The Alvarez impact theory of mass extinction; limits to its applicability and the “great expectations syndrome”

GRZEGORZ RACKI

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For the past three decades, the Alvarez impact theory of mass extinction, causally related to catastrophic meteorite impacts, has been recurrently applied to multiple extinction boundaries. However, these multidisciplinary research efforts across the globe have been largely unsuccessful to date, with one outstanding exception: the Cretaceous–Paleogene boundary. The unicausal impact scenario as a leading explanation, when applied to the complex fossil record, has resulted in force-fitting of data and interpretations (“great expectations syndrome”). The misunderstandings can be grouped at three successive levels of the testing process, and involve the unreflective application of the impact paradigm: (i) *factual misidentification*, i.e., an erroneous or indefinite recognition of the extraterrestrial record in sedimentological, physical and geochemical contexts, (ii) *correlative misinterpretation* of the adequately documented impact signals due to their incorrect dating, and (iii) *causal overestimation* when the proved impact characteristics are doubtful as a sufficient trigger of a contemporaneous global cosmic catastrophe. Examples of uncritical belief in the simple cause-effect scenario for the Frasnian–Famennian, Permian–Triassic, and Triassic–Jurassic (and the Eifelian–Givetian and Paleocene–Eocene as well) global events include mostly item-1 pitfalls (factual misidentification), with Ir enrichments and shocked minerals frequently misidentified. Therefore, these mass extinctions are still at the first test level, and only the F–F extinction is potentially seen in the context of item-2, the interpretative step, because of the possible causative link with the Siljan Ring crater (53 km in diameter). The erratically recognized cratering signature is often marked by large timing and size uncertainties, and item-3, the advanced causal inference, is in fact limited to clustered impacts that clearly predate major mass extinctions. The multi-impact lag-time pattern is particularly clear in the Late Triassic, when the largest (100 km diameter) Manicouagan crater was possibly concurrent with the end-Carnian extinction (or with the late Norian tetrapod turnover on an alternative time scale). The relatively small crater sizes and cratonic (crystalline rock basement) setting of these two craters further suggest the strongly insufficient extraterrestrial trigger of worldwide environmental traumas. However, to discuss the kill potential of impact events in a more robust fashion, their location and timing, vulnerability factors, especially target geology and palaeogeography in the context of associated climate-active volatile fluxes, should to be rigorously assessed. The current lack of conclusive impact evidence synchronous with most mass extinctions may still be somewhat misleading due to the predicted large set of undiscovered craters, particularly in light of the obscured record of oceanic impact events.

Key words: Bolide impacts, extraterrestrial markers, impact craters, mass extinctions, Cretaceous–Paleogene boundary, Triassic–Jurassic boundary, Frasnian–Famennian boundary.

Grzegorz Racki [grzegorz.racki@us.edu.pl], Department of Earth Sciences, Silesian University, ul. Będzińska 60, PL-41-200 Sosnowiec, Poland.

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Introduction

Initially, the impact theory of mass extinction (or the theory of impact crises) was outlined in the outstanding 1980 *Science* paper by the Alvarez group, who presented reasonable geochemical evidence of a massive meteorite impact (i.e., abnormally high iridium abundances) and a spectacular scenario of an impact-induced environmental disaster recorded in the thin boundary clay at the Cretaceous–Paleogene boundary (K–Pg; formerly K–T), dated at ~65.5 Ma. This theory was first formally introduced in the next papers by Alvarez and co-authors (1982, 1984, 1989); they confirmed the theoretical palaeontological prediction of the worldwide cataclysm reflected in instantaneous mortality among numerous, unrelated groups of fossil organisms exactly at the Ir anomaly horizon, synchronous with the K–Pg boundary.

The ~170 km diameter Chicxulub crater, buried under more than 1 km of post-impact sedimentary succession (Hildebrand et al. 1991; see current data in www.passc.net/EarthImpactDatabase/chicxulub.html), has provided strong

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evidence of a K–Pg boundary impact event, in showing that an asteroid ~10 km in diameter struck the carbonate- and evaporate-rich target substratum on Yucatán peninsula in southern Mexico. Three decades of multidisciplinary studies around the globe have revealed the worldwide distribution of a unique geochemical and mineralogical signature paired with the synchronous fallout from stratospheric dust. There are multiple lines of evidence, including high-resolution Ir peaks and a variety of other chemical and physical features that originated from the impact event, such as shocked minerals, glassy spherules, Ni-rich spinels, osmium isotopes (^{187}Os/^{188}Os ratios), microdiamonds, amino acids, among others (see summaries in Kyte 2002a; Alvarez 2003; Koeberl 2007; French and Koeberl 2010).

Schulte et al. (2010) summarized thirty years of international research and presented comprehensive support for the Alvarez impact scenario, as proposed for end-Mesozoic ecosystem collapse, and the most amazing demise of non-avian dinosaurs (see also summary of the kill mechanisms in Claeys 2007 and Kring 2007). Of course, as seen in the subsequent debate, some controversy still exists, because a combination of volcanic (Deccan traps) and impact-related, adverse environmental effects remains more plausible to some authors, while others subscribe to the multiple impact hypothesis as opposed to a single giant impact event (Courtillot and Fluteau 2010; Keller et al. 2010; see also e.g., Tsujita 2001; Ellwood et al. 2003a; Chatterjee et al. 2006; Jolley et al. 2010; Kidder and Worsley 2010; Keller 2011).

In the context of the extraterrestrial paradigm, the hot polemics almost instantaneously centred on the issue whether relatively slow-acting, Earth-bound calamities, such as caused by massive volcanism, are an alternative (or a supplement) to the hypervelocity impact-generated killing episodes (see a selection of recent views in Alvarez 2003; Palmer 2003; Morgan et al. 2004; Glikson 2005; Keller 2005, 2011; MacLeod 2005; White and Saunders 2005; Twitchet 2006; Claeys 2007; Kelley 2007; Arens and West 2008; Şengör et al. 2008; Prothero 2009; Kidder and Worsley 2010). Nevertheless, the Alvarez theory has rapidly been established as the leading concept for the K–Pg mass extinction, explaining in addition not only other Phanerozoic biotic crises, but also introducing eventually the new catastrophism paradigm in geosciences (e.g., Berggren and Van Couvering 1984; Alvarez et al. 1989; Hsü 1989; Marvin 1990; Ager 1993; Glen 1994; Palmer 2003; Reimold 2007). Many workers have looked for comparable extraterrestrial evidence at all known extinction horizons and have frequently claimed compelling multi-disciplinary evidence of "impact crises" (see exemplary reviews in McLaren and Goodfellow 1990 and Rampino and Haggerty 1996a). The desperate search for a widespread cosmic signature was most notably a priori reasoned by notion highlight in the popular book of Raup (1991) that no global stress triggers other than different-magnitude impacts could be responsible for both "background" and mass extinctions (see also McLaren and Goodfellow 1990; Raup 1992). This "revolution" in mainstream geosciences and space sciences was also especially striking when paired with purportedly cyclical collisions with Earth-crossing asteroids and comets, as manifested by the "Shiva Hypothesis" of Rampino and Haggerty (1996b), evolving rapidly into "a unified theory of impact crises and mass extinctions" of Rampino et al. (1997) and, finally, into "the galactic theory of mass extinctions" of Rampino (1998). So far, however, periodic astronomic impact on the Earth biosphere as well as periodicity in the terrestrial fossil record have remained a highly controversial matter (see diverse recent ideas in Lewis and Dorne 2006; Gillman and Erenler 2008; Prothero 2009; Bailer-Jones 2011; Feulner 2011; Melott and Bambach 2011).

In consequence, immediately following the hypothesis that the K–Pg biotic turnover was triggered by the collision of a giant asteroid with the Earth, the impact as a general prime cause was comprehensively tested for the "big five" mass extinctions of Phanerozoic marine life (Raup and Sepkoski 1982; see review in Hallam and Wignall 1997; Keller 2005; Alroy 2010). However, the K–Pg boundary clay (= impact ejecta) remains exceptional in preserving abundant impact proxies arranged in a clear proximal-distal palaeogeographic trend (Schulte et al. 2010). This common view is broadly accepted in "classic" monographic works and textbooks by Walliser (1996), Hallam and Wignall (1997), Courtillot (1999), Stanley (1999), and Hallam (2004), and also exemplified in recent overviews by Lucas (2006), Morrow (2006), Kelley (2007), Reimold (2007), McCall (2009), Prothero (2009), French and Koeberl (2010), and Reimold and Jourdan (2012). On the other hand, the major extinction events, particularly the end-Permian apocalyptic catastrophe, remain the subject of continuously intensive exploration for extraterrestrial markers despite previous impressive misinterpretations and pitfalls. As reviewed below, the themes are so attractive to public perception that even erroneous data and vague explanations invariably open doors to the most prestigious journals and mass media (see e.g., Twitchet 2006; cf. "media science"of Officer and Page 1996), but, in fact, only repeatedly increase information noise.

An updated overview of the impact theory applicability is the main goal of the present paper, with examples mostly from the Frasnian–Famennian (F–F), Permian–Triassic (P–T) and Triassic–Jurassic (T–J) global events, and supplementary Eifelian–Givetian and Paleocene–Eocene data, and with the emphasis on the critical terrestrial cratering record [data and images from the Earth Impact Database (EID), www.passc.net/EarthImpactDatabase, managed by the University of New Brunswick, Canada; some ages corrected after Jourdan et al. 2012]. The time scale used is mostly after the International Commission on Stratigraphy Chart 2010 (www.stratigraphy.org/ics%20chart/StratChart2010.pdf).

Abbreviations. —CAMP, Central Atlantic Magmatic Province; E–G, Eifelian–Givetian; EID, Earth Impact Database; ISC, International Commission on Stratigraphy; KW, Kellwasser; PDF, planar deformation features; PETM, Paleocene–Eocene thermal maximum; PGE, platinum group element.

Conclusive and incredible impact tracers

The discovery of Alvarez et al. (1980) has promoted widespread speculation as to whether such cataclysmic extraterrestrial events have had a strong impact on the whole history of life. In fact, key impact indicators have been thoroughly tested and frequently questioned, such as iridium anomalies (widened to high levels of all platinum group elements), spherules and shocked quartz, considered as the original "big three" of the impact paradigm (Alvarez 2003; see also Reimold 2007; French and Koeberl 2010; Koeberl et al. 2012; Reimold and Jourdan 2012). Thus, diagnostic criteria display highly evolving histories, and some of them have proved to be erroneous and have recently been discredited (Table 1), whilst innovative, increasingly consistent proxies are continuously tested, such as He, Os, and Cr isotopes. The value of other proposed tracers is still unclear, exemplified by the magnetic susceptibility field method to identify ejecta horizons (Ellwood et al. 2003c), as shown by two case stories below.

