Research article

JGS
Journal of the Geological Society

Published Online First

https://doi.org/10.1144/jgs2021-055

Meteorites that produce K-feldspar-rich ejecta blankets correspond to mass extinctions

M.J. Pankhurst[1,2]*, C.J. Stevenson[3] and B.C. Coldwell[1,2]

[1] Instituto Tecnológico y de Energías Renovables, 38600 Granadilla de Abona, Santa Cruz de Tenerife, Spain
[2] Instituto Volcanológico de Canarias, 38600 Granadilla de Abona, Santa Cruz de Tenerife, Spain
[3] Earth, Ocean and Ecological Sciences, University of Liverpool, Liverpool L69 7ZX, UK
MJP, 0000-0001-6844-9822; CJS, 0000-0003-0406-9892; BCC, 0000-0001-9240-6240
* Correspondence: mpankhurst@iter.es

Abstract: Meteorite impacts load the atmosphere with dust and cover the Earth's surface with debris. They have long been debated as a trigger of mass extinctions throughout Earth history. Impact winters generally last <10^0 years, whereas ejecta blankets persist for 10^3–10^5 years. We show that only meteorite impacts that emplaced ejecta blankets rich in K-feldspar (Kfs) correlate to Earth system crises ($n = 11$, $p < 0.000005$). Kfs is a powerful ice-nucleating aerosol, yet is normally rare in atmospheric dust mineralogy. Ice nucleation plays an important part in cloud microphysics, which modulates the global albedo. A conceptual model is proposed whereby the anomalous presence of Kfs post impact is posited to have two key effects on cloud dynamics: (1) Kfs reduces the average albedo of mixed-phase clouds, which leads to a hotter climate; and (2) Kfs weakens the cloud albedo feedback mechanism, which increases climate sensitivity. These mechanisms offer an explanation as to why this otherwise benign mineral is correlated so strongly with mass extinction events: every Kfs-rich ejecta blanket corresponds to a severe extinction episode over the last 600 myr. This model may also explain why many kill mechanisms only variably correlate with extinction events through geological time: they coincide with these rare periods of climate destabilization by atmospheric Kfs.

Supplementary material: Extended Fig. 1 from main text is available at https://doi.org/10.6084/m9.figshare.c.5690646

Received 18 May 2021; **revised** 31 October 2021; **accepted** 2 November 2021

Meteorite impacts as a cause of mass extinctions have been vigorously debated since 1980 (Alvarez *et al.* 1980). The only two instances that have gained acceptance as triggers of mass extinction events are also the two largest in the last 600 myr: Chicxulub, with a transient crater diameter of *c.* 85 km at the Cretaceous–Paleogene boundary (*c.* 66 Ma) (Hull *et al.* 2020), and Acraman, with a *c.* 51 km wide transient crater associated with the Acritarch Crisis (*c.* 580 Ma) (Grey *et al.* 2003) (Fig. 1). This creates the impression that extreme size is a prerequisite for a specific meteorite impact to affect change on a global scale (Tohver *et al.* 2012).

The primary kill mechanism invoked for a meteorite impact is an impact winter. This is a short-term phenomenon (Toon *et al.* 1997) whereby impact ejecta block out solar radiation, which directly affects photosynthetic life and global temperatures. Hence the larger the impact, the more severe these effects will be on the biosphere. This hypothesis implies a very close temporal correlation between cause and effect that is predicated first upon size: larger meteorite impacts should affect the global biosphere in a geological instant, whereas smaller impacts are predicted to not affect the biosphere on a global scale.

Age dating methods now provide a high temporal resolution of impacts (Schmieder and Kring 2019), as good or better than geological substages (see Supplementary Material). This shows that many smaller impacts (with a transient crater 10–20 km wide) occur in the same geological substage as severe ecological turnover (Fig. 1). However, many other impacts correspond precisely with times of relatively stable or decreased global extinction rates (Rohde and Muller 2005), including the fourth largest (the Manicouagan), which had a transient impact crater *c.* 48 km wide at 215.56 ± 0.05 Ma.

Patterns of extinction temporally associated with meteorite impacts display a range of styles, from catastrophic to stepwise and graded (Kauffinan 1994). Ecosystem recoveries and speciation largely take place in tandem on timescales up to a million years (Holland 2020). Any argument for a causative link between meteorite impacts and mass extinctions must therefore address three questions: (1) why many large impacts do not coincide with extinction events; (2) why many smaller impacts do coincide with extinction events (Fig. 2); and (3) why the style, magnitude and timescales of potential kill mechanisms are so different between different impacts.

Atmospheric ice nucleation efficiency

Recent advances in atmospheric science show that the mineralogy of aerosols is an important factor in climate function and sensitivity. K-feldspar (Kfs) is the most important mineral as a result of its role in nucleating ice in mixed-phase clouds (Atkinson *et al.* 2013; Vergara-Temprado *et al.* 2017). The degree of glaciation of clouds modulates their albedo and hence the fundamental contribution of clouds to balancing the global radiation budget (Vergara-Temprado *et al.* 2018; Murray *et al.* 2020).

Meteorite impacts have the unique potential to produce sudden, major and persistent changes to the mineralogy of atmospheric aerosols (Coldwell and Pankhurst 2019). Because the impact excavates the local rocks and spreads them across the Earth's surface, the mineralogy of the atmospheric dust produced by a meteorite impact is dominated by the composition of the rocks that were hit by the meteorite. The initial dust and debris cloud quickly settles out of the atmosphere (Toon *et al.* 1997), but the ejecta blanket persists as a voluminous and readily aerosolized source of mineral dust to the lower atmosphere for tens to hundreds of thousands of years (White *et al.* 2001; Coldwell and Pankhurst 2019).

