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On the impact theory of mass extinction*

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Abstract. The impact theory of mass extinction for Earth's biota has not yet received either its final confirmation or complete rejection and remains a working hypothesis, often explaining what is not explicable by other theories. Among all the five mass extinctions recorded in the stratigraphic annals of the Earth, only the most recent K-T boundary (transition from the Cretaceous to the Tertiary period) has been proved to be associated with the impact (or impacts). In this paper, we used the data of the Earths Impact Structures catalog (developed by the author) in evaluating how the known impact events are related to these major five boundaries. The given data show that the impact factor, unlike alternatives, has a sufficient evidence of its mandatory participation in the biota mass extinction.

Keywords: impact structures catalog, mass extinctions of the Earth's biota.

1. Introduction

During the last four decades, Alvarez's impact theory of mass extinction (1982–2003 [1, 2]), which assumes a causal relationship between the stratigraphic boundaries identifying a sharp change in biota with catastrophic meteoritic falls, has not received either final confirmation or complete refutation.

The only striking exception is the proven connection between the impact and extinction occurred at the boundary of the Cretaceous and Tertiary periods (the K-T layer). Presently, this is the most studied boundary which is clearly expressed in many stratigraphic sections of the world. They have clear markers in the form of a horizon of the hydrothermal black clay with 1–3 cm thickness with high concentrations of Ir and other platinum group elements: As, Zn, Cu, Pb, Cr, Co, V, Ni (up to 4 times higher than for the background), as well as deposits of glass spherules (tektites). The discovery more than 30 years ago in Gubbio (Italy) and Caravaca (Spain) of the horizons of that type and their timing to the most recent major extinction of biota in the Earth history, which occurred 65.5 million years ago (Ma), is still considered one of the most important discoveries in the Earth sciences [3]. The boundary for extinction of six groups of oceanic microorganisms (planktonic and benthic foraminifera, coccoliths, radiolarians, dinoflagellates and diatoms), brachiopods, ammonites, nonavian dinosaurs, marine and flying

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reptiles, and the abrupt changes in floral communities coincides with the impact layer containing the modified “glass” spherules, impact quartz and Ni-spinel grains, smectite and illit. All these markers are concentrated at a single level both in sections of the Chicxulub crater and in other sections remote from the Gulf of Mexico. The findings of lonsdaleite (paragenesis of hexagonal polymorphs of diamond) [4], magnetic iron spherules with spinel (probably formed in the lower layers of the atmosphere at a small angle of an asteroid impact), grains of impact quartz and other findings support the impact hypothesis [5]. Sometimes a separation of peaks in the concentration of quartz grains and iridium was observed: this allowed some authors suggest at least two impact events occurred at the Cretaceous–Paleogene boundary: one on the continental crust (which was reflected in the shaking structures in quartz) and the other one in the ocean, which led to the elevated iridium deposition [5]. The layers of impact spherules, accurately identified as the Chicxulub distal ejecta, and the layers of high Ir concentration (coinciding with the mass extinction boundary) are also increasingly found at different stratigraphic levels. In areas proximal to the Chicxulub impact site (in the crater core and throughout the northeastern Mexico) the stratigraphic position of the Chicxulub microtectites separated from the K-T boundary by a thick sediment layer (up to 60–100 cm thick) suggests that the Chicxulub event precedes by 300 (?) thousand years (later estimates by the same authors— by 100–130 thousand years) from the K-T mass extinction boundary. Here they take into account the normal sedimentation rate typical for quiet periods of the Earth’s history. Such facts were interpreted in favor of a double or multiple impacts [6].

During a geological expedition in 2009, an employee of the GIN RAS collected samples from a K-T layer of black clay in the Stevens–Klint section (Denmark) containing numerous metal particles of iron, copper, alloys of Fe–Ni, Fe–Ni–Co–Zn, Fe–Cr, magnetite and aluminosilicate spherules of small diameters, as well as grains of nanodiamonds. The results of its study [7] do not contradict the existing ideas about collision events at the end of the Cretaceous period: several fragments of the asteroid Baptistina from the inner part of the Asteroid Belt after splitting about 160 Ma ago had fell to Earth [8]. Moreover, the fragments of this body could fall not only during the Cretaceous–Paleogene boundary, but also during the late Maastrichtian and Early Paleocene. But only the fall traces recorded at the K-T boundary have been the properly studied due to the wide prevalence of Chicxulub ejecta layers far beyond its geographic limits [7].

