K-feldspar-rich meteorite ejecta blankets suppress the cloud-albedo feedback and trigger Earth crises.

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Abstract

Meteorite impacts load the stratosphere with dust and cover the Earth's surface with debris. They have long been debated as a trigger of mass extinctions through Earth's history. Impact winters generally last $<10^0$ years, whereas ejecta blankets persist for 10^3-10^5 years. Here we show that only meteorite impacts that emplaced ejecta blankets rich in K-feldspar correlate to Earth-system crises ($n=11$, $p<0.000005$). K-feldspar is a powerful ice-nucleating aerosol and plays an important role in cloud microphysics, which modulates global albedo. We propose that each K-feldspar rich ejecta blanket caused a departure from the normal function of atmospheric dust in the climate system. The dramatically increased proportion of K-feldspar had two key effects on cloud dynamics and, in turn, the global climate: 1) reducing the average albedo of mixed-phase cloud, which effected a hotter global climate; 2) weakening of the cloud albedo feedback, which meant the global climate became more sensitive. Increased climate sensitivity allowed normally benign processes to become significant drivers of climate change, and potential kill-mechanisms. This may explain why many well-established kill-mechanisms only variably correlate with extinction events through geological time: they require a sensitized climate to produce change. Together, cascading effects were catastrophic for life: every K-feldspar rich impact corresponds to a severe extinction episode over the past 600 Myrs.

1. Introduction

Meteorite impact as a cause of 'mass' extinction has been vigorously debated since 1980 (Alvarez et al., 1980). The only two instances that have gained acceptance as mass extinction triggers are also the two largest in the past 600 Myr: Chicxulub with a transient crater diameter of ~85 km at the K-Pg boundary c. 66 Ma (Hull et al., 2020), and; Acraman with a ~51 km-wide transient crater, associated with the Acritarch Crisis c. 580 Ma (Grey et al., 2003), see Fig. 1. This creates the impression that if any specific meteorite impact is to affect change at the global scale, extreme size is prerequisite (Tohver et al., 2012).

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

Age dating methods now provide high temporal resolution of impacts (Schmieder and Kring, 2019), as good or better than that of 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 others correspond precisely with times of relatively stable or decreased global extinction rate (Rohde and Muller, 2005), including the fourth largest: Manicouagan, which had a transient impact crater ~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 took place in tandem on timescales up to a million years (Holland, 2020). Therefore, any argument for a causative link between meteorite impacts and mass extinctions must address not only (i) why many large impacts do not coincide with extinction events and (ii) why many smaller impacts do coincide (Fig. 2), but also (iii) why the style, magnitude and timescales of potential kill mechanisms could be so different between instances.