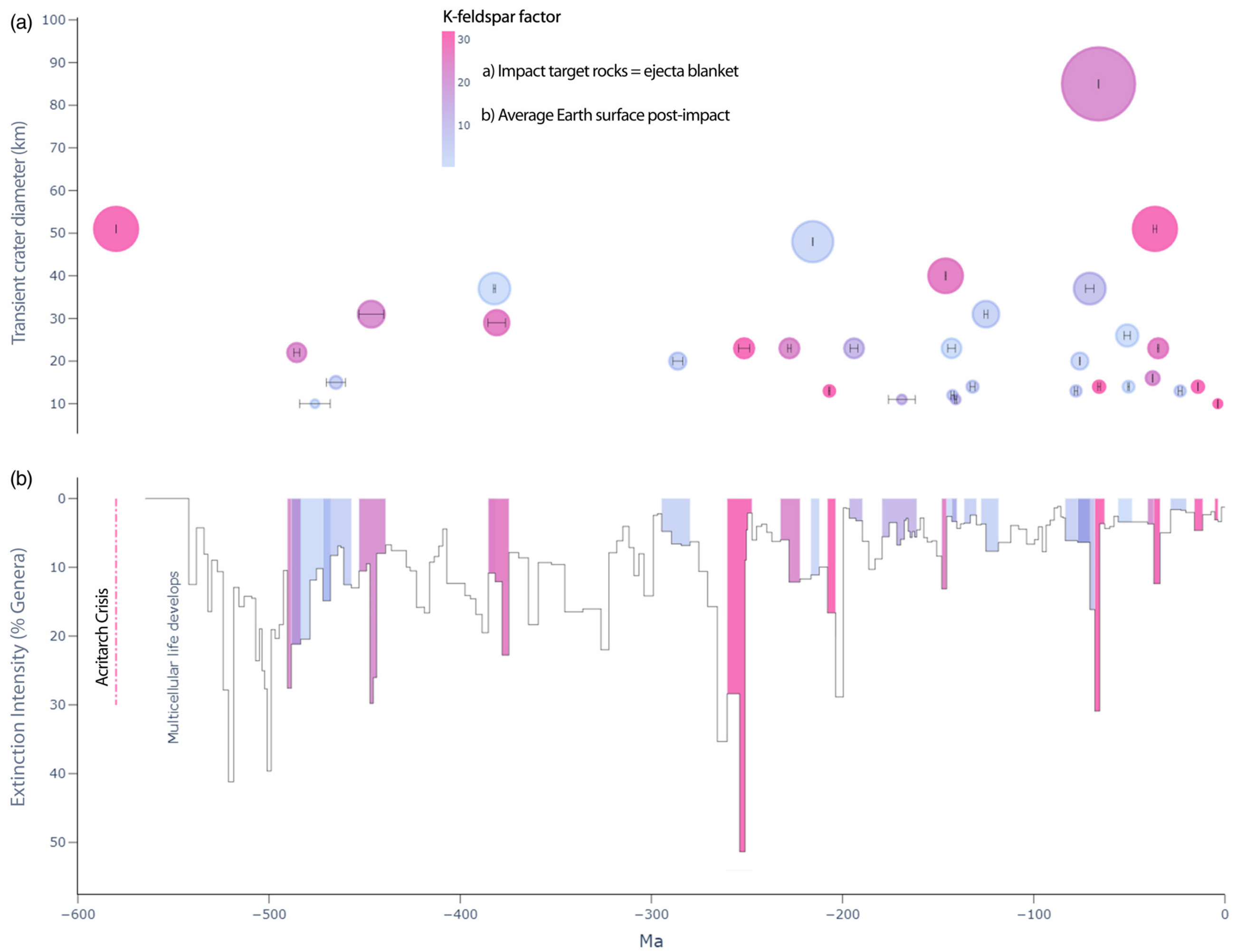

Fig. 1. Comparison of meteorite impact stratigraphy and extinction intensity of well-resolved marine genera. (**a**) Impact database of the 33 largest and best-dated impacts in the past 600 myr (Coldwell and Pankhurst 2019). Transient crater diameters ≥10 km with age precision better than ±8 myr are shown as coloured circles: circle size scaled to crater diameter, and colour the KFF factor. Updated from Coldwell and Pankhurst (2019) using revised age data (Schmieder and Kring 2019) and plotted by size and the K-feldspar factor (colour) of the target rocks. Fifteen of 33 ejecta blankets correlate with mass extinction events. (**b**) Extinction intensity for the entire duration of multicellular life highlights times of global environmental crises. The timing of the Acritarch Crisis also shown. Extinction intensity is expressed as the percentage of marine genera in their last appearance. Each K-feldspar-rich ejecta blanket corresponds to an Earth crisis and accounts for the majority of severe spikes in extinction intensity, including almost all since *c.* 250 Ma, when both records are most complete. See Supplementary Fig. 1 for K-feldspar factor timeline, meteorite impact labels and named extinction events.

We present an analysis of meteorite impacts and extinction rates over the last 600 myr and incorporate a new parameter: the Kfs content across the Earth's surface after meteorite impacts. A high Kfs content is a consistent feature of impacts coinciding with a mass extinction event. Time series statistical analysis of this correlation returns a p value <0.000005, strongly indicating causation. In direct contrast, ejecta blankets low in Kfs are consistently associated with periods of ecological stability. We propose a conceptual model that posits Kfs as the driving agent behind these severe extinction events. It is the ejecta blanket's potential to change the long-term climate, not the impact winter, that determines the link between meteorite impacts and mass extinction events through deep time.

Meteorite impacts and atmospheric mineralogy through deep time

Meteorite impact ejecta that blanket the Earth's surface have the unique potential to interrupt the clay-dominated atmospheric mineral aerosol regime at a global scale (Coldwell and Pankhurst 2019). Among other effects, each impact resulted in the geologically instant production of fresh mineral dust in the readily aerosolized ≤200 µm diameter fraction, which was probably *c.* 10–1000 times that of total modern annual dust emissions (Coldwell and Pankhurst 2019). How persistent an interruption is depends on the initial subaerial area affected, how the ejecta blanket is mechanically broken down, making more fresh minerals available for aerosolization, and the speed and pervasiveness of chemical weathering, which acts to restore the clay barrier (Coldwell and Pankhurst 2019). Based on laboratory and field studies, reasonable estimates for complete chemical breakdown of Kfs inside a highly porous blanket range to more than a million years (White *et al.* 2001). The rate of ejecta blanket removal will decelerate through time as a result of its thinner average depth with distance from the crater, hence its period of influence on atmospheric mineralogy is likely to be of the order of tens to hundreds of thousands of years (Coldwell and Pankhurst 2019).

The Earth's crust is a heterogeneous arrangement of rock types and the location of meteorite impacts is serendipitous. The Kfs contents of the target rocks of all recorded meteorite impacts in the last 600 myr with transient crater diameters ≥10 km were reviewed by Coldwell and Pankhurst (2019). The post-impact average Earth surface K-feldspar factor (KFF) (% by volume of Kfs in a material; Pankhurst 2017) was estimated as part of this review by using palaeogeographical reconstructions of the continents and the dispersal of the primary ejecta. These KFF estimates allow a