In particular, weak to moderate platinum group enhancements are truly non-diagnostic of extraterrestrial sources because they can also derive from a variety of terrestrial origins (e.g., Evans and Chai 1997). Note that the average Ir value for the Earth's crust is less than 0.1 parts per billion (ppb), whilst K–Pg abundances are at least about two orders of magnitude greater, with the largest anomaly from Denmark, reported by Alvarez et al. (1980), as high as 41.6 ppb (see updated data in Schulte et al. 2010). Iridium contents significantly below that of the K–Pg levels have usually been clarified by Ir-impoverished projectiles or masking sedimentary processes (reworking and dilution of cosmic material; e.g., Rampino et al. 1997), and may be seriously modified by diverse post-impact redistribution mechanisms (see K–Pg anomaly cases in Racki et al. 2011). On the other hand, Kyte (2002b) emphasized that since the chemostratigraphic pattern can be biased during diagenesis, physical tracers such as spinels are restricted to a thin accretionary event horizon.

The impact cratering signature might also be more or less

Table 1. Interpretative status of selected diagnostic criteria for impact identification in the stratigraphic record, mostly in distal settings (for details see Hallam and Wignall 1997; Koeberl and Martinez-Ruiz 2003; Simonson and Glass 2004; Claeys 2007; Reimold 2007; French and Koeberl 2010; see also Racki 1999, Kaiho et al. 2006b, Newton and Bottrell 2007; Algeo et al. 2008; Racki et al. 2011; Koeberl et al. 2012; Glass and Simonson 2012; Reimold and Jourdan 2012).

Diagnostic character	Postulated impact or impact-related character	Alternative non-impact interpretation
DIRECT IMPACT SIGNATURE		
Craters	Site of hypervelocity meteorite strike	Lacking
Abundant shocked quartz grains with multiple planar deformation features (PDFs)	A momentary enormous release of energy in the form of pressure of 10–30 GPa recorded in unmelted ejecta	Lacking
Iridium and other platinum group elements (PGEs) in chondritic ratios	An extraterrestrial component, mostly distributed in stratospheric dust	Microbial concentration, volcano-hydrothermal activity, post-depositional redistribution, anoxia, incorporation of ultramafic rocks (but in non-chondritic PGE pattern)
Glassy spherules	Ballistically ejected droplets of melted target rock and condensed rock vapor clouds: glassy (microtektites) or a combination of glass and crystals grown in flight (microkrystites)	Meteorite ablation debris (?also volcanic droplets and artificial contaminants, such as products of metallurgical processes)
Fullerenes-caged noble gases with planetary isotopic ratios (^{3}He)	Preserved component of impacting body	Contamination from natural mantle-derived He
^{3}He signal in sediments	Input of extraterrestrial material (especially crucial for comet showers)	Contamination from natural mantle-derived He
Excess siderophile element (Ni, Co) and Cr, Au, signatures	Chemical signature from the projectile (see PGEs)	Enrichment in target rocks and re-concentration by post-impact hydrothermal activity
Ni-rich spinels	A component directly derived from the projectile	Lacking
INDIRECT IMPACT-RELATED SIGNATURE		
Large negative δ^{13}C excursions	Collapse of primary productivity (the dead Strangelove Ocean model)	Methane ejections due to hydrate melting or freshwater diagenesis, disruptions of the global carbon cycle
Large negative δ^{34}S excursion	Gigantic release of "light" sulfur from the mantle or sulfide-rich deposits, or an overturn of a stratified H_2S-dominated ocean	Abrupt climatic change resulting in a drastic mixing event or sulfide-flux events due to chemo-cline-upward excursion in a super-stagnant ocean, volcanism
Thick and widely distributed coarse-grained deposits	Impact-induced tsunami waves	Seismically induced tsunami or extremely violent storm events, fault, volcanism, submarine channel infill at times of falling sea level

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obliterated by large-scale geologic processes, in particular plate subduction (e.g., Claeys 2007), and therefore the extra-crater cosmic signal could survive solely in the form of spherule horizons and/or PGEs enhancements in pre-Mesozoic settings (e.g., Simonson and Glass 2004; Glass and Simonson 2012). This low preservation potential is particularly envisaged for "crater-less", deep-oceanic impacts (Dypvik and Jansa 2003; Kent et al. 2003a, b), and a low-Ir comet shower into the ocean was mooted as an attractive alternative explanation for an alleged, but Ir-poor, impact horizon (e.g., Jansa 1993; Rampino and Haggerty 1996a). However, the geochemical signature of asteroids and comets, and many other extraterrestrial indicators overall is similar in both subaerial and submarine impacts (Dypvik and Jansa 2003; Koeberl 2007); a main exception is near absence of the shocked quartz grains because of basaltic oceanic crust as a main target (e.g., Simonson and Glass 2004; Claeys 2007).

This case is exemplified by the single identified abyssal Eltanin asteroid impact into a 4 km deep Antarctic Ocean, where Pliocene impact-disturbed ejecta-rich sediments contain Ir at abundances comparable with those of the K–Pg anomaly (Gersonde et al. 2002; Kyte 2002a). Hassler and Simonson (2001) claimed that an association of distinctive sedimentary features indicating high-energy regimes, as a result of the impact-triggered tsunami, represents the best data base on the reworked distal record of large-body oceanic impacts (see reviews of tsunami modelling in Wünnemann et al. 2010 and Gisler et al. 2011). Furthermore, these experimental and theoretical studies have also improved our understanding of cratering processes and their preservation in open-ocean basins (see also Gersonde et al. 2002; Davison and Collins 2007; Shuvalov et al. 2008). Craters can be produced in the oceanic crust exclusively if the projectile is large-sized enough compared to the target water depth, although their structure and morphology can diverge from the land counterparts. For example, in the case of vertical impact events at 20 km/s, these morphologic scars are formed when the oceanic basin depth is ca. 5–7 times less than the projectile size (Gisler et al. 2011). In fact, Davison and Collins (2007: 1925) found that, "the effect of the Earth's oceans is to reduce the number of craters smaller than 1 km in diameter by about two-thirds, the number of craters >30 km in diameter by about one-third, and that for craters larger than >100 km in diameter, the oceans have little effect".

The "great expectations syndrome"

As discussed by Tsujita (2001), the single-cause impact hypothesis, when applied as a paradigm, can lead to force-fitting of subsequent observations and elucidations, appropriately referred to as the "great expectations syndrome". An informative tale to the scientific community has been presented in detail by Pintera et al. (2011); they critically analyzed the Younger Dryas impact hypothesis to account for the decline of Pleistocene megafauna and collapse of the Clovis culture. Twelve main markers, acknowledged originally as signatures of a catastrophic bolide strike 12 900 years ago, have been either (i) largely rejected (e.g., impact structure; magnetic nodules in bones; elevated levels of radioactivity, iridium, and fullerenes) or (ii) suspected as representing terrestrial sources (e.g., carbon and magnetic spherules, byproducts of catastrophic wildfire, nanodiamonds). Furthermore, most of the alleged impact proxies have hitherto been demonstrated to be non-reproducible because the fingerprints have been misunderstood as single synchronous spikes, although they probably resulted from inadequate sampling methods (for details, see Pintera et al. 2011 and also Pigatia et al. 2012).

In the context of this quasi-actualistic case study, and topics raised by Morrow (2006), Twitchet (2006), Claeys (2007), Reimold (2007) and French and Koeberl (2010), among others, a refined evaluative approach to proper recognition of extraterrestrial records is proposed. The misunderstanding and misinterpretation symptoms are in fact elements in the succession of three, partially overlapping, testing levels (Fig. 1):

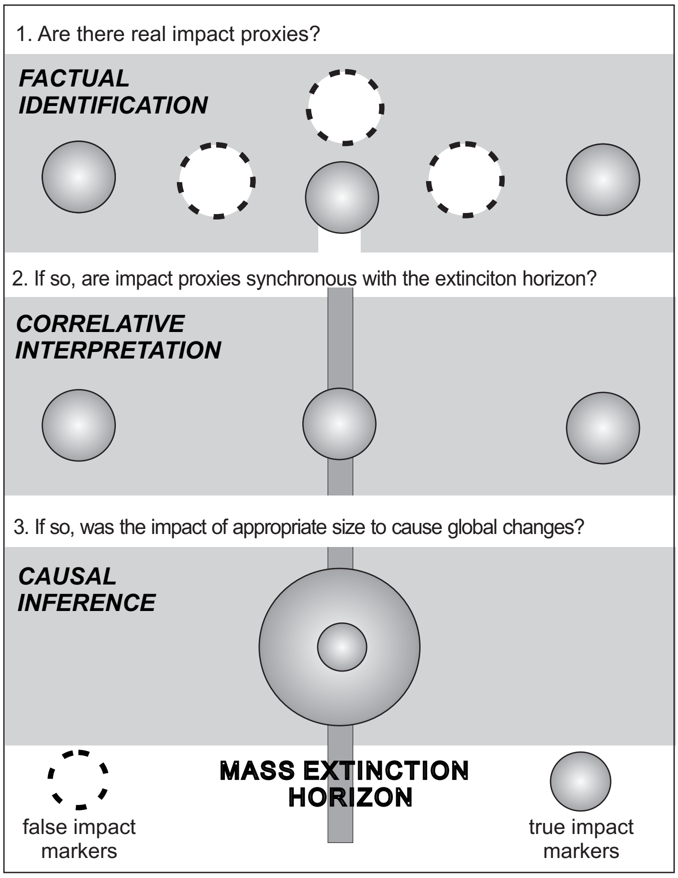

Fig. 1. Scheme of the three successive levels in the testing process, encompassing application of the Alvarez impact theory of mass extinction, and possible errors resulting from the "great expectations syndrome" (sensu Tsujita 2001).

1. *Factual misidentification*: i.e., an erroneous or indefinite recognition of the extraterrestrial record in sedimentological, physical and geochemical contexts. French and Koeberl (2010: 157) distinguished three types of errors that are typically involved in impact studies: (i) incorrect identification of normal petrographic and mineralogical features (e.g., random or non-parallel fracturing in quartz); (ii) the application of non-diagnostic criteria (e.g., brecciation); and (iii) the use of new, but unconfirmed, characters (e.g., fullerenes with trapped He).

