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Paleozoic extinctions in cosmoclimatological context: 'non-bolide' extraterrestrial causes for global chilling

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Abstract. The Paleozoic Era experienced 4 major mass extinctions; i.e., end-Ordovician, Late Devonian, end-Guadalupian, and end-Permian episodes. As a cause of significant biodiversity decline, non-biological environmental change on global scale was inevitable; nonetheless, popular claims of bolide impact and/or large igneous province (LIP) with too many *ad-hoc* assumptions have not yet been accepted as common/universal explanations for the Paleozoic extinctions. Recent research on extinction causes evolved through two stages; i.e., the heyday of the bolide impact scenario in the 1980s, and the overtaking by a LIP-mantle plume scenario in the 1990–2000s. Lately, we may sense a return trend to extraterrestrial causes since the late 2000s, which is not a simple revival of the old bolide-impact model but a new proposal for a cosmoclimatological scenario relevant to extra-solar processes; i.e., supernovae explosions and relevant migration of dark clouds over the Solar System. This short article reviews the current status of extinction-related research, which emphasizes two key issues; i.e., the categorization of extinction causes and new perspectives on non-bolide extraterrestrial causes. The categorizing of extinction causes at four distinct levels is effective in separating "global triggers" on the Earth's surface from more essential "ultimate cases" within the Earth and/or on outside of the planet. Causes of extinction can be grouped into four distinct categories in a hierarchy, from small to large scale: i.e., Category 1 – direct kill mechanism for each local biota, Category 2 – background change in global environment, Category 3 – major geological phenomenon on the planet's surface, and Category 4 – ultimate cause from the interior and exterior of the planet. Recent advances in He isotope analysis for extinction-related sedimentary records suggest extraterrestrial causes, not of bolide impact but of the encounter with a dark cloud (nebula). Emerging new perspectives of cosmoclimatology leads to an alternative extinction scenario; e.g. 1) increased flux of galactic cosmic radiation (GCR) with extensive cloud cover and 2) passage of a dark cloud (nebula) enriched with micro-dusts (IDPs) enveloping the Solar System. Both meteoric cloud coverage and IDP-screen can induce lowering/shutdown of solar irradiance, which may drive global cooling and sea-level drop associated with biodiversity decline. The past star-burst events detected in the Milky Way Galaxy apparently coincide in timing with the cooling episodes associated with major extinctions of the Paleozoic, i.e., at the end-Ordovician, Late Devonian, and Late Permian. Given such astronomical processes associated with global cooling in the past, much older global freezing episodes, i.e., Proterozoic snowball Earth events developed under high atmospheric CO_2 levels, can be likewise explained. The study of mass extinctions on the Earth is entering a new stage under new astrobiological perspectives.

Keywords: cooling, extinction, extraterrestrial cause, IDP, Paleozoic, star-burst

Introduction

Long after the initial stage of discussion on catastrophism since G. L. Cuvier in 19th century, interest in the study of mass extinction was dramatically boosted during the 1980s in terms of two stimulating messages; namely, one was the proposal of possible periodicity/cyclicity in the Phanerozoic mass extinctions based on the ambitious compilation of almost all fossil data of the Phanerozoic (e.g. Raup and Sepkoski, 1982; Sepkoski, 1996), and the other was the proposal of an extraterrestrial trigger by bolide impact to terrestrial extinction, which was exemplified in the dinosaur-killing extinction across the Cretaceous–Paleogene (K–Pg) boundary (Alvarez *et al.*, 1980; Hildebrand *et al.*, 1991 and many others). The former highlighted 5 major mass extinctions for the last 500 million years in the Earth's history, together with the re-evaluation of all period boundaries in the Phanerozoic (Figure 1), whereas the latter has stimulated almost all contemporary geologists and paleontologists to start

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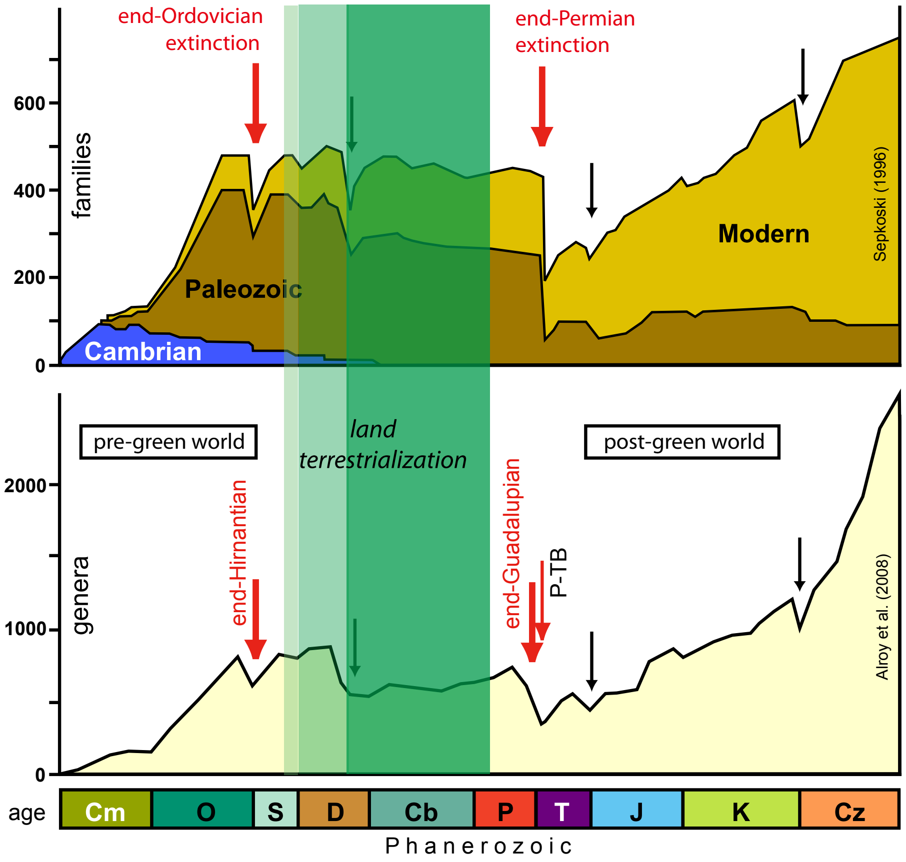