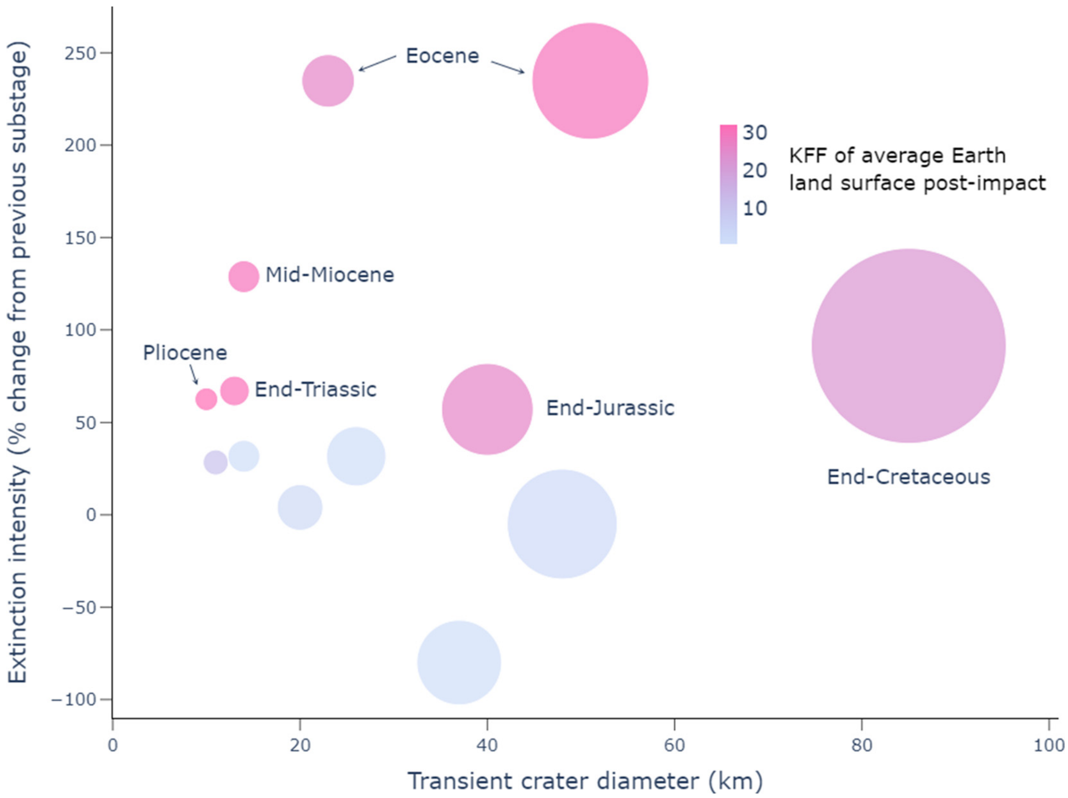

Fig. 2. Mass extinction events and extinction intensity correspond to availability of K-feldspar to the troposphere, not a larger impact size. Only those craters with an age precision that places the date of meteorite impact within a single geological substage are plotted, which provide seven K-feldspar-rich and six K-feldspar-poor events. Size of crater is represented by diameter of circle (scaled). The extinction intensity of marine genera is expressed as the percentage change from the previous substage to highlight the changes from substage to substage. Substages marked by an extinction event are labelled. See Supplementary Material for plots including less precise database entries and other projections of extinction data. KFF, K-feldspar factor.

comparison to be made between different meteorite impacts and their potential effects on the Earth system through time.

Calculations

Following on from Coldwell and Pankhurst (2019), this study considers a total of 33 impacts and (1) adds estimations of the global surface average KFF for the Clearwater West and Saint Martin impacts, (2) uses refined ages for the Carswell, Charlevoix, Dellen, Puchezh-Katunki and Steen River impacts and (3) discards the Woodleigh impact on age precision arguments (Schmieder and Kring 2019). Fifteen ejecta blankets resulted in an increased global availability of Kfs, whereas the other 18 did not (Fig. S1b; see also Coldwell and Pankhurst 2019).

The timing of these ejecta blankets is compared with the timing of extinction events over the last 600 myr. It is important to consider the nature of the extinction record in this comparison because statistical artefacts and record completeness produce bias at different times and timescales (Foote 2003; Bambach 2006; Holland 2020). A number of data treatments and tabulation methods are available to identify candidate extinction events (Foote 2003; Bambach 2006; Kocsis *et al.* 2019; Holland 2020; The Paleobiology Database 2021).

In this case, the most robust approach is to use a record that has the highest temporal resolution possible while applying consistent data treatment. The marine fossil record is the longest and best-preserved and has the highest temporal resolution available for intercomparisons at the genera level (Rohde and Muller 2005), containing 167 biostratigraphic substages from *c.* 565 Ma to the present day (Fig. 1b). A review of extinction studies focusing on the marine record and representing a range of data treatments and temporal resolutions (Bambach 2006) has identified 18 intervals as those that most consistently appear as candidate mass extinction episodes over deep time using Sepkoski's original definition (Sepkoski 1986). Five additional extinction events are recognized when applying a complementary treatment (Rohde and Muller 2005), giving a total of 23 extinction events for inclusion. Each extinction event is also identifiable at a lower temporal resolution (see The Paleobiology Database 2021). However, it is the high-resolution and consistent approach that provides the most robust method of recognizing or rejecting a correlation with the independent meteorite impact database.

The radiometric ages of large meteorite impacts are now mostly derived from dating authigenic minerals or glass from impact melts (Schmieder and Kring 2019). These impact age data are more precise than the duration of substages (see Supplementary Material). Using the time span defined by the 2σ age precision of each impact, 13 are resolved to a single substage (see Fig. 2), which allows for direct comparisons to be made at the 95% confidence level using the highest stratigraphic resolution (167 intervals), and a further 12 to one of two neighbouring substages. To derive the statistical significance of the potential correlations, the 167 geological stages/substages were made into three binary sequences: (1) whether or not they contain a severe extinction event; (2) whether or not a meteorite impact occurred; and (3) whether or not an ejecta blanket resulting from an impact caused an increase in Kfs across the Earth's surface. Event analysis using the *R* package CoinCalc (Siegmund *et al.* 2017) was conducted for a range of subsets defined by age dating precision (Supplementary Material).

Results

Three key observations are made by comparing the high-resolution meteorite impact and marine fossil records (Figs 1 and 2). First, every meteorite impact with an ejecta blanket that was rich in Kfs coincides with, or tightly overlaps (within impact age precision), a substage containing a severe extinction episode. Second, none of the impacts deficient in Kfs coincides with an extinction event, with the exception of one that overlaps within (comparatively poor) age precision. Third, there is a poor correlation between impact size and extinction intensity (Fig. 2; see Supplementary Fig. 3A for alternative projections). In addition, we note that each of the marine extinctions corresponding to a Kfs-rich ejecta blanket also has an associated terrestrial extinction event (Bond and Grasby 2017).

Time series event analysis demonstrates that the extinction episodes correlate strongly with the Kfs-rich ejecta blankets. The most conservative statistical approach using the entire database, but counting only exact simultaneity as true positives, returns a p value <0.000005. Conversely, the null hypothesis is accepted when applying the same method to Kfs-poor ejecta blankets and all meteorite impacts taken together – that is, there is no correlation between Kfs-poor impacts, or meteorite impacts in general, and severe extinction episodes (Fig. 3; Supplementary Material).

The KFF parameter cleanly discriminates between those meteorite impacts that coincide with severe extinction episodes and those that do not. The strength of the temporal correlation between Kfs-rich ejecta blankets and severe extinction episodes suggests a causal link. The clear anti-correlation between Kfs-deficient ejecta blankets and extinction intensity suggests that meteorite impacts themselves are not causally related to severe extinction events. Such is the number of true positives compared with the dataset sizes that adjustments to what constitutes an extinction event, either qualitatively (i.e. by taxa/community) or quantitatively (i.e. by thresholding to an extinction intensity rate), do not change the result that Kfs ejecta blankets, not meteorite impacts, are strongly associated with severe extinction episodes.