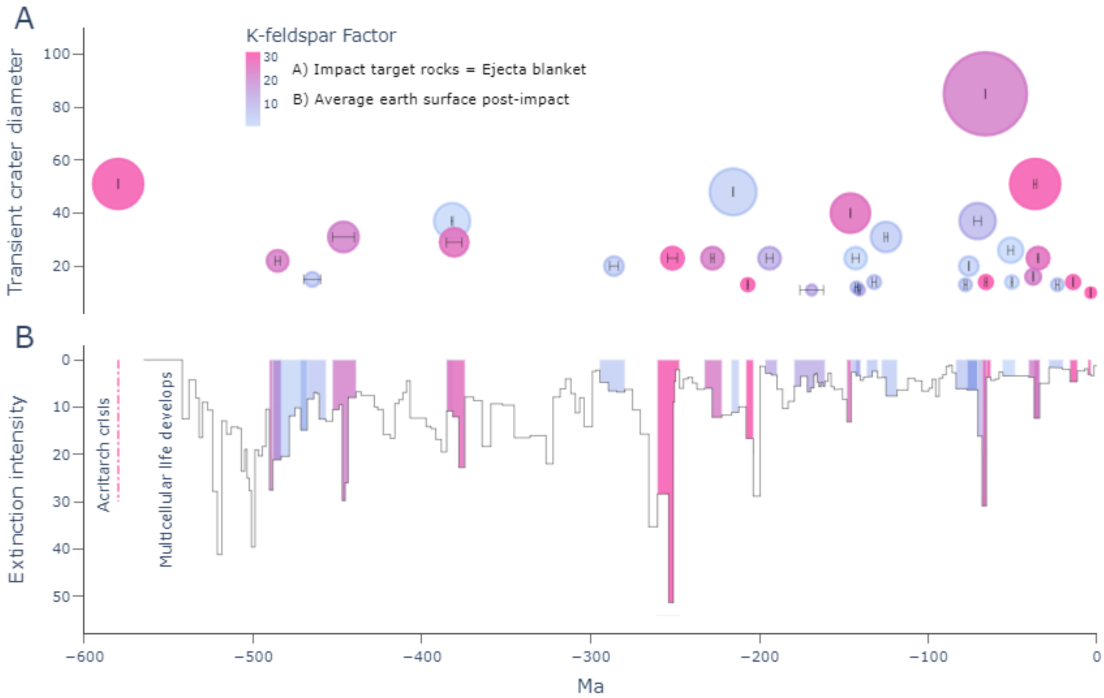

Figure 1. Comparison of meteorite impact stratigraphy, and extinction intensity of well-resolved marine genera. A) Impact database of 32 largest and best-dated impacts in the past 600 million years (Coldwell and Pankhurst, 2019). Transient crater diameter ≥10 km and age precision better than ±8 Myr. Updated from (Coldwell and Pankhurst, 2019) using revised age data (Schmieder and Kring, 2019) and plotted by size and K-feldspar Factor (KFF) of target rocks. Fifteen of 32 ejecta blankets are predicted to have caused long-term interruptions of the normal atmospheric ice-nucleation regime. B) Extinction intensity for the entire duration of multicellular life highlights times of global environmental crises. Timing of acritarch crisis also shown. Each Kfs-rich ejecta blanket corresponds to an Earth crisis, and accounts for the majority of severe spikes in extinction intensity, including almost all since ~250 Ma when both records are most complete. See SFig. 1 for KFF timeline, meteorite impact labels and named extinction events.

1.1 Atmospheric ice nucleation efficiency

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

Meteorite impacts have the unique potential to produce sudden, major and persistent changes to atmospheric mineralogy (Coldwell and Pankhurst, 2019). The initial dust and debris cloud settles out of the atmosphere quickly (Toon et al., 1997), yet the ejecta blanket remains as a voluminous and readily aerosolised source of mineral dust to the lower atmosphere for tens to hundreds of thousands of years (Coldwell and Pankhurst, 2019). By excavating local rocks and spreading them across the Earth's surface, the mineralogy of atmospheric dust is dominated by that of the rocks hit. A change of Earth surface mineralogy at this scale potentially changes the efficiency of atmospheric ice nucleation, effects global climate, and influences the evolution of life.

Here, we present an analysis of the Kfs content of the Earth's surface after meteorite impacts and the timing of accelerated extinction episodes over the past 600 Myrs. 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 of <0.000005, strongly indicating causation. In direct contrast, ejecta blankets low in Kfs are consistently associated with periods of ecological stability. We propose a new model which accounts for these observations and addresses why kill-mechanisms manifest differently for each extinction event. It is the ejecta blanket's potential to change climate and climate sensitivity, not Impact Winter, that determines the link between meteorite impact and mass extinction through deep time.