2. *Correlative misinterpretation*: the impact marker identification is convincing, but interpretation of its timing is wrong or appears to be inaccurate in the light of more constrained dating, which decisively precludes the granted causes and effects. This prerequisite is crucial especially for meteorite craters. As reviewed by Jourdan et al. (2009, 2012), precise and accurate radiometric dating of impact structures needs essential qualitative and quantitative improvements, as demonstrated by many misleading ages and/or extensive age uncertainties. A more integrated approach is called for, such as the palaeogeographic method of Schmieder and Buchner (2008). According to Morrow (2006: 314), "a major challenge of impact studies is correlating distal evidence of an event to its source crater, which often may be undiscovered or may have been obscured or destroyed by active Earth processes (…) confidently tying distal effects to a specific crater requires a sophisticated integration of high-resolution stratigraphic, biostratigraphic, radiometric, petrographic, and geochemical fingerprinting technique". Thus, identification of precisely dated ejecta and/or extra-crater sedimentary record (tsunamites) and their source crater is the most significant aim when trying to connect an extraterrestrial event with a biotic crisis (see heavy mineral correlation techniques in Thackrey et al. 2009). This is precisely the problem raised for the Chicxulub impact crater by Keller (2005, 2011); however, impact-related shelf margin collapses, large-scale mass movements and fluidization of sediments are processes that bias interpretation of surrounding depositional areas (see Hassler and Simonson 2001; Dypvik and Jansa 2003; Schieber and Over 2005; Claeys 2007; Kring 2007; Purnell 2009; Schulte et al. 2010).

3. *Causal overestimation*: the crater (or craters) and/or other extraterrestrial tracers are approved to be coincident with the biodiversity decline and other ecosystem collapse attributes. However, the established impact size and predicted destructive effects were clearly insufficient to trigger a major, global deterioration of life (see below). Note that Alvarez et al. (1980) rightly estimated the size of the impacting object using exclusively the scale of anomalous iridium values, and three other independent sets of observations.

Both demands of high correlation precision and impact magnitude threshold are invalid if many smaller collisions had cumulative adverse climate-environmental effects over several million years, leading finally to mass extinction (lag-time multiple impact hypothesis of McGhee 2001, 2005; see criticisms in Keller 2005 and Racki 2005). In the scenario of Poag et al. (2002), the impact-produced late Eocene warm pulses would have initially delayed biosphere response by interrupting a long-term cooling trend, which led to the Oligocene stepped extinctions attributable to threshold climatic conditions.

Two case histories

Diverse "great expectation" symptoms are outlined below from four successive mass extinctions, but the mid-Devonian and Paleocene–Eocene boundary examples represent outstanding introductory case histories.

The Eifelian–Givetian boundary.—The Middle to Late Devonian interval comprises several biotic crises, mostly linked with climatic and oceanographic changes, and especially anoxia (see review in Walliser 1996). Impact proxies have been recognized at the Eifelian–Givetian (E–G) boundary in Morocco by Ellwood et al. (2003a; see Fig. 2). Based on a magnetic susceptibility study, an ejecta layer has been proposed, as determined by alleged shocked quartz grains in three sections, in association with microtectites, an enrichment of chalcophile elements and a large-scale negative shift in δ^{13}C.

The mid-Devonian impact was included in some review papers (e.g., Simonson and Glass 2004: table 1), and even its climatic consequences were lastly indicated by Giles (2012). However, the apparent misidentification of the extraterrestrial signature, in particular shock metamorphism, was noted by Racki and Koeberl (2004: 471b), "The images identified by Ellwood et al. [= Ellwood et al. 2003a] (...) as shocked quartz grains are not convincing, and the orientation measurements suffer from an insufficient number of observations" (also French and Koeberl 2010: 151). Sections across the E–G transition in the Ardennes (Belgium) have not yielded impact evidence (Claeys 2004). A succeeding paper by Schmitz et al. (2006), which even includes some members of the Ellwood et al. (2003a) group as co-authors, decisively rejected an extraterrestrial origin of the Moroccan horizon because of low PGE concentrations (e.g., Ir level of 0.28 ppb), coupled with indications that post-depositional redox fronts shaped the chemostratigraphic pattern. This exclusively Earth-bound approach is confirmed in the most recent study on the Moroccan site (Ellwood et al. 2011), where the putative ejecta horizon is seen as a record of a large-scale anoxic/organic carbon burial episode (well known as the Kačák event; Walliser 1996).

The *Science* paper by Ellwood et al. (2003a) is an example of perfectly circular arguments, as highlighted by Racki and Koeberl (2004). The Kačák bio-event is marked by a modest loss of biodiversity (see Fig. 2), interpreted by Walliser (1996) as a third-order global event, largely limited to pelagic biota. Despite this, a mass extinction status for this crisis was surprisingly approved by these authors in their article title, simultaneously with the meteorite impact established at that time. In essence, a supposed impact event was used to propose a mass extinction level in the Devonian stratigraphic record.

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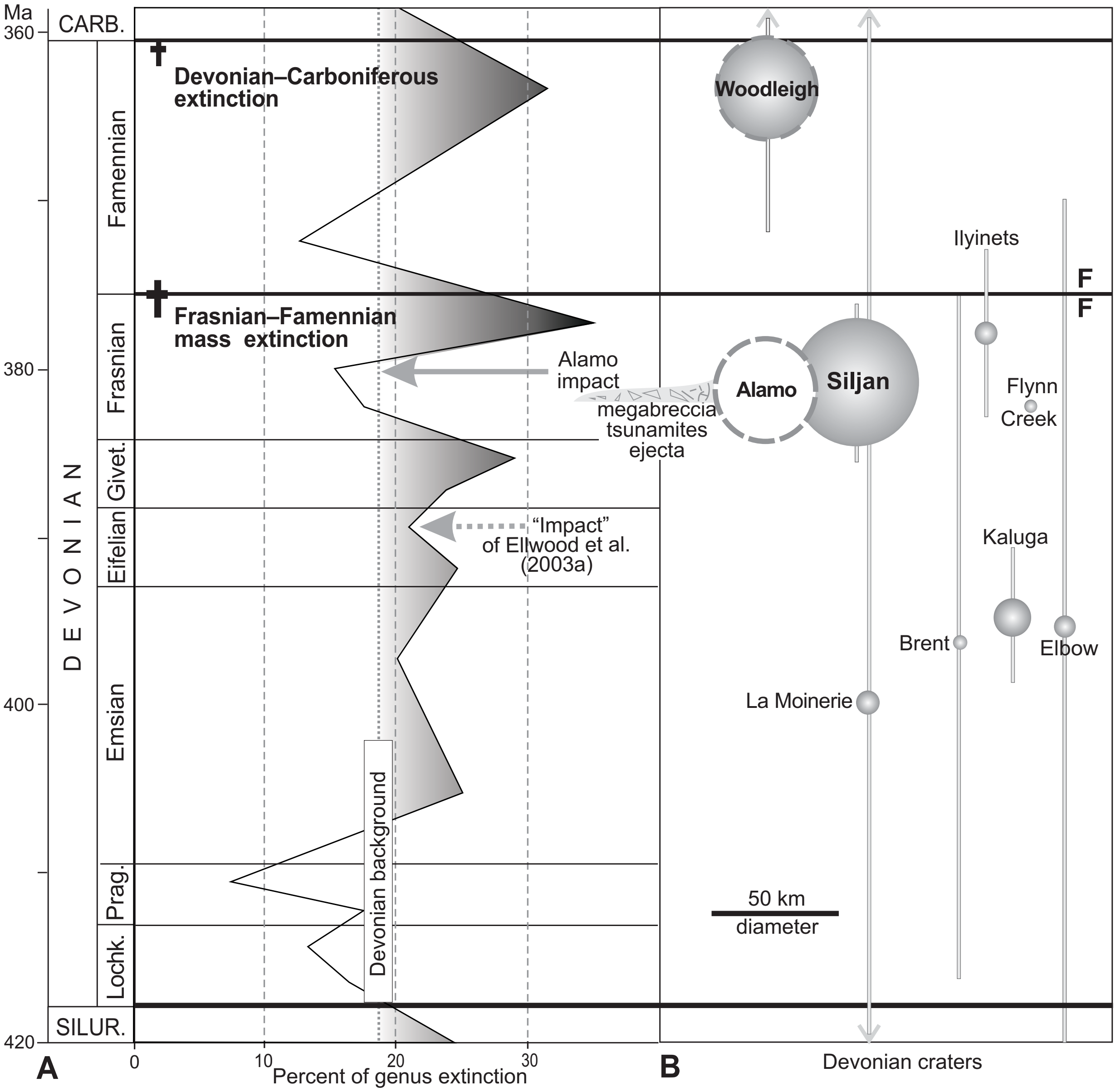

Fig. 2. Crater temporal distribution, with possible record at the F–F boundary (**A**), plotted against Devonian biodiversity losses in terms of substages (**B**), data from Bambach 2006: fig. 1 (used with permission from the *Annual Review of Earth and Planetary Sciences*, Volume 34 © 2006 by Annual Reviews, http://www.annualreviews.org.), re-arranged according to the timescale of Kaufman (2006; see the updated tiiming in Becker et al. 2012; Fig. 4); the reconstructed middle Frasnian Alamo crater is also shown to reveal low biodiversity loss in that time (arrowed), as well as the controversial Woodleigh impact structure (see Fig. 5) and the biostratigraphically dated Flynn Creek submarine crater (Schieber and Over 2005). Vertical lines correspond to possible temporal ranges. Abbreviations: Carb., Carboniferous; Givet., Givetian; Lochk., Lochkovian; Prag., Pragian; Silur, Silurian.

Paleocene–Eocene boundary.—Another characteristic example is found in five papers published mostly in the renowned *Earth and Planetary Science Letters*. Kent et al. (2003a, b) and Cramer and Kent (2005) postulated a comet impact forcing for the Paleocene–Eocene thermal maximum (PETM) and well-known negative carbon isotope excursion, interpreted as result of massive input of isotopically light carbon from a ~10 km volatile-rich projectile. The impact-promoted warming would also probably have initiated a thermal decomposition of marine methane hydrates, and abruptly accelerate climatic changes.

Deep-sea benthic foraminifera suffer the concomitant mass extinction, thought to have caused by corrosive and warmed (and hence oxygen-depleted) bottom waters. As supportive evidence for the devastating oceanic impact, Kent et al. (2003a, b) considered: (i) abnormal abundance of magnetic nano-sized particles, inferred to have originated from an impact-generated plume condensate, (ii) a small, but significant, Ir anomaly (0.14 ppb, in one section only), and (iii) the extremely rapid onset of the initial $\delta^{13}C$ shift (see also Cramer and Kent 2005).