Figure 1. Big-5 plus 1 mass extinctions of the Phanerozoic compiled from Sepkoski (1996) and Alroy *et al.* (2008), highlighting two similar extinctions in the Paleozoic, i.e., the end-Ordovician and end-Guadalupian (Permian) episodes immediately before and after the global terrestrialization, respectively (Isozaki and Servais, 2018). Owing to the development of land forests, elevated photosynthesis changed not only landscape but also atmospheric composition, particularly the increase in O_2 mirrored in decrease in CO_2 (see Figure 4).

seeking possible causes of the severe extinctions not only within our own planet but also in its surrounding universe. During the last 4 decades within an extremely active scientific community, great improvements were achieved in high-resolution geochronological constraints (e.g. Bowring *et al.*, 1999) and in renewal of the paleontological database (e.g. Alroy *et al.*, 2008). In the meantime, various and numerous lines of evidence as well as possible scenarios were reported as to the Big-5 events of the Phanerozoic. Nonetheless, no agreement has yet been reached to date, except for a solid consensus built among scientists, which admits the necessity of global and acute environmental changes for causing major extinction.

After the proposal of an extraterrestrial scenario for the K–Pg boundary event, many attempts were pursued for detecting similar signals by the same schemes/techniques for other major extinctions and for explaining them in terms of astronomical mechanics, such as orbital cycles of planets, comets and/or the galaxy (as summarized in Raup, 1992; Alvarez, 1997). For identifying solid material evidence for the claimed extraterrestrial interference, new data for supporting or disproving were reported continuously, which sometimes ignited volatile discussions (e.g. Becker *et al.*, 2001; Farley and Mukhopadhyay, 2001; Isozaki, 2001; Kaiho *et al.*, 2001; Koeberl *et al.*, 2004; Farley *et al.*, 2005); nevertheless, none could sufficiently and consistently prove and explain the other 4 major mass extinctions in terms of extraterrestrial causes to date (e.g. Racki, 2020).

Since the mid-1990s, in turn, studies on mass extinction have shifted focus to terrestrial causes rather than bolide impact, in particular, large igneous provinces (LIPs) induced by mantle plume activity and relevant environmental changes on a global scale (Courtillot, 1999; Wignall, 2001; Isozaki, 2009; Ernst, 2014; Racki, 2020). Along with the current issue on the global warming during the 21st century, volcanism-induced high atmospheric CO_2 level and relevant climate changes/biodiversity decline have been preferentially emphasized (e.g. Chen and Xu, 2021; Gastaldo *et al.*, 2021).

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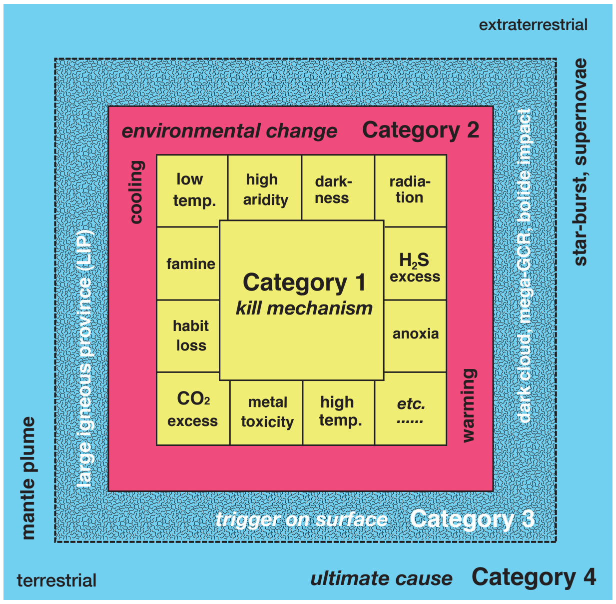

category	*processes*	*victims*
Category 1 **kill mechanism**	temperature drop	most biota
	temperature rise	warm-water dwellers
	oxygen depletion	animals with high metabolism
	hypercapnia	animals with low metabolism
	metal toxicity	animals with complex nerve system
	pH drop	calcareous test-forming biota
	aridity rise	aquatic animals/plants on land
	darkness	plants/photosynthetic bacteria
Category 2 **global environ. change**	cooling/glaciation	mid-latitude/tropical animals
	warming	tropical animals
	irradiance drop	all biota
Category 3 **trigger on surface**	bolide impact	all biota
	LIP	all biota
	mega-flux of GCR	all biota
	dark cloud	all biota
Category 4 **ultimate driver**		
terrestrial	mantle convection	all biota
	core convection	all biota
extraterrestrial	star-burst	all biota
	supernovae	all biota

Figure 2. Schematic diagram showing the hierarchy in extinction causes with categories 1 to 4 (partly modified from Isozaki, 2019). Category 1 includes direct kill mechanisms for each biota on a local basis, whereas Category 2 comprises global-scale environmental changes that may induce multiple kill mechanisms. Category 3 represents major trigger of global environmental changes, which episodically appeared on the planet's surface. Causes grouped into Category 4 are *bona fide* ultimate causes that originated not on the planet's surface but from its interior and/or in outer space. Note that agents higher in the hierarchy can initiate those in lower categories but not *vice versa*, and that kill mechanisms of Category 1 may include biological processes, whereas those of categories 2 to 4 are essentially non-biological, if at all.

