FORUM GEOGRAFI
ISSN: 0852-0682 | E-ISSN: 2460-3945

Searching for Potential Multi-hazard Events during the Last 1.5 Million Years of the Pleistocene Epoch

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Citation:

Bradak, B., Gomez, C., Kereszturi, Á., & Stevens, T. (2022). Searching for potential multi-hazard events during the last 1.5 million years of the Pleistocene epoch. Forum Geografi, 36(1).

Article history:
Received: 21 October 2021
Accepted: 28 March 2022
Published: 08 August 2022

Abstract

Increasing attention has been paid to multi-hazards in environmental disaster studies produced during the last decade. Multi-hazard studies focus on the occurrence, interaction and effect of several natural hazards in the same region. Despite the increasing number of multi-hazard studies, few investigations have focused on global-scale multi-hazard events. With the aim of closing this gap, our study focuses on the identification of periods during the last 1.5 million years of the Pleistocene epoch, with the quasi-parallel appearance of natural hazards (e.g., asteroid impacts and large volcanic eruptions with a Volcanic Explosivity Index (VEI) of 8 and 7) amplifying their individual effects and thus causing long-term, global-scale changes. Of the seven identified potential multi-hazard events, three were considered as possible global-scale events with a longer term environmental (paleoclimatic) impact; dated to c.a., 1.4 Ma (marine isotope stage – MIS45), 1.0 Ma (MIS 27), and 100 ka (MIS 5c), respectively. Two additional periods (around 50 and 20 ka) were identified as being associated with more restricted scale multi-hazard events, which might cause a “Little Ice Age-like” climatic episode in the history of the Pleistocene Period. In addition, we present a hypothesis about the complex climatic response to a global-scale multi-hazard event consisting of a series of asteroid impacts and volcanic eruption linked to a geomagnetic polarity change, namely the Matuyama-Brunhes Boundary, which might be accompanied by global cooling and result in the final step of the Early Middle Pleistocene Transition.

Keywords: multi-hazard; global-scale event; asteroid impact; supervolcano eruption; geomagnetic field fluctuation.

1. Introduction

The multi-hazard approach, a relatively new subfield in hazard research, is defined as an “approach that considers more than one hazard in a given place (ideally progressing to consider all known hazards) and the interrelations between these hazards, including their simultaneous or cumulative occurrence and their potential interactions” (Gill *et al*., 2016; http://www.interactinghazards.com/defining-multi-hazard). However, the amplifying events need to happen close in time to each other to lead to a joint consequence and, in the case of global effects, do not necessarily need to happen spatially close to each other.

As Gill and Malamud (2014) and Gill *et al*. (2016) summarised, the term “multi-hazard” is used in multiple ways: i) the overlay of single (discrete and independent) hazards; ii) the identification of all hazards in one place; and iii) the identification of all hazards in one place and description of the interaction which may occur between them.

Despite the increasing number of multi-hazard studies that focus mainly on the local and regional scale, few studies have focused on global-scale, multi-hazard events. Although extending such scale to the continental or global level is an exciting and possibly necessary step, it seems speculative from many angles. Despite the occurrence of certain events, such as the famous eruption of the Krakatau volcano (1883), or the Tohoku Oki earthquake and tsunami (2011), which both had continental and/or global-scale implications and a devastating regional-scale effect, no or only short-term (in a geological sense) global-scale consequences ensued. The lack of a long-term global-scale effect by present day (in a historical time sense) natural hazards is definitely fortunate from the perspective of, for example, the civilization and society, but it removes the opportunity for scientists to support their theories and models with observations.

Turning to the study of the geological past to gain information about the possible effect of global-scale multi-hazards may produce new information about the characteristics and magnitude of such events but, despite the rising availability of datasets and increasing number of case studies, potential multi-hazard events have rarely been studied in detail to date (one exception may be the Chicxulub impact event, a likely cause of the Cretaceous-Paleogene extinction event; see Renne *et al*., 2013, and the references therein).

The aim of this study is to reveal a potential chain of stochastic global-scale catastrophic multi-hazard events and describe their possible influence. Due to the limitation of the existing datasets and lack of information about the early geological period, this study focuses on events that occurred during the last 1.5 million years of the Pleistocene epoch (from 10 ka to 1.5 Ma), as these recent events are not unique on the geological timescales and they might even emerge in modern times.

The studied period consists of the so-called Early Middle Pleistocene Transition (EMPT), the great global reorganisation of climate/climate cyclicity, from marine isotope stage (MIS) 20 to MIS18 (~850 to 650 ka) (e.g., Heslop *et al.*, 2002). Undertaking a comparison of the timing of the global-scale hazard events and switch in the length of climate cycles during the EMPT will enable us to build a novel hypothesis: that the effect and superposition of stochastic geological events, such as a series of meteorite impacts, supervolcano eruptions and weakening of the magnetic field, trigger climatic instability and accelerate the accumulation of ice sheets. Under this scenario, these geological events act as ‘catalysts’ of climatic instability and push the system toward a threshold by strengthening the global cooling tendencies.

2. Research Method

Information about various terrestrial impacts was collected from the Earth Impact Database (EID, 2018) and the corresponding literature, listed in the references. In some cases, due to the lack of an independent, accurate numerical age estimate, the maximum age of the event was used. The latest, most reliable calculation of impact frequencies in the near-Earth region is that provided by Stuart and Binzel (2004), in which the impact of a 1 km or larger object on the Earth is estimated, with a frequency of once every 0.60±0.1 Myr (releasing 1021 J of energy), and also the impact of a 200 m diameter asteroid once every 56,000±6000 yr (releasing 4×1018 J total energy). To estimate the size of the asteroid, the following equation, provided by Hughes (2003), was used:

$$\log D\ (km) = (1.026 \pm 0.5) + (1.16 \pm 0.04) \times \log d\ (km) \qquad (1)$$

where, D is the size of the impact crater, and d the estimated size of the asteroid.

The estimation of the impact energy is based on the following equation, provided by Hughes (2003):

$$E\ (erg) = 9.1 \times 1024D2.59 \qquad (2)$$

Where, D is the diameter of the impact crater (km).