As discussed by Dickens and Francis (2003), all these selectively used, indirect markers seem highly unlikely for a cometary impact across the PETM. In particular, the anomalous content of single-domain magnetite on the coastal shelf can be explained through a sudden accumulation pulse of exhumed, bacterially-derived magnetite grains during fine-grained terrigenous deposition, probably paired with diagenesis in unsteady redox settings. Furthermore, a sole volcanic mechanism is strongly favoured by Schmitz et al. (2004) in the light of comprehensively studied PGE and osmium, helium, and strontium isotopic records, also due to the proved synchroneity of the $\delta^{13}C$ value decrease with the onset of basaltic volcanism. The Ir-enriched volcanic ashes (0.22–0.31 ppb) in the critical interval were related to the major episode of flood basalt eruptions, in connection with the seafloor spreading phase in the high-latitude North Atlantic. Consequently, "there is zero incontrovertible evidence" (Dickens and Francis 2003: 199) for an extraterrestrial trigger of the extraordinary biogeochemical and climatic perturbations in earliest Cenozoic time.

The Late Ordovician mass extinction

The Late Ordovician mass extinction, initiated 445.6 Ma ago, is essentially free of impact evidence, as seen in negligible Ir enrichments (Hallam and Wignall 1997: 57) and microspherules (French and Koeberl 2010: 152). An extra variety of cosmic killing stimulus has been postulated by Melott et al. (2004): gamma ray bursts intensively irradiated the Earth's surface to result in ozone depletion and ultimately lead to disastrous Late Ordovician global cooling.

Surprisingly, asteroid breakup tracers (small-sized craters, extraterrestrial chromite grains, Os isotopes; also worldwide mass movements at continental shelf margins; Purnell 2009) are conspicuous in their frequency in older Ordovician intervals, and Schmitz et al. (2008) argued that the asteroid shower in fact accelerated the Great Ordovician Biodiversification Event. On the other hand, there are several impact craters, the largest being 30 km in diameter, dated at 455–450 Ma, i.e., in the eventful Katian prelude of the global biodiversity change (see Kaljo et al. 2011 and Voldman et al. 2012: fig. 3).

The Late Devonian mass extinction

McLaren (1970) proposed a bolide impact scenario, with giant tsunamis as the main mass killing agent for Frasnian reef biota, but this idea was not considered seriously. An exhaustive search was initiated in the 1980s for evidence of a cosmic catastrophe as the prime cause of the F–F mass extinction [= Kellwasser (KW) crisis; see review in McGhee 1996]. Several

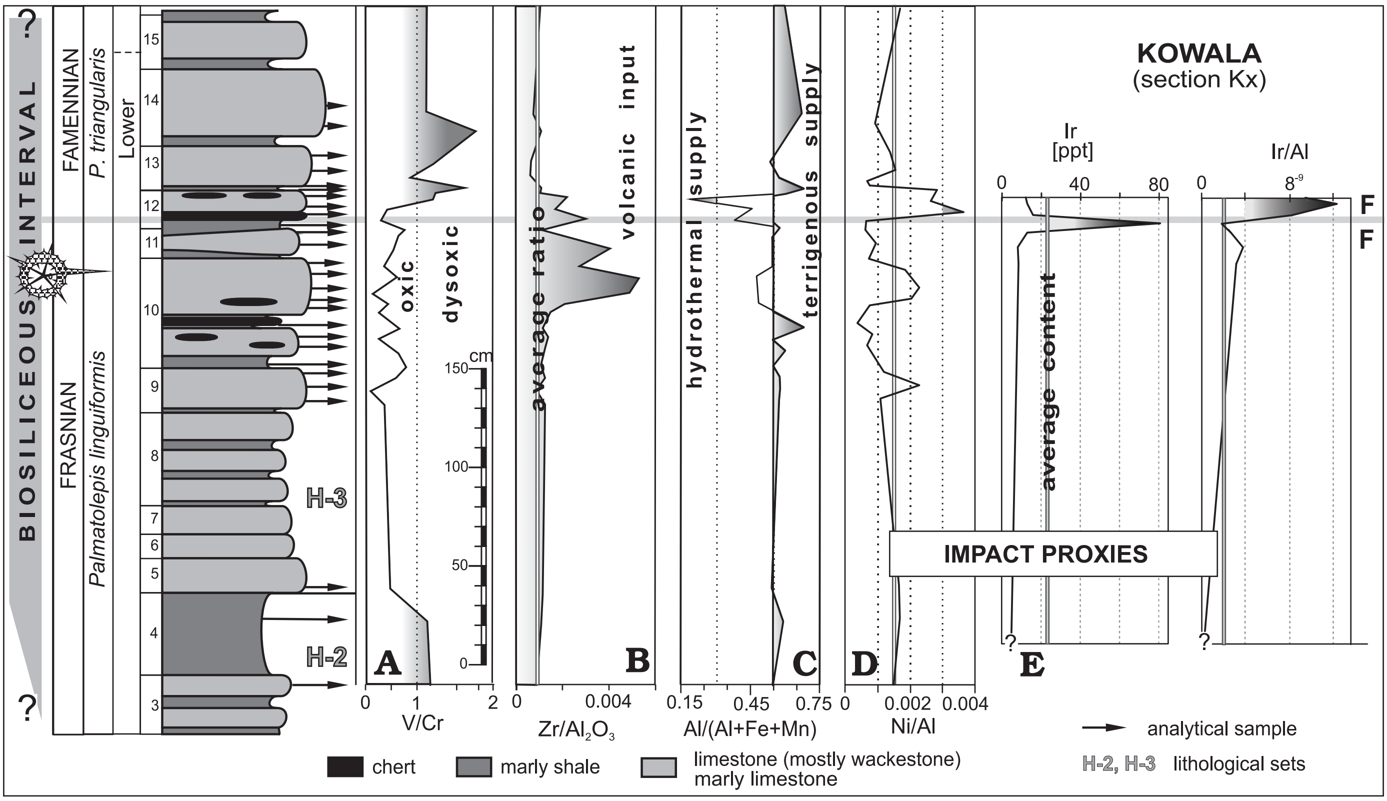

Fig. 3. Extraterrestrial elemental proxy Ir, and supplementary Ni, against other geochemical markers in the F–F boundary beds at Kowala, Holy Cross Mountains (after Racki et al. 2002: fig. 8; used with permission from Elsevier); Ir values from an unpublished report (dated 2004) by Yuichi Hatsukawa and Mohammad Mahmudy Gharaie; Ni contents from Racka (1999: table 2); for other data see references in Racki et al. (2011).

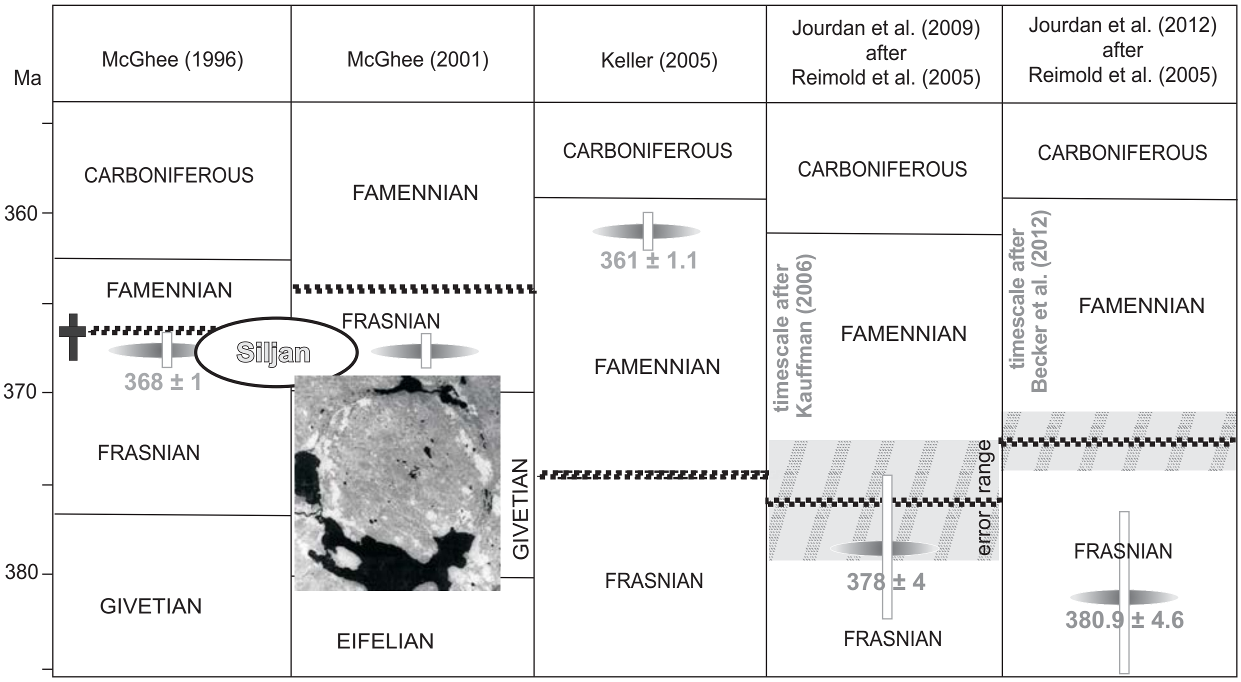

Fig. 4. Evolving timing of the Siljan Ring (53 km diameter; see Fig. 2), depending on different timescales and improved radiometric dates.

assumed extraterrestrial proxies (e.g., negative δ^{13}C excursions and violent high-energy events) were proved to be inconclusive in subsequent studies (Table 1; McGhee 1996; Hallam and Wignall 1997; Racki 1999). In the Luoxiu section, southern China, a fourfold increase in Ir values with a 0.24 ppb spike has been observed to coincide with the F–F boundary (Wang et al. 1991). In the Kowala succession of Poland, a newly recognized eightfold Ir enrichment merely reaches a maximum of 0.08 ppb (Fig. 3). Ir anomalies hitherto reported precisely at the major crisis boundary are causally linked with volcano-hydrothermal sources, sedimentary starvation, redox variations and diagenetic enhancement (Racki 1999; Over 2002; Hatsukawa et al. 2003; see also Ma and Bai 2002; Gordon et al. 2009; Zeng et al. 2011).

An extreme example of Ir enrichment (4 ppb) is seen in the western Canadian Long Rapids Formation, but this is at 85 cm below the F–F boundary (Levman and von Bitter 2002). In fact, PGE anomalies and spherules occur either in the Famennian, postdating the KW crisis by 1.5 Ma, or below the stage boundary (see summary in McGhee 1996). Similarly, four discrete levels of probable microtektites around the F–F boundary in southern China do not seem to be directly associated with the stepwise KW crisis (with only a minor microspherule peak near the F–F boundary; Ma and Bai 2002). What is more, the basal Famennian, Si-rich microtektites from the Ardennes (Claeys et al. 1992) were even suspected to reflect sample contaminants (industrial glass beads; Marini and Casier 1997), but this seems less probable in the light of a comparative compositional study (Marini 2003; Glass and Simonson 2012). More recently, the Os isotopic composition has been shown to lack a significant meteoritic component in F–F passage beds examined in western New York (Gordon et al. 2009). However, a sufficient temporal resolution of the chemostratigraphic signature has been called into question, when this is thought of as proof against the extremely short-term extraterrestrial event (compare the refined end-Cretaceous Os isotopic fingerprinting in Robinson et al. 2009 and low-resolution F–F data in Turgeon et al. 2007).