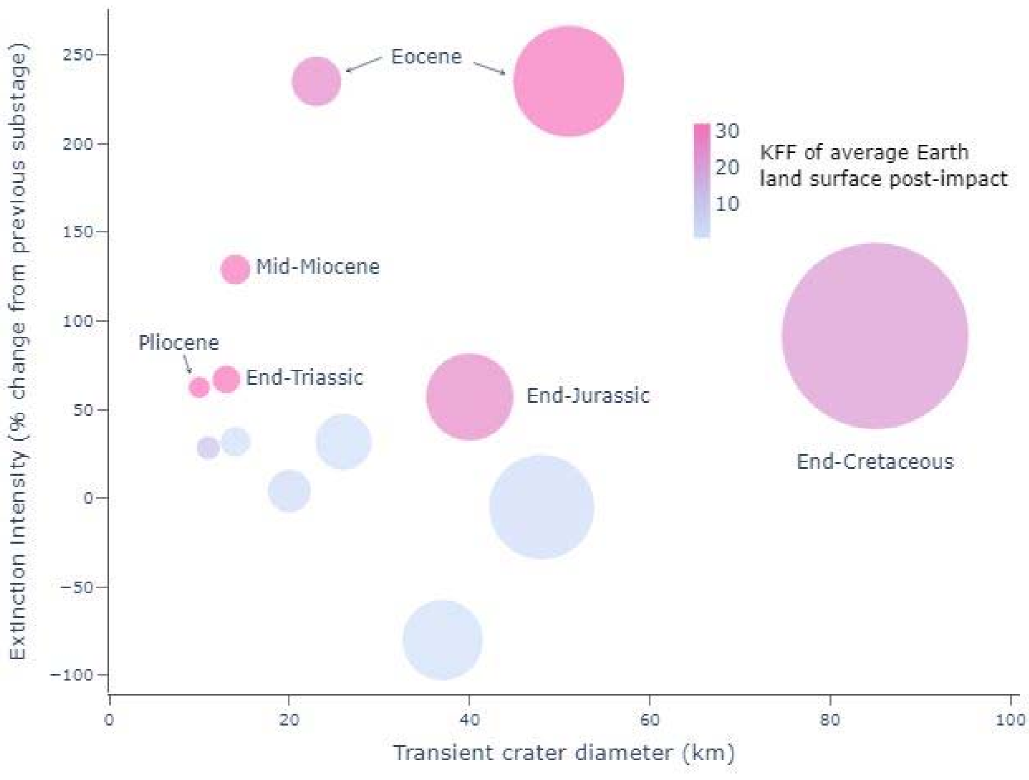

Figure 2. Mass extinction events and intensity correspond to KFF, not impact size. Only those craters with age precision that places the date of meteorite impact within a single geological substage are plotted, which provide 7 Kfs-rich and 6 Kfs-poor events. Extinction intensity of marine genera is expressed as percentage change from previous to highlight changes from substage to substage. Substages marked by an extinction event are labelled. See Supp. for plots including less precise database entries, and other projections of extinction data.

1.2 Clouds and Earth's radiative balance

Cloud plays a fundamental role in maintaining balance of the global energy budget since clouds are both reflectors of radiation from space, and insulators of radiation from the Earth's surface (Boucher et al., 2013). The net contribution of cloud to defining 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 (high albedo). Warm clouds cover a significant proportion of the Earth's surface, which affects an important net cooling forcer on the climate (Boucher et al., 2013; Murray et al., 2020). In contrast, cold clouds occur at high altitude and are composed of ice crystals at low concentrations, which means they are optically thinner than warm clouds (lower albedo: Murray et al., 2020; Storelvmo et al., 2015). In addition, cold clouds are effective at absorbing infrared radiation emitted from the Earth's surface, which overall amounts to a small net warming effect (Boucher et al., 2013).

The presence of ice-nucleating particles (INP's) in the atmosphere modulate cloud properties between these warm and cold end-members (Murray et al., 2020). Supercooled water freezes homogeneously at -39°C yet if INP's are present, ice-nucleation is induced, sometimes at far warmer temperatures depending upon the efficiency of the INPs (Murray et al., 2012). This means water vapour or droplets at lower altitudes can convert to ice particles, and leads to production of mixed-phase cloud (Boucher et al., 2013). Higher proportions of ice crystals within cloud reduces its optical depth, which reduces its albedo (Storelvmo et al., 2015). In addition, the formation of ice particles is an important precipitation triggering process (Boucher et al., 2013).

The state dependence of cloud-phase feedbacks is a crucial factor in the evolution of Earth's climate sensitivity (Bjordal et al., 2020). For example, climate models predict that global warming leads to less cloud glaciation, thicker average optical depth and increased average 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 gasses, thus acting to maintain stability (Murray et al., 2020; Storelvmo, 2017). Recent observations and insights from sensitivity studies demonstrate that the presence of INP's results in more mixed-phase cloud, and acts to suppress the cloud albedo cooling feedback (Murray et al., 2020; Tan et al., 2016). A pioneering model that includes Kfs parameterization, using modern mineralogy distribution (trace Kfs), deviates from control models in cloud forcing on regional scales (Thürmer et al., 2019).