A larger impact may cause a significant earthquake, characterized by its estimated magnitude (M), and the area of influence (A), following the calculations proposed by Bath (1981) and Toon et al. (1997):

$$M = 0.7 \times \log(\varepsilon e \times Y) + 7.2 \qquad (3)$$

Where, M is the magnitude of the earthquake, Y(=E) is the kinetic energy of the object (in Mt) and εe is defined as 10-4, a constant, representing the efficiency of the conversion of kinetic energy by the impactor into elastic wave energy in the earthquake, calculated for a typical broken and fractured crustal rock:

$$A\ (km2) = 3 \times 109 \times \{10\text{-}0.63I \times (\varepsilon e \times Y)0.63\}\text{-}h2 \qquad (4)$$

The relationship in this equation between the impactor energy and the area affected by the triggered earthquake is quasi-independent of h (epicenter of the earthquake in km), assuming that the depth is of the order of 10 km (Toon et al., 1997).

The reference chart in Table 1 summarizes the key, updated information obtained from the literature on the influence of asteroid impacts, based on the estimated size of the impactor (for additional information, please see the caption to Table 1).

Table 1. Summary of the impact events by scale and their related consequences (after Marcus *et al.* 2010). More detailed information can be found about the additional influence of impacts in various studies, such as Artemieva and Morgan (2017; gas release due to impacts), Kring *et al.* (1995), Pope *et al.* (1997) (effects of impact-released sulphur content on ozone), Butchart and Scaife (2001; how decreased ozone concentration modifies the adsorption of solar energy though the atmospheric column), Haruma *et al.* (2007; the link between an impact in the ocean and decreasing ozone), Pierazzo *et al.* (2010; estimating the decrease in

ozone content occasioned by a 0.5-1 km diameter impactor), and Ermakov *et al.* (2009; impacts and thunderstorms).

Name of event type	General consequences	Probability or period of occurrence	Consequences on climate change
Chelyabinsk category events (c.a. 20 m)	Ionospheric disturbances for hours	10-50 years	Probably unobservable
Tunguska category events (c.a., 80-100 m)	Dust injection into the atmosphere, ionospheric disturbances	1,000 years	Minor, potentially observable in an ideal case, but without any long-term global consequences
Impact of 200 m category objects	10^7 ton dust injection into the atmosphere, ionospheric disturbances, “rain of fire”, impact crater formation with 3 km diameter, some NOx generation	56,000 years	Observable cooling effect
Impact of 500 m category objects	10^8 ton dust (10^9 ton H_2O in the case of ocean impact) injection into the atmosphere, ionospheric disturbances, impact crater formation with a 7-8 km diameter, NOx generation	120,000 years	Probably globally observable consequences in the temperature records
Impact of 1000 m category objects	10^9 ton dust (in the case of ocean 10^{10} ton H_2O) impact injection into the atmosphere, ionospheric disturbances, impact crater formation with a 14 km diameter, NOx generation	600,000 years	Definitely globally observable consequences with substantial temperature deviation, might reach the bottom of the shallow ocean

Information from the Large Magnitude Explosive Volcanic Eruptions (LaMEVE) database concerning various volcanic eruptions was collected and analysed (Crosweller *et al.*, 2012; Brown *et al.*, 2014). During the search for possible multi-hazard events, Volcanic Explosivity Index (VEI) 8 and 7 volcanic eruptions were considered as a possible cause of global-scale, longer-term changes, based on the work of, e.g., Rampino (2002) and Newhall *et al.* (2018). Although there remains no agreement about the environmental influence of individual VEI 8 and 7 eruptions (e.g., the Late Pleistocene Toba supervolcano eruption), increasing evidence is coming to light of the long-term climatic influence of the series of volcanic eruptions even on the geological timescale (e.g., Ward, 2009; Newhall *et al.*, 2018; Sorenghan *et al.*, 2019).

As Rampino (2002) summarized, there exist many similarities between asteroid impacts and large-scale volcanic eruptions, so our study’s primary focus is on the identification of multi-hazard events consisting of asteroid impacts and VEI≥7 volcanic eruptions. Fluctuations in the geomagnetic field can be observed from the changes in relative paleointensity, preserved in various geological records. In this study, VADM (Virtual Axial Dipole Moment) data from Channell *et al.* (2009) (PISO-1500) and Guyodo and Valet (1999) (Sint-800) were used. Relative paleointensity data were used to indicate the weakening of the geomagnetic field, which may have contributed to climate change. Although there are many concerns about the phenomenon, the weakening of the geomagnetic field appears around events such as magnetic polarity change (e.g., at the Matuyama Brunhes Boundary - MBB), which leads to an increase in the galactic cosmic ray

(GCR) flux and exerts some degree of influence on the paleoclimate. The growing GCR may increase the low-level cloud (Swensmark effect; Svensmark and Friis-Christensen 1997) which, in turn, increases the albedo effect and decreases the temperature. This is referred to as the Umbrella effect (e.g., Kitaba *et al*. 2017). Due to its expected influence on climate together with the overlapping of magnetic polarity change and asteroid impacts, the Umbrella effect may be defined as contributing to the cause of unusual palaeoclimatic events and so is included in the study. As we suggested above, there are many concerns about the influence of the weak geomagnetic field and growing GCR on the climate. The pros and cons of these phenomena are summarized in Section 3.3.1 in detail.

3. Results and Discussion

3.1. Identification of possible multi-hazard events in the last 1.5 Ma and their evaluation

Based on the analysed datasets, seven almost overlapping events were recognized as overlapping potential multi-hazard events in the last 1.5 Ma of the Pleistocene Period (Figure 1a, and Table 2). Among the seven events, the ~1.4 Ma (MIS 45), ~1Ma (MIS 27) and ~100 ka (MIS 5c) events consist of asteroid impacts (MIS 45, and 5c) and a series of supervolcano (VEI 8; MIS 27), and/or large volcanic eruptions (VEI 7; MIS 45, and 5c), and seem to have exerted a global-scale influence through the combined effect of the asteroid impact, series of large or supervolcano eruptions (category VEI7 and 8), and, in a particular case (the ~100 ka event), the weakening of the geomagnetic field during the so-called Post Blake event (Singer *et al*., 2014).