All Late Devonian craters are well below 100 km in diameter (Fig. 2). The 52.7 km (or 65–75 km; Reimold et al. 2005) diameter Siljan Ring structure in Sweden, has been repeat-

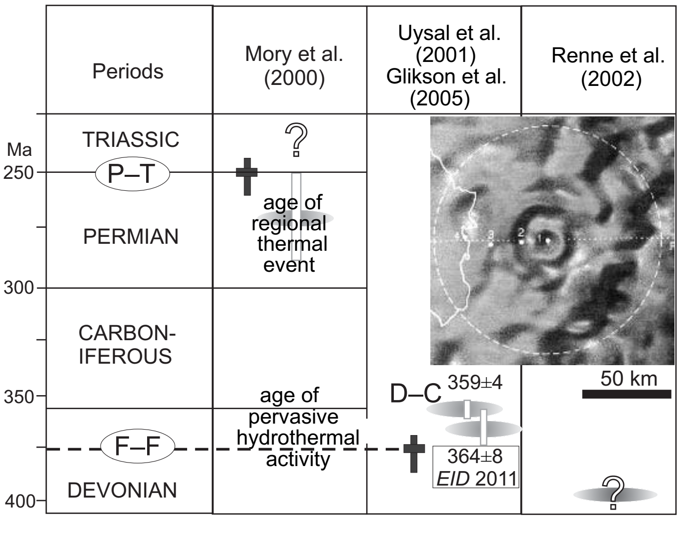

Fig. 5. Evolving timing of the multi-ring Woodleigh impact structure, manifested in purported causal connection with the P–T and F–F mass extinctions, as a reflection of variously dated processes. Age constraints still range from post-Middle Devonian to pre-Early Jurassic, but the connection with the D–C global event seems to be most likely (Glikson et al. 2005).

edly seen as the major F–F impact site since *Nature* paper by Napier and Clube (1979; see Raup 1992; McGhee 1996), but it was variously dated between middle Frasnian to Devonian–Carboniferous transition (Fig. 4). The more recently re-examined laser argon date of Siljan melt breccia (377±2 Ma, Reimold et al. 2005), constrained by Jourdan et al. (2012) to 380.9±4.6 Ma, has doubtfully placed this bolide strike within error at the F–F boundary in the recalibrated Devonian numerical timescales (376.1±3.6 Ma, Kaufman 2006; 372.24±1.63 Ma, Becker et al. 2012). In the light of previous correlative pitfalls, exclusively direct conodont dating of undoubted Siljan impact ejecta will be only decisive, but neither proximal-distal sedimentary effects nor ejecta have been firmly identified: the suspected spherule-bearing level in the Belgian Ardennes distinctly postdates the key time boundary (Claeys et al. 1992; McGhee 1996), and a similar finding above the upper KW level has been noted from Morocco (Ellwood et al. 2003b). On the other hand, several coarse-grained intercalations are known around the F–F boundary in Pomerania, ~700 km south from the Swedish impact site, but these have been attributed to the lowstand collapse of a carbonate platform edge (Matyja and Narkiewicz 1992; see also review in Racki 1999: 618).

Even more questionable is the Woodleigh multi-ring structure in Western Australia (Uysal et al. 2001; Fig. 5). According to Renne et al. (2002: 247), its size is poorly constrained and subject of an ongoing debate (between 40 and 120 km), while the age "could have been much older than mid-Devonian" (see also Hough et al. 2003; Reimold et al. 2003; Glikson et al. 2005; Uysal et al. 2005).

Consequently, a multiple impact scenario, complementary to the ecosystem destabilization due to Earth-derived stresses, is hypothesized as the only option able to explain the observed data (see discussion in McGhee 1996; also Sandberg et al. 2002; Alvarez 2003). As a meaningful alternative to the sole impact hypothesis, McGhee (2001, 2005) speculated that the stepwise F–F extinctions were triggered by a rapid drop in global temperature (impact winter) that followed on an anomalous greenhouse interval caused by several mid-Frasnian impacts. However, this climate prognosis is not supported by the palaeotemperature curve of Joachimski et al. (2009) that shows a gradual Frasnian warming trend (see also Keller 2005). In fact, such proponents of lag-time biotic response have failed to provide a trustworthy model for why impacts should be cumulative over millions of years in their deteriorating effect (Reimold 2007; Prothero 2009).

The impact theme is still referred to in Late Devonian extinction studies (Casier and Lethiers 2002; Sandberg et al. 2002; Ellwood et al. 2003b; McGhee 2005; Du et al. 2008; Zeng et al. 2011). Thus, Alvarez (2003: 155, table 1) considered this epoch to have been characterized by "(…) substantial evidence of impact in that ca. 16 Myr interval" (see also Glikson 2005). There is overall consensus, however, that the destructive impact of extraterrestrial catastrophic factors on the generally stressed Frasnian marine biosphere was unlikely (Racki 1999, 2005; Ma and Bai 2002; Reimold et al. 2005; Morrow 2006; Gordon et al. 2009). Still, the final conclusion by McGhee (1996: 244) is compelling: "It is thus puzzling, and not a little frustrating, to note at this point the best evidence yet produced in the worldwide search, i.e., microtektite layers, points to impacts that both occur after the most critical biological intervals of the Frasnian–Famennian crisis had passed (…). The impacts are not principal killers in the mass extinction".

The End-Permian mass extinction

Most current studies and the continuing multi-theme dispute have focused on the apocalyptic "Mother of all Mass Extinctions" at the end of the Paleozoic Era. Merely the extreme abruptness of ecosystem disruption is a priori seen as sufficient to imply an extraterrestrial control (e.g., Jin et al. 2000). Chapman (2005) argued, "(…) absent countervailing evidence or some other equally sudden, energetic modifier of the ecology (no terrestrial alternative is so sudden or energetic), presumption must favor the inevitable NEO [near-Earth objects] impacts to explain mass extinctions".

To date, comprehensive results are still elusive. Misidentification is ascribed to supposedly unaltered micrometeorites and an ejecta blanket stratum with shocked quartz, spherules, enhanced Ir and siderophiles and fullerenes trapping extraterrestrial noble gases, as recently reviewed in depth by French and Koeberl (2010; see also Koeberl and Martinez-Ruiz 2003; Keller 2005; White and Saunders 2005; Coney et al. 2007; Koeberl 2007; Reimold 2007; Ward 2007: 67–81). Interestingly, firstly identified fullerenes from P–T black claystone in Japan have been interpreted by Chijiwa et al. (1999: 767) as a primary terrestrial combustion because the C_{60} "(...) likely synthesized within locally anoxic zone in the extensive wildfires on the supercontinent Pangea and deposited on an anoxic deep-sea floor of the superocean Panthalassa" (see also Li et al. 2005; Yabushita and Kawakami 2007).

The first reports from China postulated an Ir excess of up to 8 ppb (see Hallam and Wignall 1997: 131), but sophisticated analyses in several successions around the globe exhibit contents not significantly above crustal values (below 0.2 ppb), and PGE patterns favouring a basaltic volcanic source (Koeberl et al. 2004; Coney et al. 2007; Xu et al. 2007; Yabushita and Kawakami 2007; Brookfield et al. 2010). Osmium isotope ratios do not have extraterrestrial characteristics, nor does the ^{3}He signature argue for a cometary episode (Koeberl et al. 2004; Farley et al. 2005; Georgiev et al. 2011). No convincing evidence has been found to corroborate the predicted huge delivery of isotopically light sulfur from the penetrated mantle, as a result of an enormous impact of a 30 to 60 km sized asteroid (or a 15- to 30-km in diameter comet) on the ocean that produced a ~600 to 1200 km crater (Kaiho et al. 2001, 2006a; see critical discussion in Koeberl et al. 2002). The interpretation of the large negative δ^{34}S anomaly, perhaps induced by an upwelling of euxinic deep-ocean water masses or chemocline upward-shift, is still unclear (see Newton et al. 2004; Kaiho et

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al. 2006a, b; Newton and Bottrell 2007; Algeo et al. 2008; Luo et al. 2010).

Several possible impact craters have been postulated for this mass extinction time (see the recentmost summary in Barash 2012 and Tohver et al. 2012). The initially proposed 120 km-sized Woodleigh impact structure (Mory et al. 2000) is now known to be closer in age to the Late Devonian mass extinction (Fig. 5). The next aspiring site to "a smoking gun" was the so-called Bedout impact structure, located offshore northwest of Australia (Becker et al. 2004). However, this claim was discarded for a range of reasons, including the absence of undisputed shocked grains and impactites (e.g., Renne et al. 2004; French and Koeberl 2010), as well as vague isotopic dating (Jourdan et al. 2009). The more refined geophysical assessment of the puzzling Bedout High reveals its genetic link with two rifting episodes roughly perpendicular to each other (Müller et al. 2005).

The Wilkes Land crater of East Antarctica (von Frese et al. 2009) is another highly speculative, giant impact site, based exclusively on satellite geophysical data. The age interpretation of this major positive free-air gravity anomaly, over a ~500-km diameter sub-ice depression, is very uncertain. The inevitable correlation with the "Great Dying" is based on commonly rejected micrometeorite evidence in Antarctica by Basu et al. (2003; see French and Koeberl 2010). In addition, von Frese et al. (2009) stressed coeval antipodal volcanism of the Siberian Traps and were tempted to associate causally this collision with the development of the hot spot beneath the thick cratonic lithosphere that initiated the cataclysmic flood basalt activity. The exact mechanism of the proposed trigger remains cryptic. The impact volcanism hypothesis, however, including computer simulations, is a frequently returning motif since the start of the mass extinction debate (e.g., Öpik 1958; Rogers 1982; see Palmer 2003: 220), as seen in variety of current views (e.g., Glikson 2005; Jones 2005; White and Saunders 2005; Chatterjee et al. 2006; French and Koeberl 2010). Even if there is no credible statistical correlation between hypervelocity impacts and extrusive activity (Kelley 2007; see also Tejada et al. 2012), and thus no reason to advocate a persistent causative link, this testable model is especially attractive for oceanic igneous intrusions developed on young thinned crust (Glikson 2005; Jones 2005). Large-body meteorite and cometary impacts may rather only accelerate the pulsed, long-term volcanic intensity from active mantle plumes (Abbott and Isley 2002), because of shock-induced melting and extra decompression melting of the heated target, sub-crater mantle (Jones 2005).

