewed volcanism associated to the Garie Tuff (Fig. 3b).

Multiple local environmental crises are likely to have been exacerbated by both the short- and longer-term consequences of catastrophic eruptions. These would include the initial cooling associated with the albedo effect of ash, followed by the prolonged greenhouse forcing related to the vast emission of volcanic aerosols10. Extensive drought, forest fires and higher atmospheric carbon are inferred at this time based on pollen records from the intervening sedimentary layers to the tephra that correspond to the volcanic sequence (Fig. 3b)28. Generally, the c. 254–252 Ma period marks a significant change from cold glaciated conditions to progressive warming in Australia as well as globally (Fig. 4)28,37,39,44,45,49-51. In particular, the pronounced increase in seasonal temperatures just before 252.54 Ma47 is proposed to have led to the demise of the Glossopteris forests in Gondwana forming a prominent extinction horizon (Figs 3 & 4)47,48.

The excellent geological record of flare-up in Eastern Australia provides a direct link between continental arc volcanism and localised records of ecosystem stress, beyond previously utilised stratigraphic coincidences35. The record from Eastern Australia is consistent with arc eruptions being influential to progressive species demise, but not the ultimate fatal blow. The synchronous pulse of arcs documented around Pangea at c. 252–260 Ma33-36 is a likely contributor to inducing ecosystem collapse via warming7,35,56 prior to the catastrophe at c. 251.9 Ma (Fig. 4). Volcanic outbursts present an under recognised contributor that can plausibly account for the temporal variability and pulsed nature of the end Permian mass extinction event, as well as others generally throughout Earth’s past.

**Declarations**

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**Author contributions**

T. C, L. A. M., I. M and P. L. B initiated the project and contributed to the analysis of the data. J. C. completed the data collection and interpretation. All authors contributed to writing and reviewing the manuscript.
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Figures
Figure 1

Global arc activity on the Pangea supercontinent at c. 253 Ma.
Figure 2

Geological maps of eastern Australia Permian–Triassic magmatism including (a) depositional-basins with locations of bore holes with published dated tephra (green circles) and (b) the southern New England Orogen, without Cenozoic cover, displaying locations of CA-TIMS dates from this study (white circles).
eastern Australia magmatic flare up. (a) Histogram of magma addition rates (MAR in km$^3$/myr per km) along the eastern Australia margin during the Permian–Triassic. (b) Correlation of ignimbrite deposits from the Wandsworth Volcanic Group to published age dates of Tephra in the Sydney, Gunnedah, Bowen and Galilee basins$^{25,26,31,58}$, and granites in the southern New England Orogen (SNEO: GR = Gwydir River monzogranite; PM = Parlour Mountain leucomonzogranite; DS = Regional Felsic Dyke Swarm).
Identified Eastern Australia greenhouse crises\textsuperscript{52} are shown with extinction intervals based on floral species\textsuperscript{47}. The thickness of the symbology encompasses the uncertainty on each age date.

![Figure 4](EAmagmaMapCover.pdf)  
**Figure 4 Chapman et al.**

Eastern Australia flare-up and the end-Permian mass extinction. The age distribution of volcanism in Eastern Australia at 260–247 Ma in relation to global magma activity based on zircon age systematics\textsuperscript{59}. Identified Eastern Australia greenhouse crises\textsuperscript{52} are corrected for age systematics\textsuperscript{25} and associated with floral species demise\textsuperscript{28,47,48}. Carbon isotope curves from marine carbonates in South China\textsuperscript{43}, terrestrial organic material from eastern Australia Basins\textsuperscript{25}, Genera diversity curves from Paleobiology database and sea surface temperature estimates based on conodont Oxygen isotopes\textsuperscript{37,38,44}. The eruption of the Emesishan\textsuperscript{46} and Siberian Traps and intrusive correlatives\textsuperscript{3,4} are shown together with the P4 glaciation\textsuperscript{25}.

**Supplementary Files**

This is a list of supplementary files associated with this preprint. Click to download.

- SupplementaryMethods.docx
- FigS23.pdf
- EAmagmaMapCover.pdf
- NEOLAICPMSdatatable.xls
• NEOCATIMSUPbdatable.xls