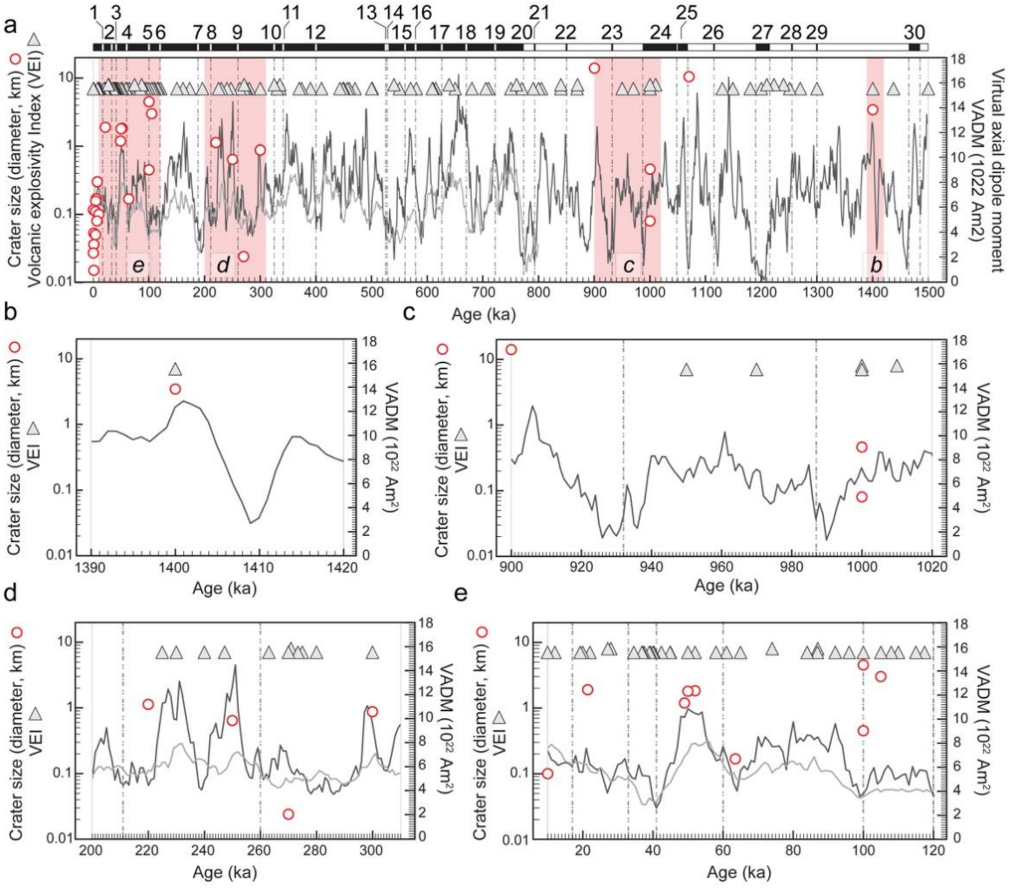

Figure 1. Overlapping asteroid impact, volcanic eruption and geomagnetic polarity change events in the last 1.5 Ma of the Pleistocene (Holocene excluded) (a): the past ~1.4 Ma multi-hazard event (b); the past ~1.0 Ma multi-hazard event (c); the past ~300 and 270 ka multi-hazard events (d); and the past ~100, ~50, and ~20 ka multi-hazard events (e). About the identified events please find additional information in Table 2. The red circles mark known asteroid impacts, the grey triangles indicate VEI7 and 8 volcanic eruptions, and the dotted-dashed lines mark geomagnetic polarity changes (excursions and reversals), respectively. The magnetostratigraphy of the studied period is shown in Figure 1a, with the normal and reverse geomagnetic polarity indicated by black and white sections, respectively (based on Cande and Kent, 1995; Laj and Channel, 2007). Excursions on Figure 1a: 1-Hilina Pali; 2-Mono Lake; 3-Laschamp;4-Norwegian-Greenland Sea; 5-Post Blake; 6-Blake; 7-Iceland Basin; 8-Pringle Falls; 9-Calabrian Ridge 0; 10-Calabrian Ridge I; 11-

Laguna del Sello; 12-Un-named; 13-Calabrian Ridge II; 14-West Eifel 5; 15-Big Lost; 16-West Eifel 4; 17-West Eifel 2; 18-Stage 17; 19-West Eifel 1; 20-MBB Reversal; 21-MBB Precursor; 22-Kamikatsura; 23-Santa Rosa; 24-Jaramillo; 25-Jaramillo Pre; 26-Punaruru; 27-Cobb Mtn.; 28-Bjorn; 29-Meseta del Lago (Buenos Aires); 30-Gardar.

Table 2. A comparison of the quasi-parallel environmental disasters in the last 1.5 Ma of the Pleistocene Period, including asteroid impacts, large and supervolcano eruptions and the change in the geomagnetic field. ^-impact with potential global influence (e.g., global cooling), based on Toon et al. (1997); * - potential VEI 8 supervolcano eruption (based on the LaMEVE data from Crosweller *et al*., 2012) ¤ - observable cooling effect, based on the impactor size (see Table 1). Events marked in "bold" (in the first column of Table 2) are identified as multi-hazard events with a global-scale and possibly longer-term effect. Events in normal script might have a globally recognizable effect, with a short-term influence. Events marked in italics are those with a stronger local and/or regional influence, but weak or negligible global-scale influence on the paleoenvironment. An MIS abbreviation with a number refers to the Marine Isotope Stages (odd number – interglacial; even number – glacial periods). In the case of MIS 5c, c indicates a shorter warmer period during the interglacial era. Please find additional studies about the listed impacts and eruptions at Earth Impact Database (http://passc.net/EarthImpactDatabase/New%20website_05-2018/Index.html) and the Natural Global Volcanism Program (National Museum of Natural History, Smithsonian Institution, USA; https://volcano.si.edu/), respectively.