On the contrary, I currently sense a swing-back of the pendulum toward seeking extraterrestrial causes once again but in a different context, due to unexpected new observations/discoveries from outer space and newly claimed astrophysical interpretations (e.g. Shaviv and Veizer, 2003; Svensmark and Calder, 2007; Kataoka *et al.*, 2014; Isozaki, 2019; Onoue *et al.*, 2019). The emerging perspectives are totally different from the classic view of the bolide impact scenario but are novel in explaining more diverse phenomena of larger magnitudes, in particular, those related to episodic supernovae explosions and relevant astrophysical consequences. To encourage stimulating brain-storming, this short review article briefly introduces some newly emerging aspects in the extinction issues based on the latest lines of evidence concerning extraterrestrial causes.

Extinction causes: Variety and hierarchy

According to the widely accepted view, mass extinction represents a sharp biodiversity decline in a relatively short duration, which affected numerous taxa thriving in diverse environments at almost all latitudes/altitudes (e.g. Raup and Sepkoski, 1982; Hallam and Wignall, 1997; Erwin, 2006). For driving such an abrupt and global mass killing, a large-scale change needs to appear on the Earth's surface, i.e., over the biosphere. In the past debate on extinction, the term "cause" was indeed tricky because it has been used in diverse connotations of geological processes and for various time-space dimensions (Racki, 2020). Each of the commonly claimed geological causes, such as bolide impact, global cooling, and oceanic anoxia, represents a distinct process of unique rate and/or magnitude potentially of global scale. In order to avoid unnecessary confusion derived from the poorly defined term "cause", Isozaki (2019) recently classified all previously claimed "causes" into four distinct categories from small- to large-scale, i.e., Category 1 for direct kill mechanism(s), Category 2 for global-scale environmental changes that can induce various kill mechanisms at the same time, Category 3 for large-scale physical triggers for global environmental changes, which appear on the crust's surface, and Category 4 for the "ultimate causes" within the deep interior of the Earth or in outer space, that can drive large-scale phenomena on the Earth's surface (Figure 2).

Category 1 includes all direct kill mechanisms for animals and plants, such as temperature drop or rise, oxygen depletion, hypercapnia, metal toxicity, pH drop, aridity rise, darkness etc. (e.g. Stanley, 1988; Isozaki, 1997; Grasby *et al.*, 2011; Figure 2). These phenomena, both biological and non-biological, are capable of affecting

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specific groups of animals and plants in a local or regional context; nonetheless, the solitary kill mechanisms cannot cause mass extinction for the entire biodiversity of the globe. In other words, the simultaneous onset of multiple kill mechanisms is necessary for mass extinction.

Category 2 covers much large-scale processes in a global context, such as global temperature drop or rise, global eustacy, irradiance drop, which are generally regarded as global environmental changes. These are mostly non-biological processes, although some microbial activities may naturally have intimate connections with chemical processes in the air and water, which can cause various kill mechanisms of Category 1 mentioned above.

Category 3 comprises global-scale acute non-biological phenomena that appeared strictly on the Earth's surface, such as impact of a large bolide and the onset of supervolcanism of a LIP (e.g., Alvarez *et al.*, 1980; Wignall, 2001; Ernst, 2014). These represent large-scale physical disturbance or redistribution of solid-state crustal material and covering fluids, which may act as critical triggers for global environmental and biospheric changes of Category 2. In general, these processes have been often claimed as possible "main causes" of mass extinction (Figure 2).

Category 4 includes the deep-seated ultimate causes, often cryptic, which can start the above-mentioned causes of categories 2 and 3 on the Earth's surface. The causes of this category include large (supra-global) scale non-biological processes, which need to originate from somewhere within the deep interior of the planet or in its surrounding exterior space. For example, an impact of an asteroid or planetary body onto the Earth's surface can be mechanically driven by gravitational instability in the asteroid belt of the solar system, whereas a LIP is formed by episodic activity of the deep-seated mantle within the Earth's interior. In addition, further candidates may include extra-solar processes in the deep universe, as will be discussed later.

The hierarchy among the above-mentioned 4 distinct categories is definite according to the order of magnitude; i.e., ultimate causes of Category 4 can affect those of Category 3 but not in the other way (Figure 2). Likewise, changes of Category 3 may unidirectionally control those of Category 2, as well as Category 2 over Category 1, but never *vice versa*. It is also noteworthy that kill mechanisms of Category 1 may involve various biological phenomena, whereas processes of higher categories are essentially non-biological, if at all.