Discussion

Kfs has been a major constituent of the Earth's upper crust for >2 billion years. Kfs is present and often common in most soil types (Pankhurst 2017) and is not considered to be adverse to life (Mohammed *et al.* 2014). Kfs does not readily convert into secondary chemical compounds while in the atmosphere. This benign chemical nature contrasts sharply with other materials that are excavated and/or formed as a result of meteorite impacts, including sulfurous aerosols and hydrocarbons that cause acid rain, ozone depletion and increased atmospheric CO_2 (Kaiho *et al.* 2001; Ohno *et al.* 2014; Kaiho and Oshima 2017).

Although not chemically gregarious, Kfs has been shown to be the most powerful ice-nucleating mineral in the modern atmosphere (e.g. Harrison *et al.* 2019). As such, we draw upon our understanding of the modern climate system and cloud physics to explore how the mineralogy of ejecta blankets could affect the Earth's palaeoclimate. From this, we propose a conceptual model whereby Kfs-rich ejecta blankets can profoundly influence cloud dynamics, their albedo and, in turn, the global climate.

Clouds and Earth's radiative balance

Clouds have a fundamental role in maintaining the balance of the global energy budget because they are both reflectors of radiation from space and insulators of radiation from the Earth's surface (Boucher *et al.* 2014). The net contribution of clouds to defining the Earth's thermostat is determined by their coverage, temperature and optical properties (Murray *et al.* 2020). Warm clouds form at low altitudes and are mainly composed of microscopic water droplets (Murray *et al.* 2020). Their dense arrangement produces an optical thickness that efficiently reflects solar radiation (a high albedo). Warm clouds cover a significant proportion of the Earth's surface, which effects an important net cooling forcer on the climate (Boucher *et al.* 2014; Murray *et al.* 2020). By contrast, cold clouds occur at high altitude and are composed of ice crystals at low concentrations, which means that they are optically thinner than warm clouds (Storelvmo *et al.* 2015; lower albedo, Murray *et al.* 2020). In addition, cold clouds are effective at absorbing infrared radiation emitted from the Earth's surface, which amounts to a small net warming effect overall (Boucher *et al.* 2014).

The presence of ice-nucleating particles (INPs) in the atmosphere modulates cloud properties between these end-members (Murray *et al.* 2020). Supercooled water freezes homogeneously at about −35°C, but ice nucleation is induced if INPs are present, sometimes at far warmer temperatures depending on the efficiency of the INPs (Murray *et al.* 2012). This means that water droplets at higher temperatures can convert to ice particles and leads to the production of mixed-phase clouds (Boucher *et al.* 2014). Higher proportions of ice crystals within clouds reduce their optical depth, which, in turn, reduces the albedo (Storelvmo *et al.* 2015). In addition, the formation of ice particles is an important triggering process for precipitation (Boucher *et al.* 2014).

The state dependence of cloud-phase feedbacks is a crucial factor in the evolution of the Earth's climate sensitivity (Bjordal *et al.* 2020). For example, present day climate models predict that global warming leads to less cloud glaciation, a thicker average optical depth and an increased average cloud albedo (Storelvmo *et al.* 2015). The increased cloud albedo exerts a cooling effect on the climate, which counteracts warming forcers, such as increases in greenhouse gases, thus acting to maintain stability (Storelvmo 2017; Murray *et al.* 2020). Recent observations and insights from sensitivity studies demonstrate that the presence of INPs results in more mixed-phase clouds and acts to suppress the cloud albedo

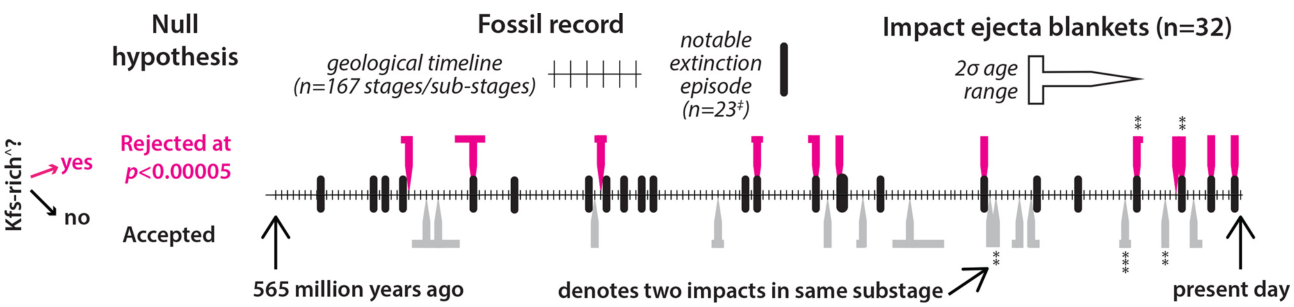

Fig. 3. Time series event analysis of Earth crises, meteorite impacts and ejecta blanket K-feldspar content from *c.* 565 Ma to the present day. The timing of every K-feldspar-rich ejecta blanket plausibly coincides with an extinction episode. The most precisely dated subset (see Fig. 2 and Supplementary Material) returns 100% simultaneity. By contrast, just one of 18 ejecta blankets that did not cause an increase in K-feldspar availability could possibly overlap an extinction event, and the most precisely dated subset (Fig. 2) has 0% simultaneity. The End-Triassic extinction is codified into both the Upper Norian and Rhaetian.

cooling feedback (Tan *et al.* 2016; Murray *et al.* 2020). A pioneering model that includes Kfs parameterization, using modern mineralogy distribution (trace amounts of Kfs), shows significantly reduced cloud albedo with warming on regional scales compared with modelling without INPs (Thürmer *et al.* 2019).

Mineral aerosols and clouds

Mineral dust accounts for around half of the aerosols by mass in the modern atmosphere (Knippertz and Todd 2012) and there was a greater proportion in pre-industrial times (Carslaw *et al.* 2017). The dust cycle is characterized by primary emission events (dust storms), dispersion mainly through the lower troposphere and, eventually, removal by dry or wet deposition (Shao *et al.* 2011). Clay minerals form at the Earth's surface, which results in a thin, yet nearly ubiquitous, barrier between fresh rocks and the atmosphere. This is why clay dominates today's atmospheric dust and has defined the normal atmospheric mineralogical regime since at least the Neoproterozoic (Pankhurst 2017).