M-h. event	**Impact crater**	**Volcanic eruption (VEI 7 and 8)**	**E (Mt)**	**Eq (M)**	**Eq A ($\times10^4$ km^2)**	**Short evaluation of the event**
The ~1.4 Ma (MIS 45) multi-hazard (Fig. 1b)	Pingualuit^, ¤ (New Quebec)	Taisetsuzan (Japan); Hodakadake (Japan) Mangakino (New Zealand)	5.3×10^3	7.0	7.7	The impact might cause observable cooling on a global-scale (Table 1, and Toon *et al.*,1997); the overlapping impact and series of VEI7 volcanic eruptions, possibly triggered long term climate change ("small ice ages") (Ward, 2009; Newhall *et al.*, 2018).
The ~1 Ma (MIS 27) multi-hazard event (Fig. 1c)	Montura qui (Australia)	Mangakino*(New Zealand); Corbetti Caldera* (Ethiopia); Yabakei caldera* (Shishimuta cal., Japan); Tokachi-Mitsumata (Japan)	2.9×10	5.4	2.9	The global influence of the impacts may be negligible, but the recorded three super- and two large volcanic eruptions might exert a significant influence on the climate and environment (e.g., Rampino, 2002; Ward, 2009; Newhall *et al.*, 2018; Sorenghan *et al.* 2019).
	Veevers (Australia)		3.1×10^{-1}	4.0	1.2	
The ~300ka (MIS 9-8 trans.) multi-hazard event (Fig. 1d)	Wolfe Creek (Australia)	Calabozos (Chile) Vulsini (Italy)	1.5×10^2	5.9	4.0	Concerns about the chronometric age and global influence of the impact, as well as the two eruptions, compared to the magnitude of other events.
The ~270ka (MIS 8) multi-hazard event (Fig. 1d)	*Dalgaranga (Australia)*	*Kapenga (New Zealand); Aso (Japan)*	1.4×10^{-2}	*3.1*	*0.7*	*The impactor size and energy seem too small to cause global-scale disasters; the volcanic eruptions might cause observable changes on a global-scale e.g., short-term cooling (Newhall et al., 2018).*
The ~100ka (MIS 5c) multi-hazard event (Fig.1e)	Agoudal (105 ka; Morocco) ¤	Toya (105 ka; Japan); Vulsini (100ka; Italy); Emmons Lake (96ka; USA)	3.7×10^3	6.9	7.2	The overlapping of a series of asteroid impacts with considerable size and impact magnitude possibly caused global changes (Table 1; and Toon *et al.*, 1997), along with the three VEI 7 volcano eruptions (Ward, 2009; Newhall *et al.*, 2018), and weakening of the geomagnetic field (Post-Blake event; Fig. 1e).
	Rio Cuarto^, ¤ (100 ka; Argentina)		1.1×10^4	7.2	8.8	

Table 2. Continued

	Amguid (100 ka; Algeria)		2.7×10	5.4	2.9	
The ~50ka (MIS 3) multi-hazard event (Fig. 1e)	Lonar (52ka; India)¤	Ischia (58 ka; Italy); Maninjau (52ka; Indonesia); Campi Flegrei (50ka; Italy) Nemo Peak (45ka; Kuril Island)	1.0×10^3	6.5	5.7	The asteroid impacts might cause globally observable, shorter-term cooling, which environmental influence was possibly reinforced by four VEI7 large volcanic eruptions (Ward, 2009; Newhall *et al*., 2018).
	Xiuyan (50ka; China)¤		1.0×10^3	6.5	5.6	
	Barringer (49ka; USA)		3.4×10^2	6.2	4.6	
The ~20ka (MIS 2) multi-hazard event (Fig. 1e)	Tenoumer¤ (21.4 ka; Mauritania)	Opala (22ka; Kamchatka Island); Zavaritsky (20ka; Kamchatka Island); Lon Island (19.245ka; New Guinea)	1.1×10^3	6.5	5.8	The asteroid impact might exert a globally recognizable, short-term effect (Table1), strengthened by the series of VEI 7 volcanic eruptions (Newhall *et al*., 2018).

The events date back to the Late Pleistocene Period; namely, the ~100ka (MIS5c), ~50ka (MIS 3), and ~20ka (MIS 2) multi-hazard events, consist of overlapping series of asteroid impacts and VEI 7 volcanic eruptions. Although the potential global influence of such multi-hazard events is less than the three events suggested above (MIS45, 27 and 5c), they might cause observable shorter-term (e.g., Little Ice Age-like) global environmental changes (Figure 1e and Table 2).

There are two multi-hazard events, which might have negligible global effects, compared to the other five. The asteroid impacts and volcanic eruptions may exert a significant local/regional influence during the ~300 ka, and ~270 ka events but, due to the magnitude of the impact events, might not cause any global-scale longer-term environmental changes (Figure 1d and Table 2).

3.2. Some segments of the global-scale influence of multi-hazard events

Three to five possible multi-hazard events were recognized in the last 1.5 Ma years of the Pleistocene Period, the influence of which will be briefly reviewed in the following.

Toon et al. (1997) provided a detailed description of the influence of the impacts, based on their energy and influence on the environment. The study defines asteroids ranging in size from c.a. 850 m to 1.4 km, with a 104-105 Mt impact energy, as the smallest which may have a global influence due to the stratospheric water vapor injection, dust load to the atmosphere, and ozone loss. This impact energy level may have been reached in two cases in our list: namely, during the Pingualuit (~1.4 Ma, MIS45) and Rio Cuarto (~100 ka; MIS 5c) impact events. Other events are considered smaller impact events, with local and/or regional effects only.

Rampino (2002) compared supervolcano eruptions (supereruptions) to asteroid impacts. The study suggests that supereruptions produce >1000 km3 of ejected material, inject ≥1000 Mt aerosols and submicron size dust into the atmosphere, and are capable of creating global climatic disturbance, similar to the influence of an impact by an asteroid measuring ≥1 km in diameter. Based on the studied datasets, the concomitant appearance of such eruptions, combined with asteroid impacts at a local and regional scale, happened during MIS 27 (~ 1 Ma).

As the example of the MIS 27 above demonstrates, the data mining for this study did not simply focus on individual events, but the sequencef and/or overlapping of possibly larger-scale hazards (multi-hazard events). As the study of Ward (2009) suggests, the effect of individual ("sporadic") large volcanic eruptions may be cooling due to the sulfuric acid formation in the lower atmosphere. The study suggests that the series (sequence) of such eruptions may push the climate into an "ice age". The findings of Soreghan *et al*. (2019) are in line with those of Ward (2009): frequent explosive volcanism can sustain icehouse conditions due to, e.g., the increasing atmospheric acidity, and the ash and dust that are injeceted into the atmosphere. Such conditions, with a series of large (VEI7 and 8) volcanic eruptions, may apply throughout the period covered by this study.