1.3 Mineral aerosols and clouds

Mineral dust accounts for around half the aerosol in the modern atmosphere by mass (Knippertz and Todd, 2012), and a greater proportion existed in pre-industrial times (Carslaw et al., 2017). The dust cycle is characterised by primary emission events (dust storms), dispersion mainly through the lower troposphere, and eventual removal by dry- or wet-deposition (Shao et al., 2011). Clay minerals form at the Earth's surface which results in a thin, yet near-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 (Harrison et al., 2019) and is identified as playing the key role since it nucleates ice at about -15°C (Atkinson et al., 2013). Perthite (Kfs with a micro-texture of sodic feldspar lamellae) is the exceptional polymorph, as 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 within the Earth's continental crust (Coldwell and Pankhurst, 2019). Kfs is comparatively stable at surface conditions (White et al., 2001) yet in the presence of water it will eventually breakdown, which is why Kfs comprises only ~3% of modern mineral dust (Atkinson et al., 2013), mostly emitted from arid regions where chemical weathering is slowest (Pankhurst, 2017), and is present primarily in coarse mode dust (Thürmer et al., 2019).

1.4 Meteorite Impacts and atmospheric mineralogy through deep-time

Impact ejecta that blankets the Earth's surface has the unique potential to interrupt the clay-dominated mineral aerosol regime (Coldwell and Pankhurst, 2019). Among other effects, each impact resulted in the geologically instant production of fresh mineral dust in the readily aerosolised ≤200 μm diameter fraction that was likely ~10-1000 × that of total modern annual dust emissions (Coldwell and Pankhurst, 2019). How persistent an interruption is depends upon 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 Kfs chemical breakdown inside a highly porous blanket range to over a million years (White et al., 2001). The rate of ejecta blanket removal will decelerate through time owing to its thinner average depth with distance from the crater, hence its period of influence on atmospheric mineralogy is likely to be on the order of tens to hundreds of thousands of years (Coldwell and Pankhurst, 2019).

The Earths' crust is a heterogeneous arrangement of rock types, and meteorite impact location is serendipitous. The Kfs content of target rocks of all recorded meteorite impacts in the last 600 myr with transient crater diameter ≥10 km were recently reviewed (Coldwell and Pankhurst, 2019). Post-impact average Earth surface KFF (% by volume of Kfs in a material: Pankhurst, 2017) was estimated as part of that review by using palaeogeographic reconstructions of the continents, and primary ejecta dispersal.

2. Calculations

Here, estimations of global surface average KFF for the Clearwater West and Saint Martin impacts are added. Carswell, Charlevoix, Dellen, Puchezh-Katunki and Steen River were refined, and Woodleigh discarded, on age-precision arguments (Schmieder and Kring, 2019), for a total of 33 impacts. Fifteen ejecta blankets likely resulted in increased global Kfs availability, the other 18 did not (Supp. Fig. 1B, see Coldwell and Pankhurst, 2019).

The timing of these ejecta blankets is compared to the timing of extinction events over the past 600 myrs. It is important to consider the nature of the extinction record in this comparison, since statistical artefacts and record completeness produce bias at different times and timescales

(Bambach, 2006; Foote, 2003; Holland, 2020). A number of data treatments and tabulation methods are available in order to identify candidate extinction events (Bambach, 2006; Foote, 2003; Holland, 2020; Kocsis et al., 2019; “The Paleobiology Database,” 2021).

In this case, the most robust approach is to use a record that has the highest temporal resolution possible, whilst applying consistent data treatment. The marine fossil record is the longest and best-preserved, and at the highest temporal resolution available for inter-comparison at the genera level (Rohde and Muller, 2005) contains 167 biostratigraphic sub-stages from ca. 565 Ma to present (Fig. 1B). A review of extinction studies that focused on the marine record, and representing a range of data treatments and temporal resolutions, identifies eighteen intervals as those that most consistently appear as candidate mass extinction episodes over deep time (Bambach, 2006) using Sepkoski’s original definition (Sepkoski, 1986). Five additional extinction events are recognised when applying a complementary treatment (Rohde and Muller, 2005), for a total of 23 extinction events for inclusion. Each mass extinction event is also identifiable at lower temporal resolution (see the Palaeontology Database 2021). However, it is the high-resolution and consistent approach gives the best chance of recognising or rejecting a correlation with the independent meteorite impact database.