Relative to other minerals, Kfs exhibits extraordinary ice nucleation properties and is identified as playing a key part in cloud microphysics because it nucleates ice at about −15°C (Atkinson *et al.* 2013; Harrison *et al.* 2019). Perthite (Kfs with a micro-texture of sodic feldspar lamellae) is the exceptional form because this texture leads to a high density of active sites for ice nucleation (Whale *et al.* 2017). Perthite is characteristic of granitic intrusions, which are common, yet unevenly distributed, within the Earth's continental crust (Coldwell and Pankhurst 2019). Kfs is comparatively stable at surface conditions (White *et al.* 2001), yet it will eventually break down in the presence of water, which is why Kfs makes up only *c.* 3% of modern mineral dust (Atkinson *et al.* 2013). It is mostly emitted from arid regions where chemical weathering is slowest (Pankhurst 2017), and is present primarily in the coarse modal fraction of dust (Thürmer *et al.* 2019). Our knowledge of the ice-nucleating efficiency of minerals is far from complete and there is evidence that members of the pyroxene family may exhibit comparatively high ice activity (Jahn *et al.* 2019; Maters *et al.* 2019). However, the overall contribution of pyroxenes to ejecta blankets is very low (Coldwell and Pankhurst 2019) as a result of their paucity in sedimentary successions and because they are more common in deeper parts of the crystalline crust. As such, they are not a focus of this study.

Model for the effects of meteorites on the Earth's climate

When a large meteorite hits the Earth and transfers its kinetic energy into the lithosphere, the meteorite itself is vaporized, the local crust melts, and extreme volumes of dust and secondary particulates are ejected into the full atmospheric column as part of the cratering process and its immediate aftermath (Toon *et al.* 1997). In a geological instant, normal terrestrial dust cycle processes (Fig. 4a) and the effects of clouds on the Earth's climate are overshadowed by the direct effects of the impact, particularly from stratospheric dust (Fig. 4b). Dust directly blocks incoming solar radiation, causing dimmer and colder conditions at the Earth's surface. The fine dust resides in the atmosphere for days to months (for more than a year for a Chicxulub-sized impact). As the primary dust and secondary particulates (e.g. soot) settle and wash out of the atmosphere, the direct cooling decreases and more sunlight reaches the Earth's surface. The Earth returns to its pre-impact equilibrium temperature (Toon *et al.* 1997).

As the impact winter wanes, cloud regains its importance in direct radiative forcing and its role in balancing the Earth's energy budget. The normal mechanisms and fluxes of the terrestrial dust cycle also resume. Mineral particles are entrained by surface winds and the bulk of atmospheric dust transportation is restricted to the troposphere. However, a defining portion of that dust is now composed of minerals from the meteorite ejecta blanket. This means that the aerosol mineralogy may have changed and this may affect the properties of average low-altitude clouds.

Kfs-poor ejecta blankets are predicted to have negligible effects on cloud glaciation because their mineral aerosols have a similar ice-nucleating efficiency to clay (Fig. 4b; Atkinson *et al.* 2013; Harrison *et al.* 2019). Low-altitude warm clouds are primarily composed of water droplets, are optically thick with a high albedo and therefore produce a net cooling effect on the Earth's climate; all else being equal, the Earth's climate system will rebalance towards its pre-impact equilibrium (from Fig. 4b to Fig. 4a). The response of

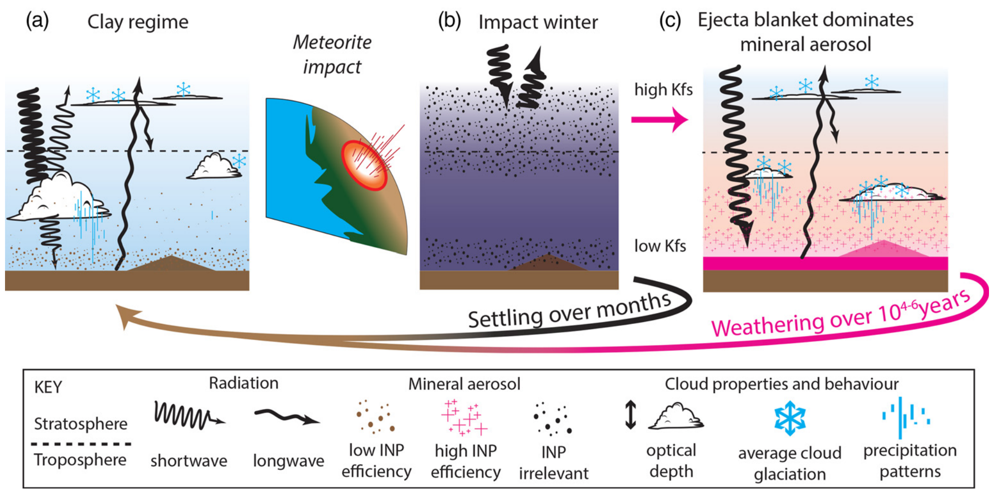

Fig. 4. Enhanced cloud glaciation hypothesis for driving accelerated global climate and evolutionary change. (**a**) Normal clay regime results in low and well-buffered atmospheric ice nucleation for *c.* 99% of the last 600 myr. Short- and longwave radiation are in dynamic balance, modulated by warm and cold clouds. (**b**) Meteorite impact generates an impact winter and short-term cooling over months. Low K-feldspar ejecta blankets have a negligible effect on atmospheric ice nucleation. (**c**) The presence of a K-feldspar-rich ejecta blanket increases the ice nucleation efficiency of mineral aerosols as part of the normal dust cycle flux and results in enhanced cloud glaciation. The optical depth of low clouds is thinned and their albedo is reduced, resulting in net warming. The cloud albedo feedback mechanism is suppressed, the climate is sensitized and the Earth is made more vulnerable to other climate forcers, such as greenhouse gas concentrations. The effects of K-feldspar aerosols decrease with weathering, which eventually reverts the surface and atmospheric mineralogy back to a clay-dominated regime. The instability of the climate, including the inducement of kill mechanisms, effects accelerated ecosystem change and biological turnover, recorded most prominently in the fossil record as mass extinctions. INP, ice-nucleating particle; Kfs, K-feldspar.

clouds to warming forcers (e.g. an increase in atmospheric greenhouse gases) is expected to operate in the same manner as during periods without any influence from the ejecta blanket (i.e. the modern pre-industrial climate system; Storelvmo *et al.* 2015; Bjordal *et al.* 2020).

By contrast, Kfs-rich ejecta blankets are likely to increase the importance of dust in the Earth's climate system by supplying particles with powerful ice nucleation efficiency to the troposphere. In this scenario (Fig. 4c), cloud conditions that would previously have been ice-free or ice-poor at temperatures below −15°C are now far more likely to be glaciated. The increased proportion of ice particles in an average tropospheric cloud reduces the optical thickness and albedo, resulting in increased earth surface temperatures. Above the dust transportation level, high-altitude clouds are comparatively unaffected and their small net warming effect continues. The overall general effects that can be expected from Kfs-rich ejecta blankets are (1) for the planet to warm past the pre-impact climate equilibrium due to the reduced global albedo and (2) by acting to keep a higher proportion of ice at higher temperatures, a weakening of the state-dependent cloud albedo feedback mechanism. Over time, the amount of Kfs will decrease as a result of weathering and will return the atmospheric mineralogy to normal clay-dominated conditions (Coldwell and Pankhurst 2019). Hence the proposed effects on clouds and the Earth's climate will reduce over weathering timescales of tens to hundreds of thousands of years (from Fig. 4c to Fig. 4a).