It seems important to highlight that long-term, global-scale paleoenvironmental influence/changes tend to happen following the appearance of a series or sequences of (overlapping) events, compared to individual eruptions or impacts that occurred during the studied period. There might be some exceptions, such as the eruption of Toba volcano during the Late Pleistocene Period (c.a. 70 ka ago), but the existence of the long-term effect (producing a widespread glaciation period) of the Toba "mega-eruption" continues to spark ongoing scientific arguments (e.g., Rampino and Self, 1992, 1993a, 1993b; Zielinski *et al.*, 1996; Oppenheimer, 2002; Robock *et al.*, 2009).

Besides the role of a series of impact events and volcanic eruptions in triggering longer-term global-scale (paleo)climatic changes by strengthening each other influence, there is one additional connection between asteroid impacts and volcanic activity to be considered. The studies of Watt *et al.* (2009) and Namiki *et al.* (2016) suggest that there exists a connection between larger earthquakes and volcanic eruptions, triggered by dynamic and static stress, and stress-related processes, associated with the earthquakes. Although the estimated timescale of a triggered volcanic eruption is only several months, we believe that it is worth mentioning the possible connection between an impact triggered ≥7M earthquake (e.g., in the case of the studied impacts: Pingualuit and Rio Cuarto impactors) and volcanic activity.

3.3. Some thoughts about "hidden" global-scale catastrophic multi-hazard events

As shown in Figures 1 and 2, there exists a significant gap in the number of asteroid impacts in the studied period, especially between 900 and 300 ka during the early Middle Pleistocene Period. As demonstrated in Figure 2, a considerable number of estimated asteroid impacts are "missing", probably due to various reasons. The lack of a known impact crater does not necessarily mean the lack of an impact event as, e.g., i) the impact crater may simply not have been discovered yet, or its existence may not have been verified by various studies (e.g., a recently discovered Pantasma crater from the early Middle Pleistocene Period, Rochette *et al.*, 2019); ii) some terrestrial impact craters may be covered by various substances (e.g., continental ice; Kjær *et al.*, 2018); iii) impacts in the marine environment could still have happened which, e.g., turbidity currents would cover (e.g., the Eltanin impact). The Eltanin impact provides a useful reference point for the examination of the potential influence of a meteorite impact on longer-term climate transitions and changes, being one of the suggested climatic drivers marking the Pliocene/Pleistocene boundary (Gisler *et al.*, 2011; Goff *et al.*, 2012). Signs of a meteorite impact, such as the presence of anomalous amounts of iridium, sedimentary disturbance, and changes in the environment, were discovered and reported in drilling cores (Bellinghausen Sea, Eastern Pacific Southern Ocean) by Gersonde *et al.* (1997), Colodner *et al.* (1981), and Ward and Asphaug (2002). Based on high-resolution bio-, and magnetostratigraphical investigations, the impact event is dated to ~2.511±0.07 Ma. The impacting body was 1-4 km diameter, and its impact energy ranged from 105 to 107 Mt. It would have left a 35 km diameter crater, though this has yet to be identified (Kyte *et al.*, 1988). This asteroid possibly caused environmental change on a global-scale, including a mega-tsunami and the destabilization of the Antarctic ice shelf area (Gersonde *et al.* 2005). As already suggested above, it served as a climatic driver of the Plio-Pleistocene transition.

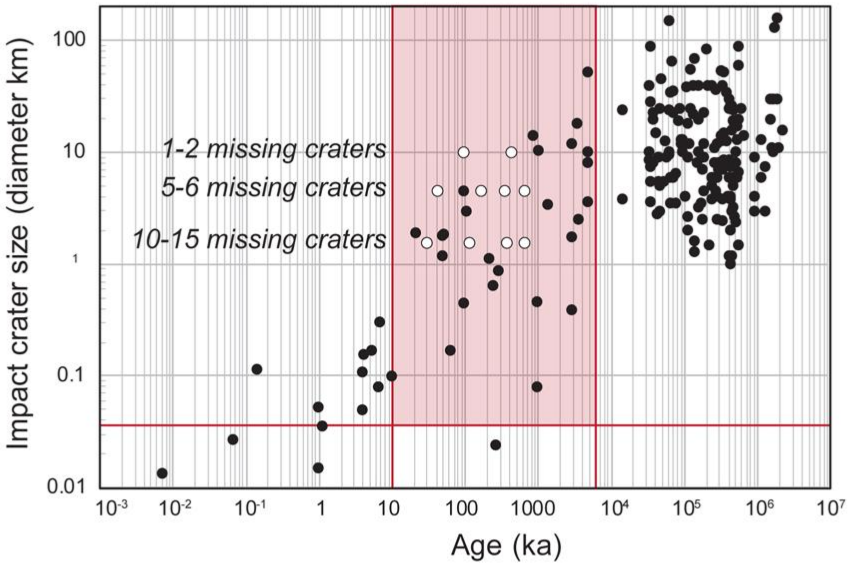

Figure 2. The identified terrestrial and possible unidentified impacts of the last 1.5 Ma of the Pleistocene Period. Identified (black dots) and expected and unidentified impacts (white dots) according to the size and

age of the craters, based on the Earth Impact Database: http://www.passc.net/EarthImpactDatabase. Based on the size distribution of the impactors (known from astronomical surveys (Heinze *et al*., 2021) and crater size frequency distribution on the Moon (Fassett, 2016), it can be estimated how many craters should be observable on the Earth due to recent impacts (Hergarten and Kenkmann, 2015). extracting this from the number of observed ones, the values for the "missing" ones arises. The red area indicates the studied timeframe, between 10 ka and 1.5 Ma.).

In general, according to the calculations, the impact of a 500 m diameter asteroid in the marine environment could inject 1,011 tons of water into the atmosphere (Gisler *et al*., 2003). Such an event may well have happened more than once in the last million years. The impact of a 1 km diameter asteroid produces a global level of ozone destruction comparable to the so-called ozone hole discovered in the 1990s, while a 500 m body's impact results in ozone depletion confined mainly to a half hemisphere (Pierazo *et al*., 2010). In this particular case, the Eltanin impact might eject a large amount of water vapour and salt into the atmosphere, thereby increasing the albedo effect, depleting the ozone layer and causing surface acidification by sulphur and vaporized water (Goff *et al*., 2012). Although the suggested time period for the impact overlaps the Pliocene/Pleistocene climate transition, an event marked by major glaciation in the Northern Hemisphere, the cooling effect of such an impact remains questionable; i.e., the atmospheric H2O along with dust might trigger either warming (via the greenhouse effect) or cooling (brought about by ice clouds).