Thus, data available are not compatible with the existence of an impact event of an apocalyptic scale at the P–T mass extinction boundary, and recurrently presented hypotheses are unverified or premature at best (French and Koeberl 2010). As pointed out by Erwin (2006: 216), "Impact enthusiasts claim that the simplest explanation is that an impact triggered the Siberian Flood basalt. That would certainly be an interesting result, and may be the only way the Permian will ever succeed in Hollywood, but nothing we know about either the Siberian volcanism or impacts provides much support".

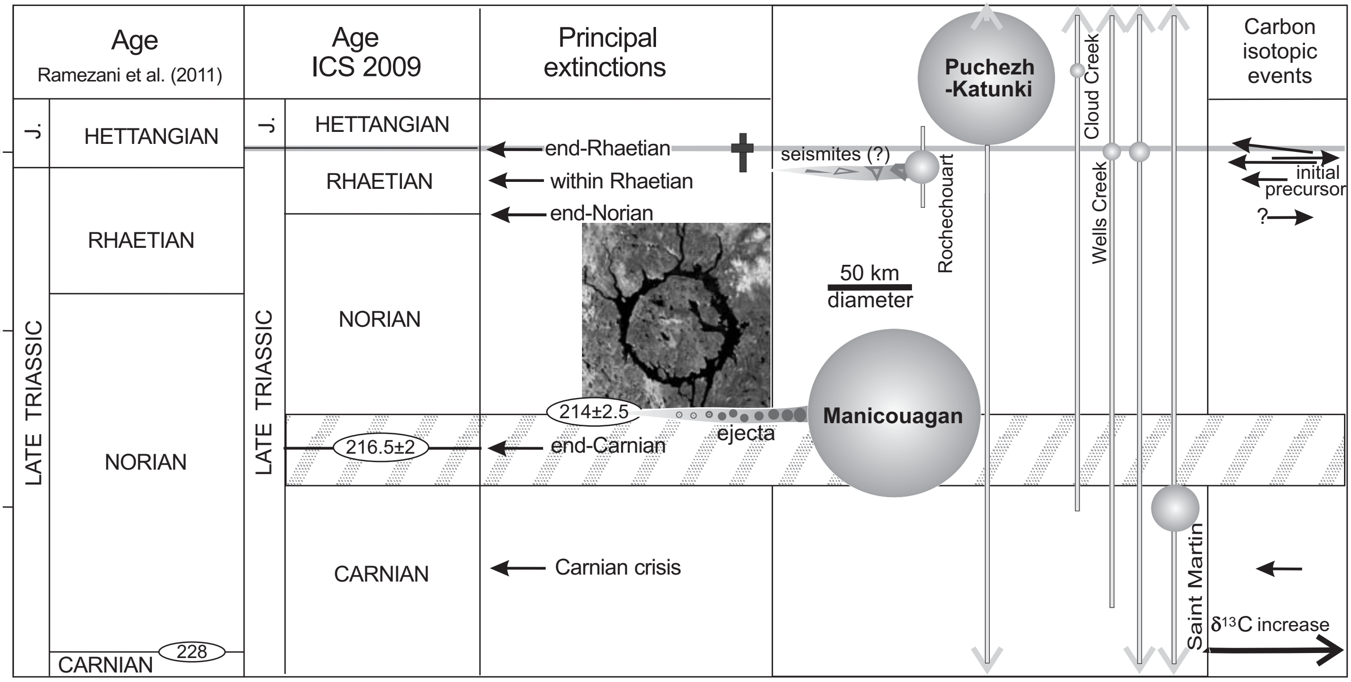

Fig. 6. The Late Triassic cratering record plotted against extinction events (based on Lucas and Tanner 2008: fig. 8; crater dates modified after Schmieder and Buchner 2008 and Martin Schmieder personal communication, 2011) and two alternative time scales. Note that the 100 km-sized and precisely dated Manicouagan crater (214.56±0.05 Ma; see ottawa-rasc.ca/wiki/index.php?title=Odale-Articles- Manicouagan) is within the age range of the end-Carnian extinction only in the ICS 2009 geochronologic scheme (see also Lucas et al. 2012). Carbon isotope events compiled from Tanner (2010) and Ruhl and Kürschner (2011: fig.1). Vertical lines correspond to possible temporal ranges. J., Jurassic.

The End-Triassic mass extinction

Significant progress is noted in the study of the T–J mass extinction boundary. In this case, there are also a series of papers, published mostly in *Science*, that advocate the application of the Alvarez impact theory, based largely on circular reasoning (Hallam and Wignall 1997; Koeberl and Martinez-Ruiz 2003; Tanner et al. 2004; White and Saunders 2005; Ward 2007: 93–102). The debate was opened by Olsen et al. (1987), who argued that the large, 100 km diameter Manicouagan impact structure in Quebec (Fig. 6), one of the best-preserved and largest Earth craters (in the "top four" to date; Spray et al. 2010), is broadly correlative with the T–J boundary, and thus the inescapable contributory candidate for this mass extinction (e.g., Raup 1992). It was hardly surprising that the extraterrestrial cataclysm concept was strengthened five years later when quartz grains containing multiple PDFs were described from northern Italy by Bice et al. (1992: 443), who believed in "at least three closely spaced impacts at the end of the Triassic". This finding has been questioned (Hallam and Wignall 1997: 157); there is no subsequent confirmation, nor have other, more reliable, data been presented on the ejecta spanning the T–J boundary (e.g., Mossman et al. 1998).

Radiometric dating of the Manicougan crater (214±1 Ma; Hodych and Dunning 1992; 214.56±0.05 Ma; Jourdan et al. 2012) has shown that the impact event substantially predated the mass extinction event by 13 Ma. However, it does not seem to preclude any correlation with changes in the contemporary biosphere (as quoted by Tsujita 2001 and Kring 2003), although the flawed timescale of this epoch (see Fig. 6) has not allowed a confident correlation. Already Hodych and Dunning (1992) proposed another viable hypothesis: the Manicougan impact may possibly have participated in an earlier biotic turnover spanning the Carnian–Norian boundary (also e.g., Rampino et al. 1997), whilst others considered a coincidence with the end-Norian extinction (e.g., Sephton et al. 2002; Tanner et al. 2004). In actuality, several different-sized impact structures predate the T–J extinction boundary (Fig. 6), and the poorly dated, 80 km diameter Puchezh-Katunki structure may be allegedly added to the impact set (Pálfy 2004; Schmieder and Buchner 2008). Although their ages scatter considerably, Spray et al. (1998) proposed a multiple impact event, caused by fragmented comets or asteroids colliding with the Earth 214 Ma ago, and recorded five impact structures (see critical discussion in Jourdan et al. 2012).

Thus, a causal link with the end-Carnian crisis remains a possibility (see updated data in Fig. 6; Tanner and Lucas 2004). Importantly, an ejecta blanket horizon with shocked quartz and spherules in the Upper Triassic of southwest England (Walkden et al. 2002; Kirkham 2003), dated at 214±2.5 Ma, is within the range of the Manicouagan impact event. This relationship, approved by heavy mineral correlation (Thackrey et al. 2009), provides a potential reference to high-resolution verification of the scenario postulated by Hodych and Dunning (1992) and Spray et al. (1998). However, there are two basic uncertainties linked with this promising association: (i) the biotic turnover magnitude is disputable (Hallam and Wignall 1997: 144–147; Brusatte et al. 2010; Hunt et al. 2002; Irmis 2011), and (ii) there is great disagreement on the age of the Carnian–Norian boundary, 228 Ma having recently been proposed by Ramezani et al. (2011; see discussion in Lucas et al. 2012). If this date is correct, the Manicouagan impact lethal effects may be causally linked, according to Olsen et al. (2011: 223), with "an abrupt though modest turnover" in late Norian tetrapod diversity.

Another hopeful correlation (Martin Schmieder, personal communication 2011) concerns the re-dated 23 km diameter Rochechouart crater (Schmieder et al. 2010; Smith 2011; see Fig. 6) and 2–4 m thick seismite/tsunamite deposits of Rhaetian age covering ca. 250 000 km^2 in England, Ireland, and France (Simms 2007). In addition, Hori et al. (2007) reported possibly impact-related PGEs enrichment in uppermost Rhaetian deep-sea sediments of Panthalassa (Ir peak at 0.07 ppb), linked to the first phase of radiolarian crisis. Also Ruhl and Kürschner (2011) demonstrated late Rhaetian ("precursor"; Fig. 6) disruption of the carbon cycling in marine and continental, preceding the lastly highlighted, catastrophic commencement of eruptive volcanic activity in the Central Atlantic Magmatic Province (CAMP; see below). Vegetation changes prior to the stage boundary additionally argue against a single cataclysmic episode across the T–J transition (McElwain et al. 2007).

Discussion of an end-Triassic impact hypothesis was briefly revived, again in a *Science* article, by Olsen et al. (2002), who showed elevated levels of Ir in the eastern USA at the T–J boundary (ses also "fullerene data" in Perry et al. 2003). The "modest" anomaly of 0.285 ppb is coincident with a fern bloom in palynological signature. Also in *Science*, Ward et al. (2001) argued for a catastrophic productivity collapse at the stage boundary recorded in the δ^{13}C value decrease, synchronized with an abrupt extinction pulse among radiolarians. The negative carbon isotope anomaly is better explainable by an input of ^{12}C-rich carbon in effect of methane release from different sources (see Whiteside et al. 2010; Ruhl and Kürschner 2011), combined with massive CO_2 outgassing from the CAMP extrusives (Tanner 2010; Sobolev et al. 2011) The dramatic end-Triassic radiolarian diversity collapse has recently been questioned by Kiessling and Danelian (2011) on the basis of analyzed extinction dynamics (but see Wignall et al. 2010).

Tanner et al. (2008) also discovered multiple PGE enhancements in latest Triassic to Jurassic-age strata of eastern Canada, with a distinctive Ir peak of 0.45 ppb. The authors found no compelling support for an extraterrestrial source for the enrichment levels, and instead proposed redox control. The onset of the CAMP furthermore provides a source for the fairly small PGEs excess observed, that this non-impact scenario is clearly visible also in the marine Os isotope record and ^{3}He proxy (Farley et al. 2002; Kuroda et al. 2010). In summary, the evidence linking end-Triassic impact event(s) and extinction(s) is still much disputed, and refers rather to pre-extinction biotic events (Fig. 6).