Complexity and uncertainty in the response of the climate system

The model proposed to explain the potential effects of Kfs-rich impact ejecta blankets on the Earth's palaeoclimate is derived from our understanding of how factors influencing the cloud state modulate the present day climate. For decades, global climate model predictions for enhanced climate sensitivity under warming conditions ranged from *c.* 2 to 4.5°C, yet cloud feedback responses were not well captured (Bjordal *et al.* 2020). Modelling now shows that the response of clouds under warming conditions from increasing greenhouse gas concentrations has a strong influence on climate sensitivity. Models appropriately capturing cloud albedo feedbacks predict increases in equilibrium climate sensitivity between 6.5 and 7.1°C (95% confidence interval) under a four times increase in CO_2 concentrations with respect to pre-industrial conditions (Bjordal *et al.* 2020). This modelling of warming of the modern atmosphere predicts that mixed-phase clouds will lose a proportion of their ice and increase the fraction of supercooled liquid, initially suppressing global warming via a cloud albedo cooling feedback mechanism. When all the ice is converted to liquid, this cooling feedback is exhausted, after which net warming cloud feedbacks dominate.

The presence of INPs in supercooled clouds promotes glaciation and this change of state has been shown to significantly reduce the reflectivity of mixed-phase clouds (Murray *et al.* 2020) at local scales by hundreds of watts per square metre (Vergara-Temprado *et al.* 2018). The retention of ice at higher temperatures contributes to dampening the cloud albedo feedback under global warming conditions (Tan *et al.* 2016). This means that it is plausible that the extreme abundance and proportions of Kfs in the atmosphere from a meteorite ejecta blanket, relative to modern mineral dust, could significantly reduce the initial cloud albedo cooling feedback stage by promoting glaciation (or, rather, resisting deglaciation) in mixed-phase cloud conditions below −15°C. By inhibiting deglaciation, relative to normal scenarios where the INP efficiency is far lower, and limiting a key negative feedback mechanism, it follows that one effect would be increased climate sensitivity.

Estimating specific climate equilibrium temperatures from these meteorite-induced Kfs effects is problematic due to the complexities and uncertainties surrounding the climate system. In the first instance, clouds can produce a range of feedbacks depending on their abundance, type and latitudinal position (Ceppi *et al.* 2017; Bjordal *et al.* 2020). For example, as the planet warms, tropical tropospheric convection mixes saturated air to higher altitudes. This increases the height of free tropospheric clouds, which means they are colder and absorb a greater amount of the longwave radiation emitted from the Earth's surface (Ceppi *et al.* 2017). This results in a positive (warming) feedback. Warming at mid- to high latitudes sees a variety of antagonistic processes reduce the amount of low-altitude cloud, which results in a positive (warming) feedback (Ceppi *et al.* 2017). The interplay between the amount of cloud, the cloud type and how these factors change in the presence of INPs and their efficiency is poorly understood in present day climate models. Therefore it remains unclear how the manifest range of cloud processes and feedback mechanisms may interact under an extreme meteorite-induced INP scenario.

In addition to the uncertainties based on present day climate models, deep time sees a variety of continental arrangements, ocean circulation patterns and physical geography. These factors have likely played parts in modulating atmospheric patterns, affecting average cloud type distributions as part of the global climate and therefore also in governing the sensitivity of the Earth's climate to a variety of forcing mechanisms over time. The spectrum of Earth system configurations through geological time could potentially result in climate states that respond differently to modern day climate scenarios. Furthermore, secular changes in the evolution of life affecting the structure of the biosphere also influence how changes to the climate are reflected by the extinction rate and lethality of discrete events (Newman and Eble 1999).

It is therefore striking that, despite the variety of Earth's configurations, climate states and potential responses from life, every Kfs-rich ejecta blanket over the past 600 myr coincides with a severe extinction event (Figs 1 and 2). This suggests that Kfs ejecta blankets had a fundamental role in destabilizing the biosphere each time, regardless of the specific configurations of the Earth systems.

Atmospheric change and Earth crises

The atmosphere is a first-order control on climate. It is linked to both terrestrial and marine biospheres and, through element cycling and gas exchange, it regulates all the ecosystems across the planet. The most severe extinction episodes include both terrestrial and marine biospheres (Bond and Grasby 2017). This strongly suggests that the driver of severe extinction episodes is a critical change in atmospheric function.

Reduced atmospheric shielding of solar radiation has been linked to increased levels of UV-B radiation reaching the Earth's surface, resulting in DNA damage and mass extinctions (Marshall *et al.* 2020). Warming of the atmosphere has been linked to a variety of kill mechanisms, including marine anoxia and acidification (Bond and Grasby 2017). Geological records demonstrate that aridification, mass wasting and increased biomass burning are also linked to climate warming (Benton and Newell 2014).

The global mean cloud albedo during much of Earth history could have been twice as sensitive to changes in aerosol emissions as it is today as a result of the low concentrations of aerosol particles under pre-industrial conditions (Carslaw *et al.* 2017). Suppression of the cloud cooling feedback mechanism makes the climate system more sensitive to other forcers and so allows otherwise buffered forcers to affect significant climate change. For example, large igneous provinces (LIPs) have been argued to drive mass extinctions by their emission of large volumes of greenhouse gases (Bond and Grasby 2017). On longer timescales extending to >1 myr, extensive weathering of basaltic lava at LIP scales has been suggested to accelerate global CO_2 drawdown and represents an important cooling forcer (Dessert *et al.* 2001). However, many LIPs, including the world's largest, are not associated with mass extinctions (Kelley 2007). The consequence of a Kfs-rich ejecta blanket emplaced during the development of an LIP may be to suddenly suppress the atmospheric buffer on increases in global temperatures. For the same volume and rate of greenhouse gas input, initial warming from LIP emissions will likely be faster and reach higher temperatures. We note that those mass extinctions that are most clearly associated with LIPs (the end-Permian, end-Triassic and end-Cretaceous mass extinctions) are also associated with Kfs-rich ejecta blankets. This aspect may explain why a variety of Earth system phenomena that are generally associated with comparatively stable ecosystems can also be seen occasionally to drive and/or contribute significantly to environmental catastrophes.

Conclusions and implications

A synthesis of 33 meteorite impacts and extinction intensities over the last 600 myr demonstrates that it is not the size of the impact, but the Kfs content of the ejecta blanket that correlates between meteorite impacts and mass extinction events. The pattern accounts for 11 extinction episodes across the history of multicellular life, including the majority of the most severe examples, and also the Acritarch Crisis at *c.* 580 Ma. Meteorite impacts that hit Kfs-poor rocks only correspond to background extinction intensities.