The Eltanin event is not only useful as a reference point for understanding the long-term climate influence of an asteroid impact but also a starting point for understanding the problems related to investigating the effect of an impact in a marine environment. Among the around 170 known impact craters, only 15-20 are found in a marine environment (Shuvalov and Trubestkaya, 2002), partly because of the general relative youth of the oceanic lithosphere, combined with a lack of detailed knowledge about the sea floor. Using theoretical calculations and laboratory tests (Davison and Collins, 2007), it has been estimated that craters of around ten times the diameter of the impactor could be vaporized into the ocean water. In theory, in the last 100 million years, about 150 impacts in oceans would have produced 5-20 km diameter craters. About two-thirds of the <1 km diameter craters can be studied on the ocean floor, and about one-third of 30 km diameter craters, too. For example, in the case of the Eltanin impact, not a crater but only a chaotically mixed region could be identified in the Bellingshaisen Sea (Gersonde, 1997). A relatively recent event of this type is the so-called 4 kyr BP impact, that has long been confused with a climatic or volcanic event (Courty *et al*., 2007). This event was recently identified as the impact (or a multi-impact event), in which at least part of the impact in object hit water-covered areas.

3.3.1. A chain of stochastic events during the Early Middle Pleistocene Transition – a case study

Orbital forcing is accepted as the driver behind the multi-millennial climate cyclicity of the Pleistocene period climatic cycles generally. Such cyclicity has a characteristic switch around the early Middle Pleistocene period, described as EMPT, the great global reorganisation of climate including some characteristic steps from MIS 20 to MIS18 (~850 to 650 ka) (Heslop *et al*., 2002) (Figure 3). However, the cause of the shift from dominant 40 kyr to 100 kyr oscillations and increase in oscillation amplitude at the EMPT is not yet understood. It is especially critical to determine this, as the shift to 100 kyr high amplitude cycles is not marked by a corresponding change in orbital forcing, and the 100 kyr orbital cycle is the weakest cycle in terms of affecting the amount of insolation received at the Earth's surface (Maslin and Brierly, 2015). This 100 kyr cycle dominance in the post EMPT climate is often referred to as the '100 ka paradox', as no explanation for this has been agreed upon. A key theory argues that the EMPT was caused by changing the internal response of the global carbon cycle to orbital forcing. This change allowed increased ice sheet growth in the Northern Hemisphere, preventing obliquity-driven increased heat transport northward from melting them (Maslin and Brierly, 2015). A recent model describes the transition as "ramping with frequency locking" (RFL; Nyman and Ditlevsen, 2019); i.e., the periodicity change can be characterized by a long-term (ca. 1Ma) transition, in which the periodicity changes gradually (from a 40 to 80 ka period over one million years). However, this transition period consists of shorter frequency locking periods (no change in periodicity), separated by jumps (Figure 3b). Although the model provides a novel explanation about the nature of the EMPT, the mechanism behind the "jumps" between the frequency locking phases have not been fully explained. This means that a fundamental component for understanding this transition is unknown. The model emphasizes the rapid change in atmospheric CO2 as a potential driver of the jumps and the EMPT, but there is no physical explanation behind this theory.