As highlighted by Sephton et al. (2002), Lucas (2006) and Lucas and Tanner (2008), multiple extinction pulses occurred throughout at least 20 Ma (Fig. 6). They were partly tied to biogeochemical and climate perturbations (Sephton et al. 2002; Cleveland et al. 2008; Kidder and Worsley 2010; Callegaro et al. 2012; Dal Corso et al. 2012), also with a severe implication for real biotic magnitude of the T–J boundary event (Bambach 2006; Lucas and Tanner 2008). On the other hand, Kiessling et al. (2007: 219–220) concluded from detailed analyses based on the Paleobiology Database: "The enigmatic end-Triassic extinction is confirmed to represent a true mass extinction characterized by both elevated extinction rates and reduced origination rates", although probably "(…) gradual processes added to the diversity decline from the Norian–Rhaetian to the Rhaetian–Hettangian stage boundaries" (see also Arens and West 2008; Alroy 2010; Ros and Echevarría 2012). Regardless of the fact whether the Late Triassic biotic pattern was indeed determined by multiple crises or not, the carbon isotope data strongly suggest a large-scale ecosystem turnover only across T–J transition time (e.g., Ward et al. 2001; see Tanner 2010; Fig. 6)

Lessons from the submarine Alamo impact

The accounted data clearly confirm that a third level of impact-extinction connection testing (Fig. 1) is practically precluded for all mass extinctions, with the impressive exception of the K–Pg global event. However, as a kind of in-depth falsification, it is granted herein that in the results of subsequent revisions of the stratigraphic timescale, paired with timing reevaluation of craters (ascertained by biostratigraphic dating of ejecta), the lethal relationship could be potentially demonstrated for recently identified impact structures of similar age. The Alamo impact in south-central Nevada is unique in that conodonts have provided confident dating of its widely distributed (al least 28 000 km^2) proximal ejecta (the Alamo Breccia): middle Frasnian *Palmatolepis punctata* Zone (i.e., 382 Ma; see Fig. 2), which thereby offers an excellent opportunity to examine biotic consequences.

The Alamo impact and its aftermath.—A relatively large bolide, probably a comet, crashed into the Earth in a carbonate shelf slope-to-basin setting, coincidentally like the Chicxulub impact site. Crater-scaling approximations, based on excavation depth (>1.7 km), suggest a minimum crater size of 44 to 65 km in diameter (and a maximum, outer diameter limit of ~150 km; Morrow et al. 2005; Pinto and Warme 2008). The impacting object penetrated a shelf-slope sedimentary succession beneath the 300 m deep seafloor, down to at least Upper Cambrian strata, which comprise mostly dolostone and limestone, supplemented by sandstone and siliceous rocks (see Morrow et al. 2005: fig. 3). As guided by the simulated environmental catastrophe at the aftermath of the Chicxulub event (e.g., Hildebrand et al. 1991; Kring 2003, 2005; see below), comparing well with contact metamorphism around volcanic intrusions in carbonates and organic-rich rocks (Ganino and Arndt 2009; see also Arthur and Barnes 2006), the thermally shocked pre-Alamo impact sedimentary suite released voluminous climatically active gases and potentially lethal volatiles (CO_2, CH_4, hydrocarbons) and vaporized water (see McGhee 2005: 41). Thus, the highly vulnerable target strata provide a possible association with sudden environmental traumas, and it is not unreasonable to assume a comparable "kill potential" for other presently known Devonian and Triassic wet-target impact events in subtropical carbonate shelves.

In contrast, the possible coeval Siljan bolide struck (Fig. 2) a continental region in the south-eastern periphery of Laurussia (Fennoscandian High), formed in Precambrian crystalline basement covered by Ordovician conglomerate and limestone and Silurian shale and sandstone (Reimold et al. 2005), and likely associated with comparatively low volatile fluxes. A similarly two-layered target within shield terrains, predominantly Precambrian crystalline rocks with a thin (< 200 m) cover of Ordovician carbonates and shales (Spray et al. 2010), in the arid intra-supercontinental setting of Pangea, characterized the larger Manicougan impact (see modelled biotic damage of this "lucky" event in Walkden and Parker 2008; Kring 2003). The insufficiently recognized complex Woodleigh structure in the Carnarvon Basin is within sandstone- and dolomite-dominated sedimentary strata, overlying a granitoid basement (Uysal et al. 2005).

Despite the volatile-prone nature of its target rocks, the Alamo impact did not produce an ecosystem collapse even in adjacent shelf regions. As summarized by Morrow et al. (2009), this unexpected conclusion is based on thorough analysis of pre- and post-impact assemblages of ostracods, stromatoporoids, brachiopods, corals and ichnofaunas (e.g., Casier et al. 2006). Furthermore, fragile stromatoporoid-coral reef biotas rapidly recovered directly at top the Alamo Breccia, which provides "(…) direct local evidence that the Alamo event apparently had no major, long-lived negative affects on shallow benthic ecosystems" (Morrow et al. 2009: 107). It is also difficult to decipher the influence this impact may have had on global climate during a contemporaneous cooling trend (Pisarzowska and Racki 2012).

Magnitude of impact versus its terrestrial setting.—The data above on the Chicxulub-like (in general terms of localization features) impact catastrophe from sensitive reef ecosystem correspond to well-constrained, negligible lethal consequences of the late Eocene cluster of two very large craters, Popigai (100 km diameter) and Chesapeake Bay (90 km; see Poag 1997; Kring 2003). Conversely, the devastating Chicxulub impact specifically struck 3-km thick evaporate-rich target lithologies within the carbonate shelf (e.g., Kring 2005;

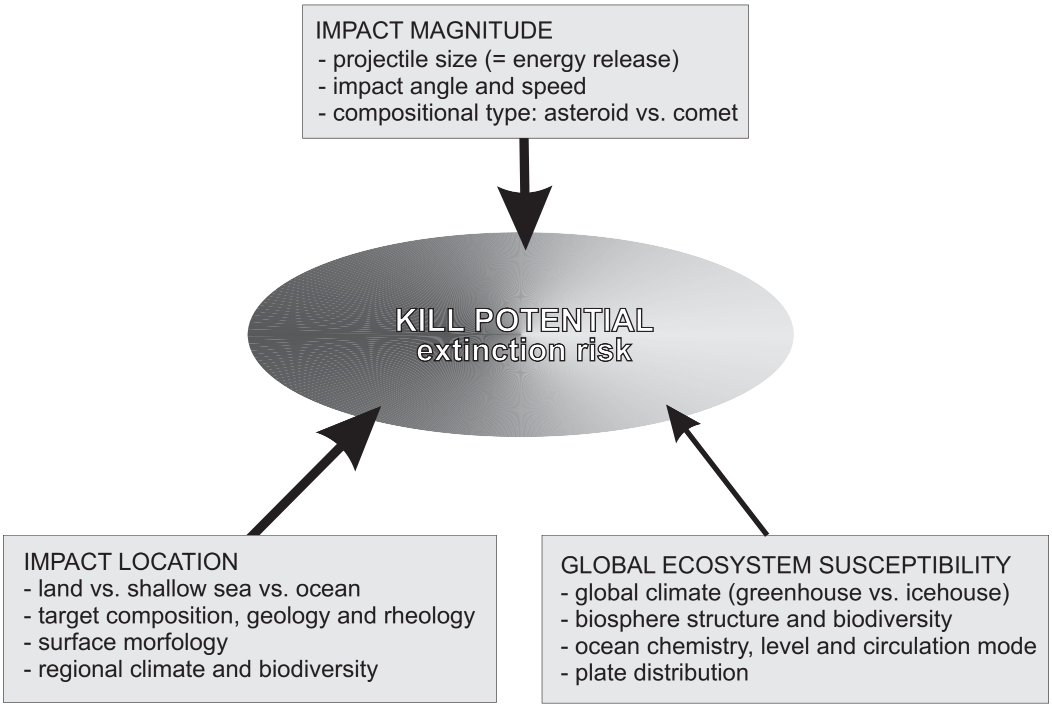

Fig. 7. Major factors that control impact kill potential and extinction risk, relating what, how, where and when the Earth was struck, with emphasis on underestimated vulnerability variables reflecting impact place (global positioning) and its timing (moment in biosphere history; based, in part, on Walkden and Parker 2008: fig. 5; see also Kring 2003); arrow thicknesses reflect a predicted influence scale.

Claeys 2007), that propelled into the stratosphere a dense sulfate aerosol clouds produced by the interaction of S-rich gases and water vapor, with significant climatic effects (see modellings in Toon et al. 1997 and Pierazzo et al. 2003, among others). Simulations show that also ozone destruction due to lethal nitric oxide addition resulted from substantial changes in atmospheric chemistry generated by the shock-heated air, but likely supplemented by release of chemically activated halogens (chlorines, bromines) from the vaporized target rocks. Therefore, an increase in ultraviolet radiation is expected to have happened several years after the impact (e.g., Ishida et al. 2007; Kring 2007).

Strikes of a cosmic body into the vast oceanic basins should be more than twice numerous as continental impacts, and this critical point was immediately recognized in the K–Pg debate (Emiliani et al. 1981; Rogers 1982). However, the possible kill mechanisms, in particular a climatic response, are still poorly understood (Gersonde et al. 2002; Kring 2003; Dypvik et al. 2004; Gisler et al. 2011). These cataclysmic events differ in several respects from those in subaerial settings (as reviewed already by Croft 1982), and some lethal effects could be buffered by water mass screen (Arens and West 2008). A huge volume of shock-vaporized oceanic water, and sediment and mantle rocky debris might have been ejected into the stratosphere (see simulations in Toon et al. 1997; Saito et al. 2008, Pierazzo et al. 2010 and Gisler et al. 2011), paired with mega-tsunami waves (Gersonde et al. 2002; Dypvik and Jansa 2003; Wünnemann et al. 2010). Prolonged residence of vaporized water in the stratosphere, an important greenhouse gas, is especially hazardous, and, according to the most recent calculations of Gisler et al. (2011: 1187): “The vaporized water carries away a considerable fraction of the impact energy in an explosively expanding blast wave which is responsible for devastating local effects and may affect worldwide climate”. Furthermore, stored halogens from sea salt included in seawater vapor can generate deleterious changes in upper atmospheric chemistry. Stress on the global biosphere, attributed to multi-year ozone layer depletion is suggested by modelling of Pierazzo et al. (2010) even for medium-size (1 km) asteroid impacts in the mid-latitude ocean.

As simulated numerically by many authors (e.g., Toon et al. 1997; Collins et al. 2005; see review in Kring 2007), only most energetic impacts forming craters much larger than 100 km were capable of causing a catastrophic biodiversity loss on a planet-wide scale (see discussion of the extinction-impact curve in Raup 1991, 1992; Jansa 1993; Poag 1997; Rampino et al. 1997; Kring 2003; Keller 2005; Kelley 2007; Prothero 2009). In this context, the South African Morokweng impact structure, originally described as one of the largest Earth impact sites (with an overestimated size of up to 340 km in diameter; Koeberl et al. 1997), could only be reasonably causally tied to minor biotic events at the “major” Jurassic–Cretaceous boundary extinction (20% genus extinction; Bambach 2006), when its correct size (70 km) was established.