Global cooling/Sea-level drop

There are not many so-called global environmental changes of Category 2, which can drive multiple kill mechanisms of Category 1 almost at the same time. Practical candidates for Category 2 include global cooling (e.g. Stanley, 1988), global warming (Wignall, 2001), and changes in seawater redox or geochemistry (e.g. Isozaki, 1997; Veizer *et al.*, 1999; Grasby *et al.*, 2011). The first two are contrasting modes of the same process in a mirror image. In general, temperature change appears highly critical for maintaining stable environmental conditions of the biosphere, in particular, for sustaining met-

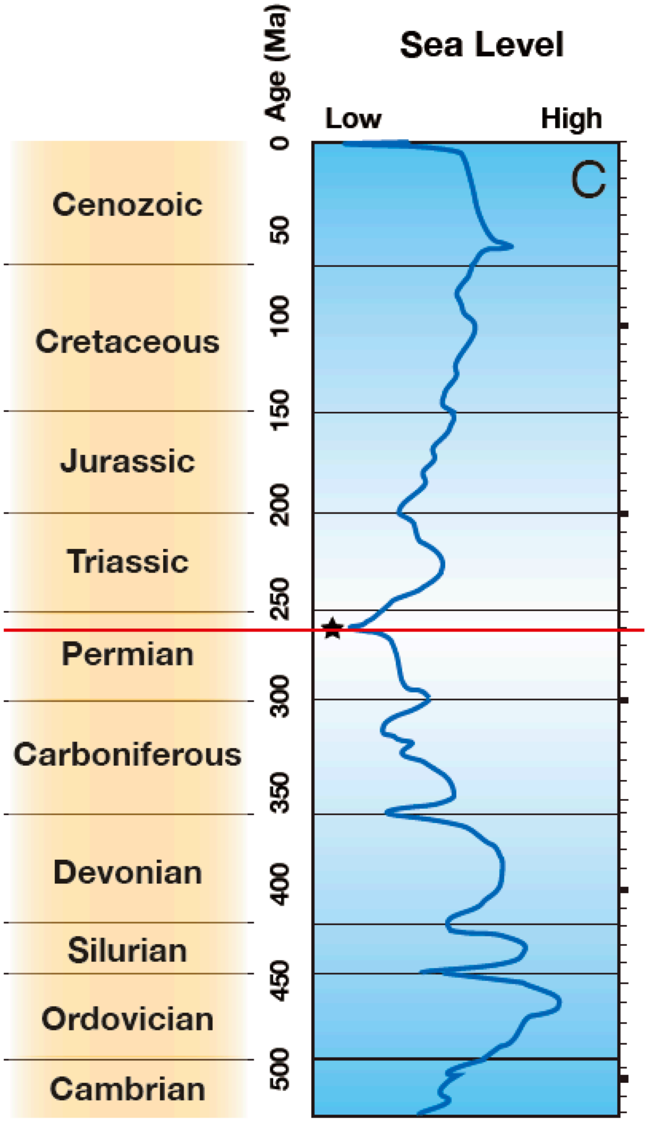

Figure 3. Sea-level change during the last 500 million years, i.e., the Phanerozoic (Isozaki, 2009), compiled for the Paleozoic from Haq and Schutter (2008) and Mesozoic–Cenozoic from Katz *et al.* (2005). The horizontal bar with star indicates the G-L boundary in the Permian with the lowest sea-level in the Phanerozoic. Note the three Paleozoic and end-Triassic extinctions occurred at the timings of global sea-level drop, i.e., global cooling.

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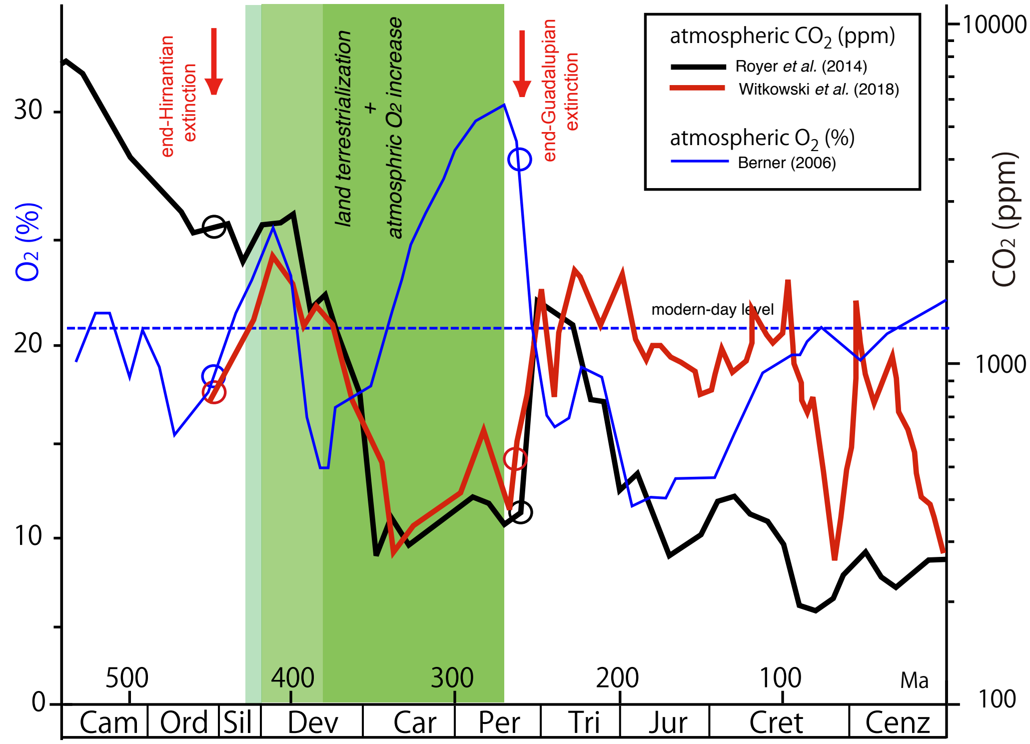