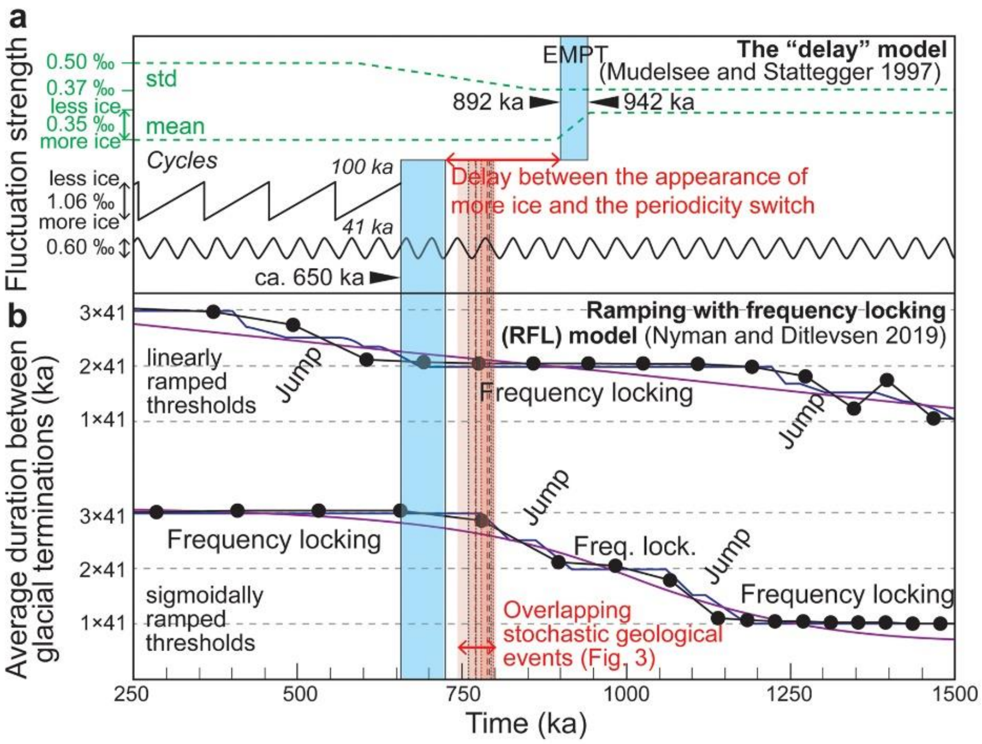

Figure 3. The characteristics of EMPT (after, Mudelsee and Stattegger, 1997; Maslin and Brierly, 2015; and Nyman and Ditlevsen, 2019). a) The results of a time-series analysis of δ18O (ice volume) data and orbital parameters. Based on model a), the EMPT is indicated by a transition in the time-dependent mean (the upper blue bar) toward higher ice volumes (higher δ18O values). The time series analysis indicates a ca. 200 ka long delay (the difference between the two blue bars, marked by a red double-ended arrow) between the significant increase in the global ice volume and the switch between the 41 and 100 ka periods, indicated by the time-dependent std (the lower blue bar). The delay includes the period of overlapping stochastic events (the red bar and vertical dotted and dashed lines). Based on model b), the EMPT is a gradual change, which consists of frequency locking phases and rapid jumps, representing changing climate variables driving the EMPT or its consequences (Nyman and Ditlevsen, 2019). Some of the rapid jumps seems to be connected to the stochastic geological events (red bar and vertical lines), appearing in the studied timeframe (MIS20-18) (for a detailed explanation, see Figure 4 and Section 3.3.1). The various curves on the diagram indicate the average duration between glacial terminations, calculated by various mathematical methods (Nyman and Ditlevsen, 2019). Both models a) and b) consist of a key period (a – delay; b – jump) that has not been explained yet and may be connected to the appearance of stochastic geological events.

Our research proposes a novel hypothesis: the superposition of random geological events (see below) drives the climate system to reach a threshold where the periodicity switch or the suggested jumps in frequency occur (Figure 3 and 4). Some theories already suggest a threshold-driven switch but, besides the model, no convincing explanation has been provided (Maslin and Brierly, 2015). A series of meteorite impacts, including ones with potential global influence, have been identified at the same time as the EMPT (~850 to 680 ka), as indicated by the Belize tektite/Pantasma impact (Rochette *et al.*, 2019) and the Australasian strewn field (Prasad *et al.*, 2007; Schwartz *et al.*, 2016; Sieh *et al.*, 2020; and the references therein) (Figure 3 and 4, I[I] and II[II]). Based on the size of the strewn field, and the possible impact crater(s), the estimated energy of the meteorite impacts was sufficient to exert severe global effects (Earth Impact Effects Program – Marcus *et al.*, 2004 and Collins *et al.*, 2010; and Toon *et al.*, 1997). Furthermore, the first supervolcano eruption of Toba occurred closet to the EMPT and might also have strengthened the influence of these meteorite impacts (Lee *et al.*, 2004) (Figure 4, T). Indeed, both meteorite strikes, and volcanic eruptions can cause significant cooling (e.g., McCormic *et al.*, 1995; Toon *et al.*, 1997; Rampino, 2002; Ward, 2009; Soreghan *et al.*, 2019). Firstly, dust injection into the atmosphere modifies the albedo by affecting the cloud coverage via an elevated number of condensation nuclei (Saunders *et al.*, 2007). Secondly, the atmospheric loading of submicron size aerosols caused by an impact or eruption can cause a "volcanic winter" via direct radiative forcing effects, with a global cooling of 3-5°C and regional cooling of up to 15°C (Rampino, 2002). The cooling triggered by the overlapping stochastic events may cause the "rapid jump" (which, based on the model indicates rapid climatic change, but has no physical explanation yet), and appears in the RFL model at around 800-750 ka, immediately prior to the stabilization of the ca. 100 ka climatic period (Nyman and Ditlevsen, 2019) (Figure 3b).