Reimold (2007: 28) pointed out that “neither the impact magnitude threshold, above which global mass extinctions must be expected, has been constrained, nor do we understand exactly why the K/P event (related to the 200 km Chicxulub impact structure) was of such lethal effect”. On the other hand, Ellwood et al. (2003c: 539), for example, noted for the K–Pg boundary event that "the chance of such extinctions occurring is tied to a unique set of circumstances". In fact, a complex shift from exclusively regional to different-scale global environmental perturbations should be thoroughly considered in the cause-effect context. This hazard gradation was related directly to impacting projectile characteristics over a variety of kinetic energies (= thermal shocks) and compositional/structural types (e.g., Toon et al. 1997; Wilde and Quinby-Hunt 1997; Kring 2003; Gisler et al. 2011), but also indirectly to a set of terrestrial circumstances: target rocks, geographic and plate-tectonic location, global climate, biosphere resilience (e.g,. provinciality), oceanographic setting jointly with ocean chemistry mode (see Sobolev et al. 2011), among others (Fig. 7). This key impact aspect for predicted extinction severity was mentioned by several authors (e.g., Raup 1992: 87; Poag et al. 1997: 585–586; Toon et al. 1997: 51; Sephton et al. 2002; Ellwood et al. 2003c; Kent et al. 2003a: 23; Pálfy 2004: 144; Tanner et al. 2004; Kring 2005; Arthur and Barnes 2006). Surprisingly, the essential difference of impact cratering process in volatile-free (= crystalline rocks) and volatile-rich (= sedimentary rocks) target lithologies was quantitatively studied as early as by Kieffer and Simonds (1980). However, more holistic approach to estimating seemingly unpredictable biotic effects was developed only by Kring (2003) and Walkden and Parker (2006, 2008), who doubt that crater size is the sole reliable proxy for collision "destructive power" (sensu Raup 1991). Kring (2003: 124) stressed importance of substantially evolving environmental states and ecosystem structures, because: "the environmental outcome of an impact event and subsequent biologic effects are a function of Earth's ambient conditions, not just the energy of the impact event". Walkden and Parker (2006, 2008) particularly scoped on the geographic (surface conditions, shallow geology, basement) and timing factors in geological history and world biodiversity evolution, paired with climatic regime. So, the basic questions for the "kill potential" are where, what, and when the bolide struck (Walkden and Parker 2006, 2008). Thus, the destructive potential of the largest continental impacts, Manicouagan and Popigai, is far removed from the threshold for mass extinctions (see Sephton et al. 2002; Kring 2003, 2005; Tanner et al. 2004). The more realistic prediction of lethal hazard should contain not only impact characteristics, but also its terrestrial spatial and chronologic settings (Fig. 7). Walkden and Parker (2006, 2008) considered two major controlling parameters: crater diameter and a generalized time/place factor (termed "vulnerability"), even if the Alamo instance somewhat counters the implied low resistance of high ambient biodiversity (see aspects of biosphere resilience in Stanley 1990; Raup 1991; Plotnick and Sepkoski 2001; Kring 2003; Arens and West 2008; Prothero 2009; Alroy 2010).

Two conclusions can be drawn from the above discussion:

1. All currently known impacts, including the Siljan and Manicougan events, are to be precluded as extraterrestrial killers in the F–F and T–J mass extinctions.

2. The typically weak negative ecosystem impact of the currently known impact events contrasts markedly with the extreme biosphere collapse at the P–T boundary, and, what is more, the probability of a bolide strike at that time is definitely low. Consequently, other catastrophic high-magnitude events and cataclysmic processes must have generated these massive biodiversity losses.

Conclusions, implications, and perspectives

The spectacular scenario proposed by Alvarez et al. (1980) for the K–Pg boundary demise of marine and terrestrial ecosystems has triggered an overwhelming interest in the possibly devastating role of bolides colliding with the Earth. However, parsimony-driven hypotheses cannot be easily applied to convoluted geologic records and problems (Tsujita 2001; see similar earlier views in Glen 1994 and Palmer 2003). In the context of impact paradigm as a general explanation of the observed biodiversity losses in the Phanerozoic, the state-of-the-art situation can be summarized as follows:

- As reviewed above, cases of "great expectations syndrome" and circular reasoning bedevil numerous impact scenarios (see other instructive examples reported by Hallam and Wignall 1997; Tsujita 2001; Koeberl and Martinez-Ruiz 2003; Prothero 2009). With reference to the proposed three successive levels of misunderstanding, which resulted from straightforward application of the impact paradigm (Fig. 1), the global events are in actuality still at the first level of testing, influenced by factual misidentification of extraterrestrial signals, such as doubtful Ir enrichments and shocked minerals.
- Occurrences of large impact structures with an age indistinguishable from that of mass mortality events are not substantiated (e.g., Kelley 2007). More speculatively, the T–J boundary is within the error of dating, associated with an 80 km-diameter impact site (Puchezh-Katunki; Pálfy 2004; Schmieder and Buchner 2008; see Fig. 6, and also Smith 2011), but only the F–F biotic crisis is seen herein in the context of a possible correlative relationship with the Siljan crater (?maybe also the debatable Woodleigh structure; Fig. 3). However, even if the discovery of undoubted Siljan impact ejecta would provide tight correlation, the crater size and cratonic/continental setting hit indicates that an extraterrestrial stimulus for this extinction is unlikely. To discuss the lethal potential of the impact events in more robust terms, its geographic and timing vulnerability factors, especially target geology in the context of associated volatile fluxes, should be rigorously assessed (size versus time and place; Walkden and Parker 2006, 2008).
- Terrestrial cratering signature is often marked by large timing and size uncertainties, particularly in deeply eroded and buried impact structures, and the third level of advanced testing (Fig. 1) applies rather to clustered impacts which

distinctly predate major extinctions with one notable exception, the end-Permian. It is exemplified by the middle Frasnian Alamo and other impacts (McGhee 2001, 2005; see also Pisarzowska and Racki 2012) and the Late Triassic Manicouagan impact (and other impact events; Tanner et al. 2004). As summarized by Alvarez (2003: 158), "Of course, absence of evidence does not constitute evidence of absence, and it may be that there have been several extinction-causing impacts, with the KT event unique in its abundant preservation of impact proxies. One may conclude that impact as a general cause of extinctions is not supported by evidence, but has not been falsified". Despite the continued debate, the current absence of prime impact signatures at mass extinction boundaries may indeed be a somewhat premature conclusion, as ca. 90% of crater record is missing (e.g., Kelley 2007: 929; Stewart 2011, who predicted 228 undiscovered craters larger than 2.5 km). The crucial constraint is provided by an erratic and at least partly lost oceanic impact record, characterized by a huge number of undiscovered craters and shock wave marks (Rogers 1982; Kring 2003; Dypvik et al. 2004; Davison and Collins 2007), and/or other extra-crater tracers (Gersonde et al. 2002; see above). Recent estimates of the bombardment rate for Chicxulub-sized events, sufficient to form craters with diameters of ~200 km, confirm only previous predictions (see Shoemaker et al. 1990; Jansa 1993; Toon et al. 1997), and are between 80 to 100 Ma (e.g., Bland 2005; Ivanov 2008; Stewart 2011; see also Claeys 2007). This is therefore an essential aim to reconstruct Earth's impact history properly because of a clearly underestimated number of identified high-magnitude events, even if the population of large craters has a distinctly higher survival potential (see also Trefil and Raup 1992; Reimold 2007; Bailer-Jones 2011). In addition, we surely have to consider that more advanced analytical techniques (e.g., for shock effects in different lithologies and minerals; French and Koeberl 2010; Reimold and Jourdan 2012) will expose subtle cosmic signals and impact-extinction links untraceable at the present state of knowledge.

- Regardless of these reservations, much more plausible to me is the diagnosis by Walliser (1996: 238): "because it is even theoretically impossible to prove the non-existence of a non-existing impact, I prefer to presume (...) that a less complicated and a less spectacular solution must not necessarily be wrong". I overall favour to seek a general testable multi-causal explanation of global-scale violent processes affecting our planet in the Earth's system rather than in space (Pluto school of Ager 1993).
- All major biocrises seem to be marked by overall lesser catastrophic signatures than the impact-promoted K–Pg boundary event (as stressed by Şengör et al. 2008 and Schulte et al. 2010; see contradictory data in Tsujita 2001; Hallam 2004, Twitchet 2006, and Prothero 2009). Therefore, approved temporal correlations between large igneous provinces and biotic crises are becoming a more acceptable alternative for the dilemmas related to the simplistic impact catastrophism theory shown above (Wignall 2005; Hough et al. 2006; Courtillot and Olson 2007; Kidder and Worsley 2010; Rampino 2010; Sobolev et al. 2011; Dal Corso et al. 2012; Greene et al. 2012). This causal connection is now more obvious for the two-step Late Permian crisis (e.g., Racki and Wignall 2005; Wignall 2005; Kidder and Worsley 2010; Sobolev et al. 2011; Brand et al. 2012; Payne and Clapham 2012). The growing evidence is better exposed in several recent papers on the T–J transition, in which use of refined integrative approaches, mostly with leading chemostratigraphy, offers a reliable time resolution with age differences beyond the refinement of available data (Deenen et al. 2010; Kuroda et al. 2010; Schoene et al. 2010; Ruhl and Kürschner 2011; Schaller et al. 2011; Callegaro et al. 2012; Greene et al. 2012, among others). The mass extinction started simultaneously with the initial lava floods of the Central Atlantic Magmatic Province, a suffocating supergreenhouse effect due to CO_2 excess and marine biocalcification crisis (Whiteside et al. 2010). These works collectively imply that the volcanic greenhouse (summer) scenario of Wignall (2005) and (super) greenhouse (= hothouse of Kidder and Worsley 2010) crises are emerging as an exclusively Earth-centred paradigm (Ward 2007; Retallack 2009), without reference to the impact trigger of magmatic activity.
- A particularly great dying episode corresponds to a uniquely complex, specific instance in the fossil record (e.g., Hoffman 1989; Walliser 1996; Hallam and Wignall 1997; Palmer 2003; Keller 2005; MacLeod 2005; Prothero 2009; Alroy 2010; Kidder and Worsley 2010). Mass extinctions are thought, for example, by Feulner (2011) as a stochastic combination of both random events and a variety of still poorly-known periodic forcings against a noisy background component (see also e.g., the multiplicative multifractal model of Plotnick and Sepkoski 2001). In the attractive press-pulse model of Arens and West (2008), mass extinction causes are seen as interaction of long-term ecosystem stress processes (e.g., sea level and/or climate change) and geologically rapid, ultimate catastrophic disturbance. Consequently, holistic event-stratigraphic approaches to multicausal environmental traumas, refined on a case-by-case basis, are the sole acknowledged way of dealing with these.

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