Figure 4. Secular change in the Phanerozoic atmospheric pCO_2 and pO_2 (Berner, 2006; Royer *et al.*, 2014; Witkowski *et al.*, 2018), and the timing of two compared extinction events, i.e., the end-Ordovician and end-Guadalupian, with respect to the mid-Paleozoic terrestrialization of continents (Isozaki and Servais, 2018). Although the two major extinctions occurred during global cooling (Fig. 3), the atmospheric compositions were significantly different between the Ordovician and Permian, before and after the major terrestrialization of continents, respectively (Fig. 1). Note that global cooling occurred at the end-Ordovician under a high atmospheric pCO_2, much higher than at the end-Guadalupian or in the Quaternary.

abolic biochemical reactions in small-size animals with lesser heat capacity. As to the 3 major extinctions in the Paleozoic, i.e., end-Ordovician, Late Devonian, and end-Guadalupian (Permian) episodes, commonly observed geological phenomena in association with biodiversity decline were global cooling and contemporary major sea-level drop (Fielding *et al.*, 2008; Haq and Schutte, 2008; Figure 3), as emphasized by Stanley (1988) and Isozaki and Servais (2018). It is also noteworthy that a global cooling often occurred in association with a following global warming within a short time interval, as observed in the cases of end-Ordovician, Late Devonian, end-Guadalupian (Permian), and end-Triassic (Racki, 2020). The Hirnantian (latest Ordovician) extinction occurred in two steps, i.e., first during a cooling and second in a warming; likewise, the end-Guadalupian biota suffered major temperature changes twice, i.e., during a cooling and a subsequent warming.

Major temperature changes on a global scale in the past have been generally explained in terms of the fluctuating greenhouse effect tuned by the partial pressure of atmospheric CO_2 (e.g. Foster *et al.*, 2017; Witkowski *et al.*, 2018). In contrast, another scenario emphasizes the fluctuation of galactic cosmic radiation (GCR) flux coupled with global cloud coverage (Svensmark and Friis-Christensen, 1997; Svensmark and Calder, 2007). The former is much more popular than the latter to date, as a CO_2-induced greenhouse effect is a well-documented physical process (e.g. Manabe and Wetherald, 1975; Keeling *et al.*, 1976; Zachos *et al.*, 2008) particularly for the current status of the Earth in the early 21st century. Nonetheless, the simple comparison may have some difficulties in explaining several geological records in the deep past, such as the snowball Earth episodes, i.e., global freezing even in the tropics, twice in the Proterozoic (e.g. Kirschvink *et al.*, 2000; Hoffman and Schrag, 2002) and also the end-Ordovician glaciation associated with extinction (Crampton *et al.*, 2016), because both occurred during the pre-terrestrialization time without land plants, thus with presumably much higher atmospheric CO_2 than that of the post-terrestrialization world (e.g. Royer *et al.*, 2014; Witkowski *et al.*, 2018; Figure 4). Given that the greenhouse effect alone can regulate the global climate, the contemporary atmospheric CO_2 needs to be

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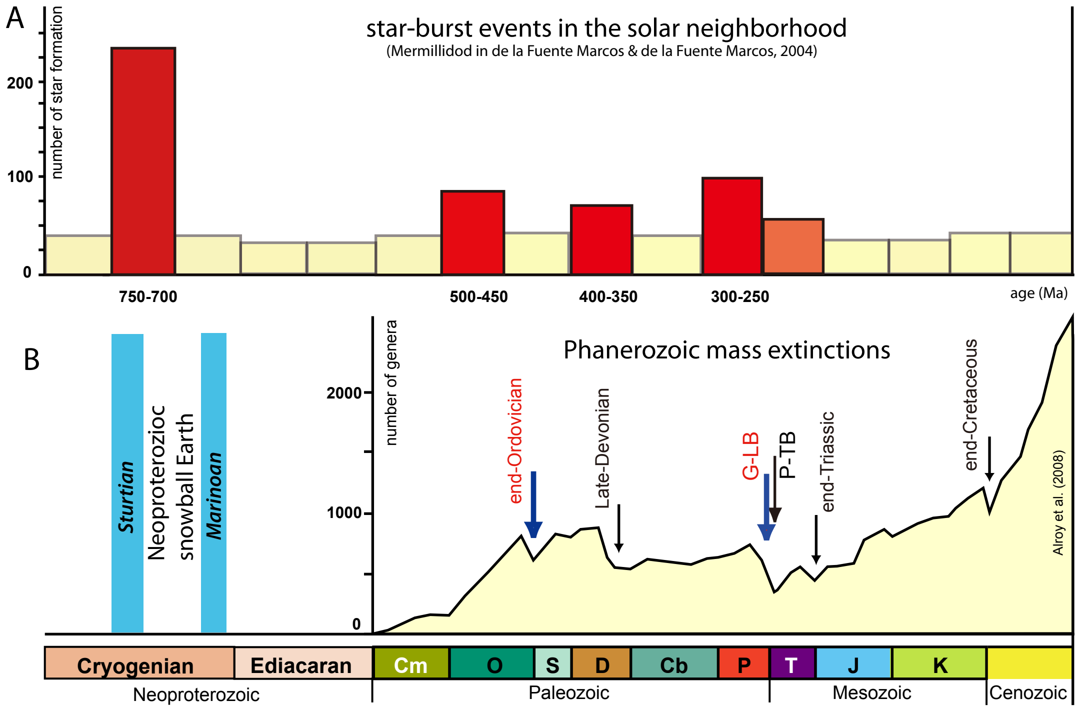