We propose a conceptual model whereby Kfs-rich ejecta blankets provide a source of efficient INPs to the atmosphere and have a period of influence on the Earth system for tens to hundreds of thousands of years. As a result of this change in aerosol mineralogy, mixed-phase clouds contain a higher proportion of ice crystals. This makes them optically thinner and reduces the contribution of the cloud albedo to cooling, which produces a relative warming effect at the Earth's surface. Enhanced Kfs cloud glaciation also suppresses cloud stabilizing feedbacks (resisting the deglaciation of clouds, leading to a lower albedo), which makes the climate more sensitive to other factors (e.g. high rates of greenhouse gas emissions). As a result, otherwise buffered (and, accordingly, not as influential) Earth system phenomena have disproportionately strong effects on the climate. The proposed model explains how Kfs, which is common in the Earth's subsurface and not directly harmful to life, correlates so strongly with mass extinctions through time when present as an ongoing high proportion of atmospheric mineral dust. Moreover, it may help explain why other Earth system phenomena had markedly different effects on the climate at different times throughout Earth history.

Kfs is recognized as the most important mineral aerosol in today's climate, despite its present scarcity. The importance of Kfs through deep time is now also apparent. The available evidence suggests that, until modern times, only meteorite impacts could change the atmospheric mineralogy with such (geological) suddenness and persistence. However, anthropogenic activities may represent similar climate forcing with the rapid input of aerosols into the atmosphere that influence cloud dynamics.

Acknowledgements The authors thank Rosalie Tostevin for their scientific editorship, and two anonymous reviewers for their thoughtful comments, questions and suggestions which greatly improved the manuscript.

Author contributions **MJP**: conceptualization (equal), formal analysis (lead), investigation (equal), project administration (lead), writing – original draft (equal), writing – review & editing (equal); **CJS**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal); **BCC**: conceptualization (equal), investigation (equal), writing – original draft (equal), writing – review & editing (equal).

Funding This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability All raw data are available in the cited references. Calculations, including scripts, are provided in the online Supplementary Material.

Scientific editing by Rosalie Tostevin

References

Alvarez, L.W., Alvarez, W., Asaro, F. and Michel, H.V. 1980. Extraterrestrial cause for the Cretaceous-Tertiary extinction. *Science*, **208**, 1095–1108, https://doi.org/10.1126/science.208.4448.1095

Atkinson, J.D., Murray, B.J. *et al.* 2013. The importance of feldspar for ice nucleation by mineral dust in mixed-phase clouds. *Nature*, **498**, 355–358, https://doi.org/10.1038/nature12278

Bambach, R.K. 2006. Phanerozoic biodiversity mass extinctions. *Annual Review of Earth and Planetary Sciences*, **34**, 127–155, https://doi.org/10.1146/annurev.earth.33.092203.122654

Benton, M.J. and Newell, A.J. 2014. Impacts of global warming on Permo-Triassic terrestrial ecosystems. *Gondwana Research*, **25**, 1308–1337, https://doi.org/10.1016/j.gr.2012.12.010

Bjordal, J., Storelvmo, T., Alterskjær, K. and Carlsen, T. 2020. Equilibrium climate sensitivity above 5°C plausible due to state-dependent cloud feedback. *Nature Geoscience*, **13**, 718–721, https://doi.org/10.1038/s41561-020-00649-1

Bond, D.P.G. and Grasby, S.E. 2017. On the causes of mass extinctions. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **478**, 3–29, https://doi.org/10.1016/j.palaeo.2016.11.005

Boucher, O., Randall, D. *et al.* 2014. Clouds and aerosols. *In*: Intergovernmental Panel on Climate Change *(eds) Climate Change 2013 – The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*.Cambridge University Press, 571–657, https://doi.org/10.1017/CBO9781107415324.016

Carslaw, K.S., Gordon, H., Hamilton, D.S., Johnson, J.S., Regayre, L.A., Yoshioka, M. and Pringle, K.J. 2017. Aerosols in the pre-industrial atmosphere. *Current Climate Change Reports*, **3**, 1–15, https://doi.org/10.1007/s40641-017-0061-2

Ceppi, P., Brient, F., Zelinka, M.D. and Hartmann, D.L. 2017. Cloud feedback mechanisms and their representation in global climate models. *WIREs Climate Change*, **8**, e465, https://doi.org/10.1002/wcc.465

Coldwell, B.C. and Pankhurst, M.J. 2019. Evaluating the influence of meteorite impact events on global potassium feldspar availability to the atmosphere since 600 Ma. *Journal of the Geological Society, London*, **176**, 209–224, https://doi.org/10.1144/jgs2018-084

Dessert, C., Dupré, B., François, L.M., Schott, J., Gaillardet, J., Chakrapani, G. and Bajpai, S. 2001. Erosion of Deccan Traps determined by river geochemistry: impact on the global climate and the $^{87}Sr/^{86}Sr$ ratio of seawater. *Earth and Planetary Science Letters*, **188**, 459–474, https://doi.org/10.1016/S0012-821X(01)00317-X

Foote, M. 2003. Origination and extinction through the Phanerozoic: a new approach. *The Journal of Geology*, **111**, 125–148, https://doi.org/10.1086/345841

Grey, K., Walter, M.R. and Calver, C.R. 2003. Neoproterozoic biotic diversification: Snowball Earth or aftermath of the Acraman impact? *Geology*, **31**, 459–462, https://doi.org/10.1130/0091-7613(2003)031<0459:NBDSEO>2.0.CO;2

Harrison, A.D., Lever, K. *et al.* 2019. The ice-nucleating ability of quartz immersed in water and its atmospheric importance compared to K-feldspar. *Atmospheric Chemistry and Physics*, **19**, 11343–11361, https://doi.org/10.5194/acp-19-11343-2019

Holland, S.M. 2020. The stratigraphy of mass extinctions and recoveries. *Annual Review of Earth and Planetary Sciences*, **48**, 75–97, https://doi.org/10.1146/annurev-earth-071719-054827

Hull, P.M., Bornemann, A. *et al.* 2020. On impact and volcanism across the Cretaceous–Paleogene boundary. *Science*, **367**, 266–272, https://doi.org/10.1126/science.aay5055

Jahn, L.G., Fahy, W.D., Williams, D.B. and Sullivan, R.C. 2019. Role of feldspar and pyroxene minerals in the ice nucleating ability of three volcanic ashes. *ACS Earth and Space Chemistry*, **3**, 626–636, https://doi.org/10.1021/acsearthspacechem.9b00004

Kaiho, K. and Oshima, N. 2017. Site of asteroid impact changed the history of life on Earth: the low probability of mass extinction. *Scientific Reports*, **7**, 14855, https://doi.org/10.1038/s41598-017-14199-x

Kaiho, K., Kajiwara, Y. *et al.* 2001. End-Permian catastrophe by a bolide impact: evidence of a gigantic release of sulfur from the mantle. *Geology*, **29**, 815–818, https://doi.org/10.1130/0091-7613(2001)029<0815:EPCBAB>2.0.CO;2

Kauffinan, E.G. 1994. Common patterns of mass extinction, survival, and recovery in marine environments: what do they tell us about the future? *The Paleontological Society, Special Publications*, **7**, 437–466, https://doi.org/10.1017/S2475262200009709

Kelley, S. 2007. The geochronology of large igneous provinces, terrestrial impact craters, and their relationship to mass extinctions on Earth. *Journal of the Geological Society, London*, **164**, 923–936, https://doi.org/10.1144/0016-76492007-026