The duration of ejecta blankets as a source of mineral aerosol is shorter than that of the smallest chronostratigraphic divisions of geological time (sub-stages). 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 sub-stages (see Supp.). Using the span of time defined by the 2σ age precision of each impact, 13 are each resolved to a single substage (see Fig. 2), and a further 12 to one of two neighbouring sub-stages, which allows for direct comparisons to be made at the 95% confidence level using the highest stratigraphic resolution (167 intervals). To derive the statistical significance of potential correlations, the 167 geological stages/sub-stages were made into three binary sequences; whether or not they contain a severe extinction event; whether or not a meteorite impact occurred, and; 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 (Supp.).

3. 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 whose ejecta blanket was rich in Kfs coincides with, or tightly overlaps (within impact age precision), a sub-stage containing a severe extinction episode (Figs 1 and 2). Second, none of the impacts deficient in Kfs coincide with an extinction event, with the exception of one that overlaps (just) within age precision. Third, there is a poor correlation between impact size and extinction intensity (Fig. 2, see SFig. 3A for alternative projections). In addition, we note that each of the marine extinctions corresponding to a Kfs-rich ejecta blanket also have an associated terrestrial extinction (Bond and Grasby, 2017).

Time series event analysis demonstrates that 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. The null hypothesis is accepted when applying the same method to Kfs-poor ejecta blankets, and all meteorite impacts taken together, i.e. there is no correlation between Kfs-poor impacts or meteorite impacts in general, and severe extinction episodes (Fig. 3, Supp.).

The Kfs parameter cleanly discriminates between those meteorite impacts that coincide with severe extinction episodes, and those that don't. The strength of the temporal correlation between Kfs-rich ejecta blankets and severe extinction episodes suggests a causal link. In contrast, the anti-correlation with Kfs-deficient ejecta blankets suggests that meteorite impacts themselves are not causally related to severe extinction events. Such is the number of true positives compared to the dataset sizes, 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) does not change the result that Kfs ejecta blankets are strongly associated with severe extinction episodes.

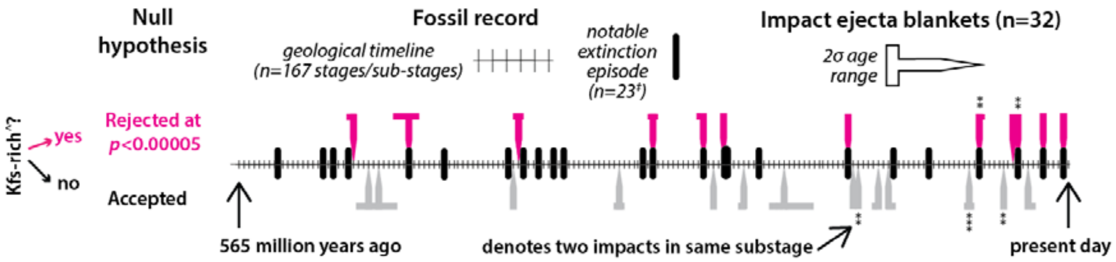

Figure 3. Time-series event analysis of Earth crises, meteorite impacts, and ejecta blanket Kfs content, from ca. 565 Ma to present. The timing of every Kfs-rich ejecta blanket plausibly coincides with an extinction episode. The most precisely dated subset (see Fig. 2 and Supp.) returns 100% simultaneity. In contrast, just 1/18 ejecta blankets that did not cause an increase in Kfs availability could possibly overlap an extinction event, and the most precisely dated subset (Fig. 2) has 0% simultaneity. ‡End Triassic extinction is codified into both the Upper Norian and Rhaetian.

4. Discussion

4.1 Direct and indirect effects of meteorite impact ejecta on climate

Impact Winter summarises the conditions at the Earth's surface due to the direct effects of the primary dust and secondary particulates, injected into the atmosphere as part of the cratering process and immediate aftermath (Toon et al., 1997). In a geological instant, normal terrestrial dust cycle processes (Fig. 4A) and the role of clouds are overshadowed by the direct effects, which act to efficiently block incoming solar radiation (Fig. 4B). Conditions at the Earth's surface rapidly cool, and fine material resides for days-months in the atmosphere (over a year for a Chicxulub-size impact). As the primary dust, and secondary particulates such as soot, settles and washes out of the atmosphere, the direct cooling forcer diminishes (Toon et al., 1997).