Figure 5. Major star-burst episodes and prominent cooling associated with mass extinctions (modified from Isozaki, 2019). Timings of past star-burst are after Rocha-Pinto *et al.* (2000) and de la Fuente Marcos and de la Fuente Marcos (2004). Note the coincidence in timing between major astrophysical processes and global cooling events that include the Paleozoic mass extinctions and Proterozoic snowball Earth events.

considerably low, lower than the present level, which is almost at the lowest in Earth's history by virtue of long-term photosynthesis and carbon-fixation or entrapment in the solid Earth. For driving an extreme icehouse condition like the Proterozoic snowball Earth, therefore, some unrecognized agent was likely inevitable, besides low atmospheric CO_2. In the following sections, the Factor X, another possible driver for global cooling, is explored.

Cosmoclimatology

Possible extraterrestrial influence on terrestrial life has been proposed and debated for more than half a century (e.g. Schindewolf, 1955; Raup, 1992; Alvarez, 1997), however, conventional scrutiny could not provide proof based on materialistic evidence, and the claimed periodicity as to the Solar System and Milky Way Galaxy was criticized from an astrophysical viewpoint (e.g. Erlykin *et al.*, 2017). Nevertheless, a noteworthy scenario for global cooling regardless of atmospheric CO_2 emphasizes a link between the passage of dark intergalactic clouds (nebulae) and global cooling (Pavlov *et al.*, 2005; Kataoka *et al.*, 2014; Nimura *et al.*, 2016). For advanced numerical modeling, two new aspects of deep space from the recent astrophysical observations were critical. First, by high-tech innovation for the cutting-edge equipment and facilities for astronomical observation, e.g. SUBARU and Hubble telescopes, and also Gaia spacecraft observatory, during the last 3 decades, numerous high-resolution data and images of deep space became available; e.g. impressive images include those of galactic collisions and mergers (e.g. NASA, 2020). Second, astronomical phenomena called "star-bursts" in the past have been detected on the basis of the statistical analyses of star ages and star clusters in the Milky Way Galaxy (Rocha-Pinto *et al.*, 2000; de la Fuente Marcos and de la Fuente Marcos, 2004; Ruiz-Lara *et al.*, 2020). These new observations suggest that stars like the Sun were not formed at a constant rate through time but episodically in several peak intervals called "star-burst" episodes characterized by an elevated formation rate; for example, the Sun was born *ca.* 4.6 Ga during one of these star-bursts. Throughout the 13.8 billion year-long entire history of the Milky Way Galaxy, extremely large star-bursts occurred twice in the Proterozoic within a bubble around the Sun with a radius of ~2 kiloparsecs. These two events apparently coincide with those of the Proterozoic snowball Earth events (Kirschvink *et al.*, 2000; Hoffman and Schrag, 2002).

As predicted theoretically, the collision of two or more galaxies can produce many supernovae remnants

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and dark clouds. The side-effects of such large-scale astronomical phenomena can cause global cooling on water-laden planets like the Earth through two possible processes, i.e., emission of high-energy GCR from supernova remnants and blocking lights from central stars by dense dust clouds (interplanetary dust particle = IDP) of migrating dark nebulae. The latter may cause prolonged global cooling when a dark cloud migrates to envelop the entire solar system by blocking solar irradiance (Pavlov *et al*., 2005; Kataoka *et al*., 2014; Nimura *et al*., 2016), whereas the former may induce short-term cloud coverage (Svensmark and Calder, 2007; Svensmark, 2012). Isozaki (2019) further speculated that minor star-burst episodes may have been responsible for the repeated global cooling and glaciations during the Phanerozoic (Figure 5). These speculations appear attractive and thus worth checking; nonetheless, they seem difficult to prove as to past events, particularly through material-based solid lines of evidence. In the final section, a new eye-opening result from Japan is introduced, which suggests a large extraterrestrial flux at the most prominent extinction across the Permo-Triassic (P-T) boundary, not by the commonly imagined bolide impact link, but by something else.

Extraterrestrial ^{3}He

Ancient deep-sea chert is the best sedimentary archive to retain scarcely recorded extraterrestrial flux in the past, simply because of its low sedimentation rate and tectonic stability in a mid-oceanic setting (Isozaki, 2014). Pre-Jurassic oceanic floors, however, have totally disappeared along subduction zones according to unstoppable plate tectonics, thus four out of the Big-5 extinctions are hard to examine in the past mid-oceanic domain that occupied nearly 70% of the Earth's surface during the Phanerozoic. Nonetheless, a small amount of their remnants can be retrieved from ancient accretionary complexes currently exposed on land (Isozaki *et al*., 1990; Matsuda and Isozaki, 1991), which provide a valuable source of information about the lost pre-Jurassic oceans, as typically demonstrated for the P-T boundary interval in Japan (Isozaki, 1997, 2014).

Earlier attempts to detect extraterrestrial signatures (e.g. Becker *et al*., 2001) were unsuccessful, and criticized for dubious measurement procedures and incorrect sample horizons (Farley and Mukhopadhyay, 2001; Isozaki, 2001; Koeberl *et al*., 2004; Farley *et al*., 2005). Nonetheless, these previous works suggest a possible approach by using a helium (He) isotope ratio in ancient sedimentary rocks. From the accreted P-T boundary cherts deposited primarily in the mid-oceanic deep-sea, Onoue *et al.* (2019) and Takahata *et al.* (2019) recently detected a significant extraterrestrial flux in terms of an extremely high ^{3}He ratio in the extinction-relevant P–T boundary interval.