Knippertz, P. and Todd, M.C. 2012. Mineral dust aerosols over the Sahara: meteorological controls on emission and transport and implications for modeling. *Reviews of Geophysics*, **50**, RG1007, https://doi.org/10.1029/2011RG000362

Kocsis, ÁT, Reddin, C.J., Alroy, J. and Kiessling, W. 2019. The R package divDyn for quantifying diversity dynamics using fossil sampling data. *Methods in Ecology and Evolution*, **10**, 735–743, https://doi.org/10.1111/2041-210X.13161

Marshall, J.E.A., Lakin, J., Troth, I. and Wallace-Johnson, S.M. 2020. UV-B radiation was the Devonian–Carboniferous boundary terrestrial extinction kill mechanism. *Science Advances*, **6**, eaba0768, https://doi.org/10.1126/sciadv.aba0768

Maters, E.C., Dingwell, D.B., Cimarelli, C., Müller, D., Whale, T.F. and Murray, B.J. 2019. The importance of crystalline phases in ice nucleation by volcanic ash. *Atmospheric Chemistry and Physics*, **19**, 5451–5465, https://doi.org/10.5194/acp-19-5451-2019

Mohammed, S.M.O., Brandt, K., Gray, N.D., White, M.L. and Manning, D.A.C. 2014. Comparison of silicate minerals as sources of potassium for plant nutrition in sandy soil. *European Journal of Soil Science*, **65**, 653–662, https://doi.org/10.1111/ejss.12172

Murray, B.J., O'Sullivan, D., Atkinson, J.D. and Webb, M.E. 2012. Ice nucleation by particles immersed in supercooled cloud droplets. *Chemical Society Reviews*, **41**, 6519–6554, https://doi.org/10.1039/c2cs35200a

Murray, B.J., Carslaw, K.S. and Field, P.R. 2020. Opinion: cloud-phase climate feedback and the importance of ice-nucleating particles. *Atmospheric Chemistry and Physics Discussions*, **21**, 665–679, https://doi.org/10.5194/acp-21-665-202

Newman, M.E.J. and Eble, G.J. 1999. Decline in extinction rates and scale invariance in the fossil record. *Paleobiology*, **25**, 434–439, https://doi.org/10.1017/S0094837300020303

Ohno, S., Kadono, T. *et al.* 2014. Production of sulphate-rich vapour during the Chicxulub impact and implications for ocean acidification. *Nature Geoscience*, **7**, 279–282, https://doi.org/10.1038/ngeo2095

Pankhurst, M.J. 2017. Atmospheric K-feldspar as a potential climate modulating agent through geologic time. *Geology*, **45**, 379–382, https://doi.org/10.1130/G38684.1

Rohde, R.A. and Muller, R.A. 2005. Cycles in fossil diversity. *Nature*, **434**, 208–210, https://doi.org/10.1038/nature03339

Schmieder, M. and Kring, D.A. 2019. Earth's impact events through geologic time: a list of recommended ages for terrestrial impact structures and deposits. *Astrobiology*, **20**, 91–141, https://doi.org/10.1089/ast.2019.2085

Sepkoski, J.J. 1986. Phanerozoic overview of mass extinction. *In*: Raup, D.M. and Jablonski, D. (eds) *Patterns and Processes in the History of Life. Report of the Dahlem Workshop on Patterns and Processes in the History of Life Berlin 1985, June 16–21*. Springer, 277–295, https://doi.org/10.1007/978-3-642-70831-2_15

Shao, Y., Wyrwoll, K.-H. *et al.* 2011. Dust cycle: an emerging core theme in Earth system science. *Aeolian Research*, **2**, 181–204, https://doi.org/10.1016/j.aeolia.2011.02.001

Siegmund, J.F., Siegmund, N. and Donner, R.V. 2017. CoinCalc—a new R package for quantifying simultaneities of event series. *Computers & Geosciences*, **98**, 64–72, https://doi.org/10.1016/j.cageo.2016.10.004

Storelvmo, T. 2017. Aerosol effects on climate via mixed-phase and ice clouds. *Annual Review of Earth and Planetary Sciences*, **45**, 199–222, https://doi.org/10.1146/annurev-earth-060115-012240

Storelvmo, T., Tan, I. and Korolev, A.V. 2015. Cloud phase changes induced by CO_2 warming – a powerful yet poorly constrained cloud–climate feedback. *Current Climate Change Reports*, **1**, 288–296, https://doi.org/10.1007/s40641-015-0026-2

Tan, I., Storelvmo, T. and Zelinka, M.D. 2016. Observational constraints on mixed-phase clouds imply higher climate sensitivity. *Science*, **352**, 224–227, https://doi.org/10.1126/science.aad5300

The Paleobiology Database 2021. www.gbif.org/dataset/c33ce2f2-c3cc-43a5-a380-fe4526d63650

Thürmer, K., Friddle, R.W., Wheeler, L.B., Bartelt, N.C., Roesler, E.L. and Kolasinski, R. 2019. *Deciphering Atmospheric Ice Nucleation Using Molecular-Scale Microscopy*. United States, https://doi.org/10.2172/1569351

Tohver, E., Lana, C. *et al.* 2012. Geochronological constraints on the age of a Permo-Triassic impact event: U–Pb and $^{40}Ar/^{39}Ar$ results for the 40 km Araguainha structure of central Brazil. *Geochimica et Cosmochimica Acta*, **86**, 214–227, https://doi.org/10.1016/j.gca.2012.03.005

Toon, O.B., Zahnle, K., Morrison, D., Turco, R.P. and Covey, C. 1997. Environmental perturbations caused by the impacts of asteroids and comets. *Reviews of Geophysics*, **35**, 41–78, https://doi.org/10.1029/96RG03038

Vergara-Temprado, J., Murray, B.J. *et al.* 2017. Contribution of feldspar and marine organic aerosols to global ice nucleating particle concentrations. *Atmospheric Chemistry and Physics*, **17**, 3637–3658, https://doi.org/10.5194/acp-17-3637-2017

Vergara-Temprado, J., Miltenberger, A.K. *et al.* 2018. Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles. *Proceedings of the National Academy of Sciences*, **115**, 2687–2692, https://doi.org/10.1073/pnas.1721627115

Whale, T.F., Holden, M.A., Kulak, A.N., Kim, Y.-Y., Meldrum, F.C., Christenson, H.K. and Murray, B.J. 2017. The role of phase separation and related topography in the exceptional ice-nucleating ability of alkali feldspars. *Physical Chemistry Chemical Physics*, **19**, 31186–31193, https://doi.org/10.1039/C7CP04898J

White, A.F., Bullen, T.D., Schulz, M.S., Blum, A.E., Huntington, T.G. and Peters, N.E. 2001. Differential rates of feldspar weathering in granitic regoliths. *Geochimica et Cosmochimica Acta*, **65**, 847–869, https://doi.org/10.1016/S0016-7037(00)00577-9