As Impact Winter wanes, cloud regains its importance on 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, yet now a defining portion is composed of minerals from the meteorite ejecta blanket. This means the aerosol mineralogy may have changed, and so potentially effect the properties of average low-altitude cloud differently. Kfs-poor ejecta blankets are predicted to have negligible effect upon cloud glaciation because their mineral aerosols have similar ice-nucleating efficiency to clay (Fig. 4C) (Atkinson et al., 2013; Harrison et al., 2019). Therefore, low-altitude warm-clouds remain composed primarily of water droplets, remain optically thick with high-albedos, continue to produce a net cooling effect on the Earth's climate, and all else being equal, the Earth climate system rebalances towards its pre-impact equilibrium (Fig. 4C).

In contrast, the atmospheric mineralogy defined by Kfs-rich ejecta blankets will profoundly affect low-altitude cloud properties, because Kfs aerosol is a powerful ice-nucleator (Atkinson et al., 2013). Efficient cloud glaciation at warmer temperatures is predicted (Fig. 4C). Compared to pre-impact conditions, warm cloud is replaced by more mixed-phase cloud, and so the average albedo of cloud decreases, and their important cooling effect is diminished. Above the dust transportation level, high-altitude cloud is comparatively unaffected, and its net warming effect continues. These effects result in the planet warming past the pre-impact climate equilibrium. As the influence of a Kfs-rich ejecta blanket on atmospheric mineralogy wanes and the proportion of clay aerosol returns to normal levels (Coldwell and Pankhurst, 2019), the corresponding effects will reduce over timescales of tens to hundreds of thousands of years.

The enhanced presence of Kfs in the lower atmosphere is also predicted to suppress the cloud albedo feedback, which limits the capacity for cloud phase change to restrain temperature rises in response to other types of climate forcing (Bjordal et al., 2020). In extreme scenarios of atmospheric INP proportions such as those described here, the cloud-albedo feedback is predicted to be greatly suppressed. The removal of the cooling feedback leaves the climate more vulnerable to warming from independent factors, such as changes in the concentration of greenhouse gases (Bjordal et al., 2020).

The effects of Impact Winter are governed by atmospheric settling of dust particles, measured in months-years (Toon et al., 1997). In contrast, changes to the cloud-albedo from Kfs aerosol is governed by silicate weathering measured in $10^{5\text{-}6}$ years (Coldwell and Pankhurst, 2019). The clear discrimination between Kfs-rich versus Kfs-poor impact ejecta with severe extinction episodes suggests that it is these long-term effects on climate and it's stabilizing mechanisms that are important in driving extinctions, more so than the size of the impact crater (Fig. 1 and 2). For example, larger impacts may produce more initial dust, but if they strike Kfs-poor rocks, the ejecta blanket is not predicted to have long-lasting climatic effects. Conversely, smaller impacts may produce less severe Impact Winters, but if they hit Kfs-rich rocks their ejecta blankets change atmospheric function.

Though deep-time a variety continental arrangements, physical geography, secular changes in the evolution of life, and ocean circulation patterns have played roles in long-term modulations in global climate. It is notable that the clay regime has prevailed throughout the past 600 myrs of this climate variation (Pankhurst, 2017), and has only been perturbed at a global and sudden scale by major meteorite impacts (Coldwell and Pankhurst, 2019). The remarkable correlation of Kfs-rich ejecta blankets with severe extinction episodes strongly suggests that destabilizing effects manifest regardless of specific background climate state (Figs 1 and 2).