It is widely known that a ^{3}He/^{4}He ratio higher than 100 indicates the primary gas condition formed strictly during the initial phase of our Solar System, which is preserved solely in primitive chondritic meteorites. Terrestrially derived materials, in contrast, have been contaminated considerably by secondarily accumulated ^{4}He from decayed heavy radiogenic elements, such as uranium and thorium, through time. The detection of an extremely high ^{3}He/^{4}He ratio in ancient deep sea sedimentary rocks therefore uniquely indicates extraterrestrial flux onto the Earth's surface. The deep-sea chert likely recorded regional or semi-global information of the Permian–Triassic superocean Panthalassa (Isozaki, 1997, 2014); therefore, a large extraterrestrial material flux on a global scale is inferred. At almost the same timing as the sharp diversity decline in dominant plankton (radiolarians) immediately before the terminal extinction at the P–T boundary (Figure 6), the significant increase in ^{3}He/^{4}He ratio first detected from the extinction-horizon thus suggests a possible cause and effect relationship between a large-scale extraterrestrial flux and a major biodiversity decline.

The incorporation of such a high ^{3}He/^{4}He-ratio signal into sedimentary rocks was not likely by high-energy bolide impact processes because impact-induced high temperatures prohibit the addition of helium gas into sediments. Instead, more gradual incorporation of fine-grained cosmic dust (interplanetary dust particle, IDP) at lower temperatures appears likely for carrying extraterrestrial He into the Earth's soft surface sediments. In this case, high ^{3}He/^{4}He helium is likely hosted in fine-grained material in solid state within IDPs. Unique micro-grain called GEMS (glass with embedded metal and sulfides) in chondritic porous (CP) IDPs (Messenger *et al.*, 2014), less than 500 nanometers with tiny minerals and organic material, is a favourite candidate for a carrier, as its amorphous phase and organic compounds may host a gas phase like helium. The origin of GEMS is not yet constrained but is assumed to have formed in the external domain within the primitive Solar System or in an interstellar nebula enriched in pre-solar material (Messenger *et al.*, 2014). From the P–T boundary samples in Japan, the host material of the unique He has not yet been identified; however, the detected extraterrestrial signature (Onoue *et al.*, 2019; Takahata *et al.*, 2019; Figure 6) is no doubt noteworthy, because it represents the first solid line of materialistic evidence not only for the extraterrestrial influence but also for possible pre-solar flux into the Earth at the major extinction timing. Generation of such an unusually high flux of extraterrestrial material,

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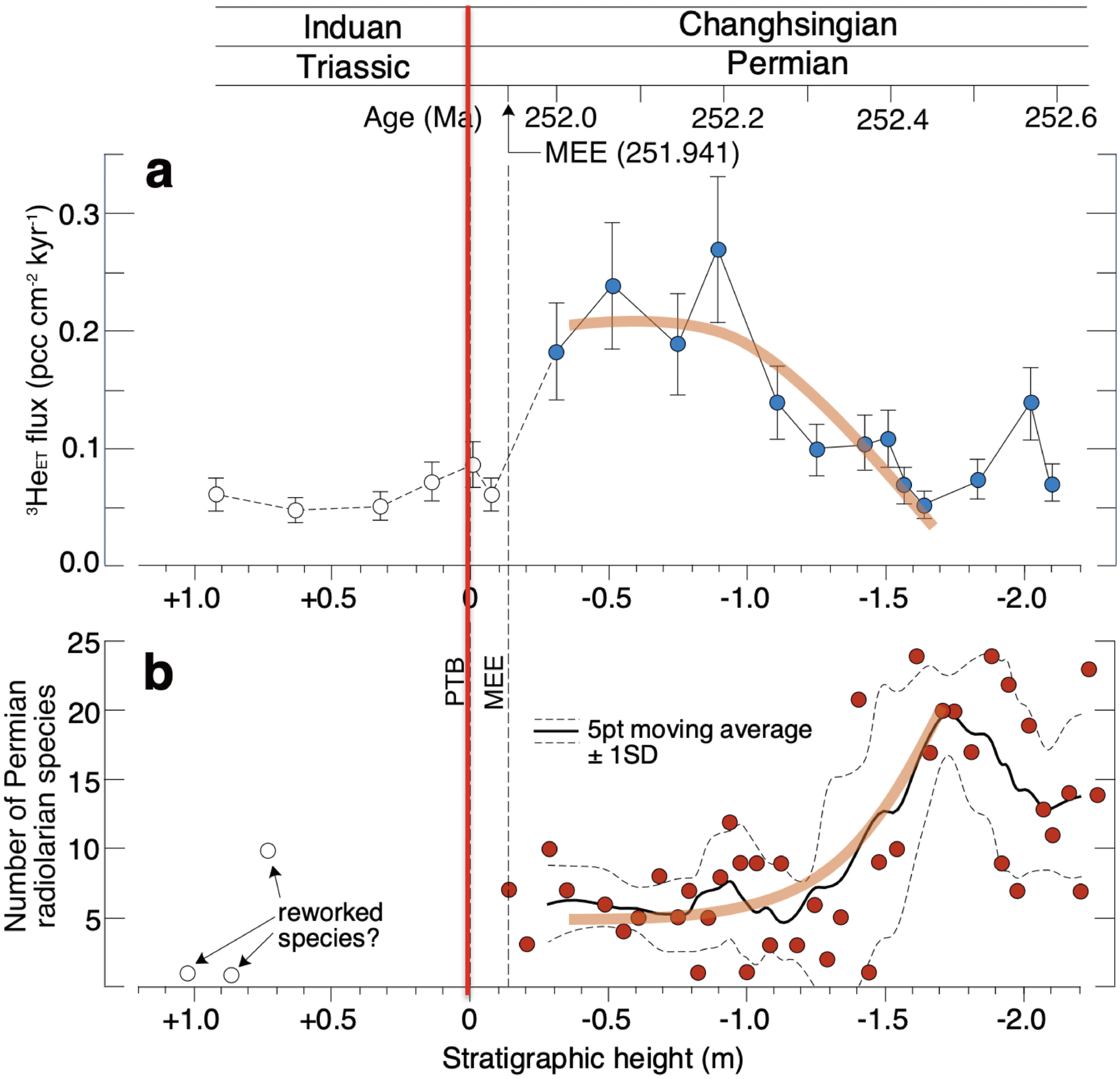