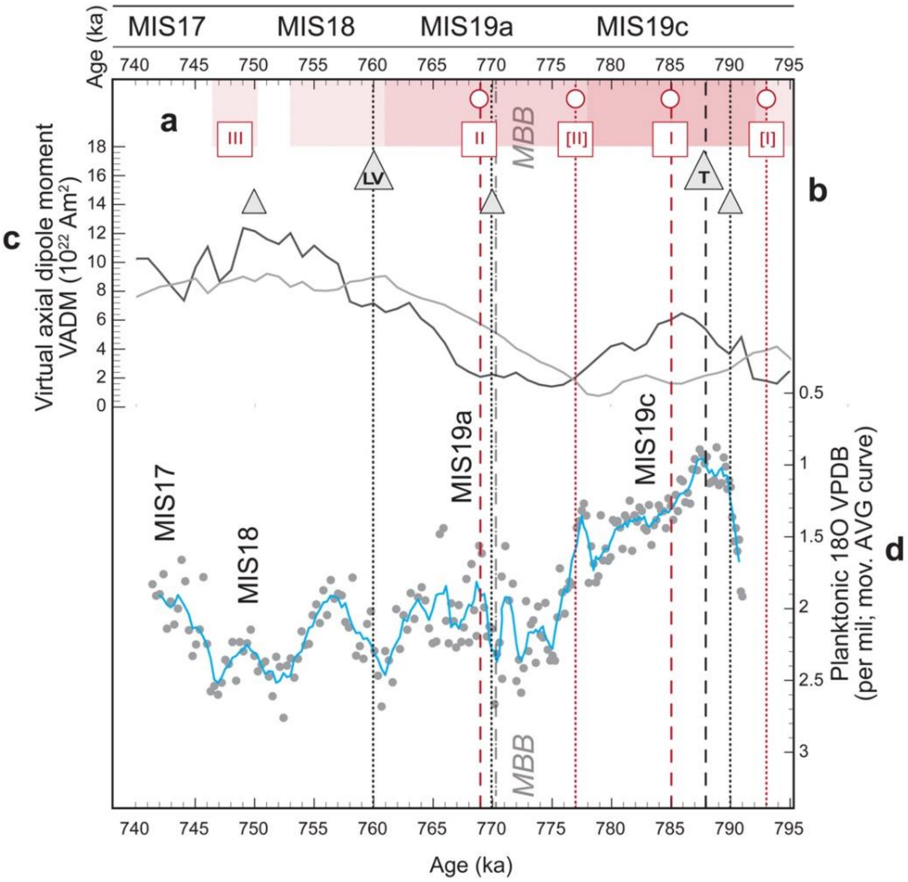

Figure 4. The appearance of the stochastic geological events during the final step of EMPT. The known impact events (a) and VEI8 and 7 scale volcanic eruptions (b) are indicated by I, [I]-Australites, Indochinites and Western Canadian tektite and II-Belize impact (785±7 ka and 769±16 ka) (Prasad *et al.*, 2007; Schwarz *et al.*, 2016; Rochette *et al.*, 2019; III-Luochuan tektite (Li *et al.*, 1993; Zhou and Shackleton, 1999). The pink/red areas (e, that also appear in Figure 3b) indicate the potential appearance of meteoritic materials with the potential impacts (I-III) and supervolcano-, (grey triangles, based on VOGRIPA-Volcanic Global Risk Identification and Analysis Project database); e.g., the Long Valley (LV) eruption (c.a., 760 ka) and Toba (T) eruption (788±2.2 ka) (Lee *et al.*, 2004). The impact events are indicated by the Australasian strewn field (australites and indochinites), Western Canadian tektite (Schwarz *et al.*, 2016) and the Belize impact glass (Prasad *et al.*, 2007). The australites are dated to 789 ± 9 ka, while the age of the indochinites is 783 ± 5 ka, the Western Canadian tektites 783 ± 17 ka, and the Belize tektite/Pantasma impact seems to have happened around 769 ± 16 ka (Schwarz *et al.*, 2016) or 815 ± 11 ka ago (Rochette *et al.*, 2019). No clear impact crater of the proposed Australasian impact event has yet convincingly been identified (e.g., Glass and Koeberl 2006; Prasad *et al.*, 2007; Mizera *et al.*, 2016; Sieh *et al.*, 2020; and the references therein). There are two additional types of geological events which might have strengthened the influence of any multiple meteorite impact in the time period of the EMPT. The Toba (Indonesia, Sumatra, 788 ± 2.2 ka; Lee *et al.*, 2004) and the Long Valley (Bishop Tuff, USA, California, ~760 ka; Smithsonian Pleistocene Database, 2010) supervolcano eruptions happened after the Australasian impact. The change in the geomagnetic field is indicated by the VADM (Virtual Axial Dipole Moment) data from Channell et al. (2009) (dark grey curve; PISO-1500) and Guyodo and Valet (1999) (light grey curve; Sint-800) (c). MBB - Matuyama Brunhes Boundary (778±1.7 - Tauxe et al. 1996; 770±7.3 - Suganuma et al., 2015). Marine 18O curve (d) is from Ferretti *et al*. (2015).

In addition to the chain of asteroid impacts and supervolcano eruption, the increasing cosmic ray flux, associated with the weakening of the geomagnetic field, might exert an observable influence on the (paleo)climate, as suggested by the Svensmark theory (Svensmark and Friis-Christensen, 1997). The climatic influence might appear during the period of geomagnetic change, such as the Matuyama/Jaramillo and Matuyama/Brunhes geomagnetic polarity reversals (Kitaba *et al*., 2013, and 2017). During the Matuyama-Brunhes geomagnetic reversal (Matuyama-Brunhes Transition, MBT)—the overlapping period of the chain of asteroid impacts and the supervolcano eruption suggested above—, the weakening of the geomagnetic field led to an increase in the GCR flux.

The growing GCR may increase low-level clouds (Svensmark hypothesis), which increases the albedo and decreases the temperature. This is called the Umbrella effect, and its climatic influence, i.e., ~6 to 9 °C cooling of the global climate, has already been identified in various records (Kitaba *et al*., 2017). In the loess profile of the Chinese Loess Plateau (CLP), which is a commonly used terrestrial record, the intensification of the East Asian winter monsoon and cooling were observed during MIS19 around the MBT, which suggests the appearance of the Umbrella effect (Ueno *et al*., 2019).

Despite the study of Marsh and Svensmark (2000), which describes the connection between cosmic ray flux and cloud formation and the possible evidence from various geological sections (Kitaba *et al*., 2013; Ueno *et al.*, 2019), the relevance of this theory has been questioned by various studies, such as Sloan and Wolfendale (2008) and Erlykin and Wolfendale (2011). Although the described physical mechanism behind the cloud formation is plausible (Tinsley, 2000; Svensmark *et al.*, 2009), it has not yet been established (Wagner *et al.*, 2001; Pierce and Adams, 2009), and the results of models that aimed to verify or deny the theory are still insufficiently convincing (Duplissy *et al.*, 2010, Kirkby *et al*., 2011). Despite the studies of Kitaba *et al.* (2013, 2017) and Ueno *et al.* (2019), no direct connection has been found between the fluctuation of the magnetic field and the paleoclimate (Suganuma *et al*., 2018), and even the existence of the long-term climatic influence of the galactic cosmic ray flux has been questioned as well (Lanci *et al*., 2020).

However, whilst compelling, detailed evidence to support this possibility is currently lacking, the analysis of the markers of the stochastic events for this period has not been fully conducted yet, and further results are needed (e.g., computer simulations, geological and geomorphological studies, etc.).

4. Conclusion

During the last decade, an increasing amount of attention has been paid to multi-hazards in environmental disaster studies. Despite the increasing number of multi-hazard studies, the majority focus on the appearance, interaction and effect of natural hazards in the same region. There is considerably less investigation of global-scale, multi-hazard events and their potential global climatic impact. Seeking to closing this gap, our study focused on the identification of periods in the last 1.5 million year of the Pleistocene epoch, with the quasi-parallel appearance of natural hazards; i.e., asteroid impacts and large, VEI 8 and 7 volcanic eruptions with the potential to trigger long-term global-scale paleoenvironmental changes.

Of the seven potential multi-hazard events identified, three were considered as possible global-scale events with a lo3nger term environmental (paleoclimatic) influence, which dated back to c.a. 1.4 (marine isotope stage – MIS45), 1.0 Ma (MIS 27), and 100 ka (MIS 5c), respectively. Two additional periods, (around 50ka – MIS3; and 20 ka – MIS2), were identified as being linked to multi-hazard events, which might have caused the “Little Ice Age (or stadial)-like” climatic episode during the Late Pleistocene period.

In addition to the identified potential multi-hazards, a theory about the complex climatic response to global-scale, multi-hazard events, which consists of a series of asteroid impacts and volcanic eruption, was introduced. The series of events, accompanied by possible global cooling appearing around a geomagnetic polarity change, namely the Matuyama-Brunhes Boundary, might have contributed to the final cooling step of the Early Middle Pleistocene Transition, a period during which the length of the glacial-interglacial periods shifted from dominant 40 kyr to 100 kyr oscillations.

We believe that our study may function as a “starting line” for studies focusing on a detailed investigation of “paleo multi-hazard events”, assigned by our data-mining approach. Such studies may reveal more paleoenvironmental-paleoclimatic information and build new theories about multi-hazard events in the future.

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