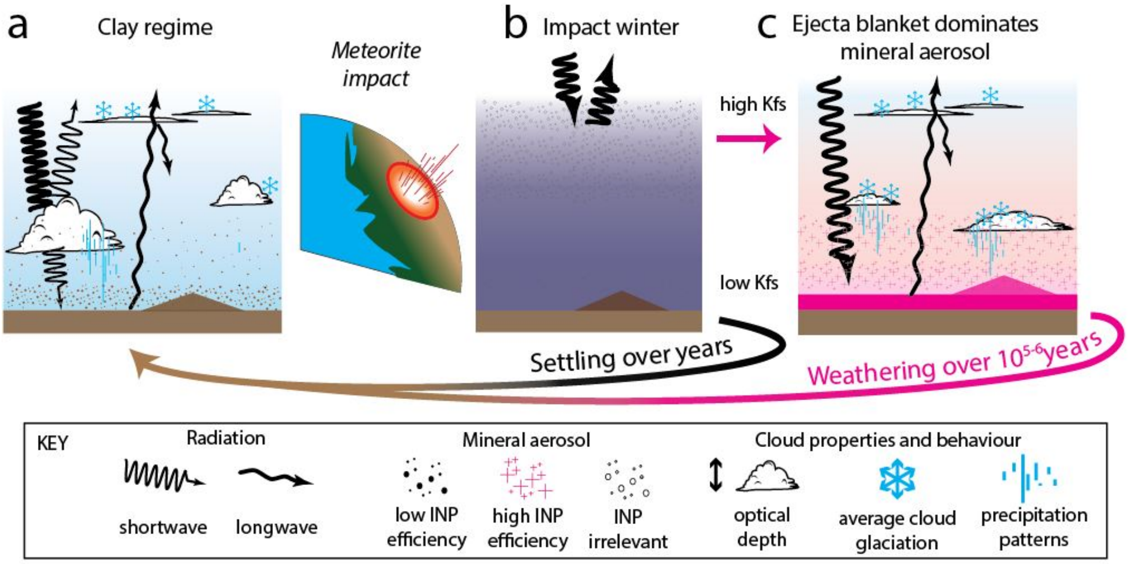

Figure 4. The enhanced cloud glaciation hypothesis for driving accelerated global climate and evolutionary change. a) Normal clay regime results in low and well-buffered atmospheric ice nucleation for ~99% of the past 600 Myrs. Short and long wave radiation are in dynamic balance, modulated by warm and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

4.2 Earth Crises and atmospheric change

The atmosphere is a first-order control on climate. It is linked into both terrestrial and marine biospheres, and through element cycling and gas exchange it regulates all ecosystems across the planet. Global mean cloud albedo during much of Earth history could have been twice as sensitive to changes in aerosol emissions as it is today, owing to the low concentration of aerosol particles under pre-industrial conditions (Carslaw et al., 2017). The most severe extinction episodes associated with Kfs-rich ejecta include both terrestrial and marine biospheres (Bond and Grasby, 2017). This strongly suggests 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). Aridification, mass wasting and increased biomass burning are also linked to climate warming (Benton and Newell, 2014).

Suppression of the cloud cooling feedback mechanism makes the climate system more sensitive to other forcers. This long-term change to atmospheric function permits otherwise buffered forcers to affect significant climate change. For example, LIPs are argued to drive mass extinctions by their emission of large volumes of greenhouse gasses (Bond and Grasby, 2017). However, many, including the world's largest, are not associated with mass extinctions (Kelley, 2007). The consequence of a Kfs-rich ejecta blanket that is emplaced during the development of a LIP is to suddenly suppress the atmospheric buffer on global temperature. For the same volume and rate of greenhouse gas input, warming from LIP emissions will likely be faster and reach higher temperatures. This aspect of our interpretation may explain why a variety of Earth system phenomena that are also associated with comparatively stable ecosystems, can also drive and/or contribute to a variety of environmental catastrophes.

5. Conclusions and implications

A synthesis of 32 meteorite impacts and extinction intensities over the past 600 myrs demonstrates that it is the Kfs content of the ejecta blanket that correlates between meteorite impacts and severe 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 ca. 580 Ma. Meteorite impacts that hit Kfs-poor rocks correspond only to background extinction intensity.

Kfs-rich ejecta blankets provide a source of efficient ice nucleating particles to the atmosphere, and have a period of influence on the Earth system for tens-hundreds of thousands of years. Due to this sudden, then persistent, change in aerosol mineralogy, low-altitude clouds contain a higher proportion of ice crystals. This makes them optically thinner and reduces the contribution of cloud albedo to cooling, which produces a relative warming effect at the Earth's surface. Enhanced Kfs cloud glaciation also suppresses atmospheric stabilizing feedbacks, which makes the climate more sensitive to other factors, e.g. high rates of greenhouse gas emissions. As a result, otherwise buffered (and accordingly, benign) Earth system phenomena have disproportionately strong effects on the climate. This mechanism explains the robust correlation between Kfs-rich impacts and high extinction intensity. Moreover, it helps explain why other Earth system phenomena can have markedly different effects on climate at different times through Earth's history.

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

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