Figure 6. Extraterrestrial flux of extremely high $^{3}He/^{4}He$ at the P-T boundary mass extinction interval first detected in Japan (from Onoue *et al.*, 2019; Takahata *et al.*, 2019). Note the correlative increase in $^{3}He/^{4}He$ ratio and decline of marine plankton (radiolarians) in mid-ocean identified within the uppermost Permian cherts immediately below the end-Permian extinction horizon.

requires a large-scale astrophysical process within the Solar System. For a possible trigger, the purported passage of a dark cloud over the Solar System (Pavlov *et al.*, 2005; Kataoka *et al.*, 2014; Nimura *et al.*, 2016) cannot be overlooked.

Cascading down along the hierarchy of categories for extinction causes (Figure 2), a non-bolide extraterrestrial cause and effect link can be speculated as follows. When a dark cloud passes through the vicinity of the Solar System, the Sun and solar planets are totally enveloped by the dark cloud enriched in IDPs (a cause of Category 4), which may considerably block the solar irradiance to the planets including the Earth (cause of Category 3), may drive a global cooling and sea-level drop (cause of Category 2), and changes in biosphere. In particular, the decline in global bio-productivity may occur in larger magnitude owing to the suppressed photosynthesis under dim light. Such an unusual condition may activate simultaneously multiple kill mechanisms (causes of Category 1) leading to a mass extinction.

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As to the P-T boundary extinction case, a global warming was claimed by assuming a large volcanogenic flux of CO_2 from the LIP in Siberia (e.g. Wignall, 2001; Grasby *et al*., 2011; Gastaldo *et al*., 2021). This may sound contradictory to the above-discussed global cooling; however, the onset of the claimed warming probably occurred immediately after the cosmoclimatologic chilling. The combination of a global cooling and a following warming in a short time interval may drive profound damages to the contemporary environments and biota rather than solitary cooling or warming, as inferred from the end-Ordovician, Late Devonian, end-Guadalupian, and end-Triassic extinction cases (Racki, 2020), in addition to the Proterozoic snowball Earth episodes (Hoffman and Schrag, 2002). In this regard, LIP-induced global warming may become more effective for causing extinction particularly when a LIP forms during a major global cooling. Among ultimate causes of Category 4, such a combined cooling-warming with a rapid turnover in temperature in large magnitudes may induce the optimal consequence for extinction and the worst fate for biota. What matters most is probably not the temperature *per se*, but the rate of temperature change in a limited time interval. This implies a possibility of the "end-Quaternary episode", i.e., an extremely rapid warming during the cool period, and its potential consequence for the Anthropocene with the highest human population in history. We need to learn much more from the past.

More data are inevitably needed to test the claimed extraterrestrial cause not only for the P–T boundary extinction but also for other extinctions during the Paleozoic, and furthermore for the Proterozoic snowball Earth events. We need to "stay tuned" for further research results, specifically from analyses on pre-Jurassic deep-sea cherts that recorded other extinction and biosphere-catastrophe episodes in deep past.

Summary

Recent research on extinction causes evolved through two stages; i.e. the heyday of the bolide impact scenario in the 1980s, and the overtaking of the LIP-mantle plume scenario in the 1990–2000s. The emerging swing-back trend to extraterrestrial causes is not the simple revival of the old-fashioned bolide impact model but a new cosmoclimatological scenario based on new astronomical observations and new evidence for extraterrestrial He flux from the extinction-relevant horizon of the latest Permian deep-sea cherts. This short article reviewed the current status of research on Paleozoic extinction events, emphasizing two issues, i.e., the categorization of extinction causes (categories 1–4) and the new He evidence for a non-bolide extraterrestrial cause.

The advantage of categorizing extinction causes in four distinct levels is explained with particular remarks on the distinction of "global triggers" on the Earth's surface (Category 3) from more essential "ultimate cases" in the interior of the planet and in outer space, such as the passage of supernovae-derived dark clouds over the solar System (Category 4). The recent discovery of extraterrestrial He flux from the P–T boundary cherts in Japan suggests that the Solar System has encountered a dark cloud at the timing of the end-Permian extinction. Given such astronomical processes associated with global cooling in the past, this perspective and approach may be applied also for the study on much older global freezing events called Proterozoic snowball Earth, which occurred in greater magnitude under assumed high atmospheric CO_2 levels.

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