Nevertheless, recent facts have emerged that cast doubts if the meteoritic impact responsible for wide biota extinction was the only reason for the Cretaceous-Paleogene boundary. For example, the distribution of foraminifera in the Gams section (Austria) looks like [9] that the genera extinction began here much before the appearance of impact material and presumably occurred under the influence of volcanism (for example, due to the spread of arsenic and other toxic elements in volcanic aerosols). To overcome this inconsistency, some authors suggested that the extinction had been occurred gradually, and the K-T boundary corresponds to the time of prolonged shocks: these factors can be multiple impacts ("Chicxulub", "Boltysh", "Shiva", craters of oceanic bottom), multi-stage volcanism (Deccan Traps) and rapid climate changes — all then eventually led to biota mass extinction (for example, [6]). These authors suggest that the Deccan volcanism (a cascade of rapid and massive volcanic eruptions that formed the largest and longest lava flows — up to 1500 km) produced the gas emissions of SO_2 and CO_2 thus, exceeding the results of the Chicxulub impact by at least 30 times. Besides, a long cascade of volcanic eruptions explains the long delay (about 0.5 million years) in complete restoration of the marine environment after the mass extinction. And the mass extinction itself occurred immediately after the most critical stage of volcanism (Phase 2) which was much more destructive than a single big impact [6]. There are publications (in addition to [6, 9]) that dispute the key participation of impact events in the phenomenon of mass extinctions on completely deny the existence of bolide impacts, in particular, the very fact of cosmic origin of the "Chicxulub" crater [10].

However, given the proven short-term nature of the Cretaceous-Paleogene mass extinction (from several years to several decades) and the distribution geography of the impact ejecta layers (recorded in stratigraphic annals), most experts still agree on this subject (see the articles of the First International Congress on Stratigraphy [11], the Supporting Material of the 41 authors [12] and the references in the papers [13, 14]). Experts agree that the fundamental causes of the K-T mass extinction are precisely the post-impact factors: "The impact winter (the rapid short-term cooling), the acid rains and the anoxia-hypoxia in the ocean depths, the strongest post-shock tsunami in the Gulf of Mexico, the destruction of the sea shelf, which gave rise to a mega-turbine massive flow of up to hundreds of meters in some parts of Cuba" [5]. Although other factors at the end of the Cretaceous period (tectonic events, powerful basalt eruptions, transgressions and regressions, subsequent episodes of cooling and heating, as well as changes in chemistry of the atmosphere and ocean) could contribute to the degradation of some groups of organisms, but they cannot explain their complete extinction. Moreover, in addition to megatsunami or mega-flows, such factors as the tectonic events and the transgressions/regressions can explain both inconsistencies in the sedimentation pattern, and the ambiguous temporal correlation for extinctions. The point is that the areas could rise up or fall down due to these factors, and the conditions at great oceanic depths could evolve by 100/150 thousand years after the events in the shallow waters and in the atmosphere [15]. It is obvious that a sufficiently wide stratigraphic layer (sometimes up 2 m thick [16]) should be considered as a marker of catastrophic events (characterized by numerous redepositions and changes in conditions).

Let us note also that according to [5] the end of the Cretaceous period (from hundreds of thousand yrs to several million yrs) was characterized by the combined influence of other cosmic factors: orbital oscillations, cosmic radiation, supernova explosion, magnetic field inversion. That is, the author offered a more general cause of all the events of this catastrophic period originating beyond the Solar System. It is possible that this galaxy-scale event can impact our planet periodically, leaving its signatures in other geological epochs.

It seems that the final point in the dispute about the root cause of mass extinctions should be put by data obtained outside the Earth, which does not allow giving priority to the internal factor associated with the activity of the Earth's interior. And such data was obtained by the Chinese Chang'e-5 lunar mission, which took samples of the lunar rocks in 2020 and delivered them to the Earth. The study of the chemical composition and radioactivity of glass spherules of impact origin contained in the samples made it possible to determine their age [17]. It turned out that dating is distributed unevenly, forming 17 statistically significant age clusters covering the last 2 billion years. In particular, the age groups of lunar impact glasses dated by 68 ± 3 Ma and 34 ± 2 Ma are remarkable due to the fact that the first age coincides well with the age of the terrestrial impact crater "Chicxulub" (and other contemporary craters like "Boltysh", "Kara", "Manson", "Lappajarvi"). The second, age cluster is close to the concentration age of large Late Eocene impact craters ("Popigai", "Chesapeak", "Wanapitei" and "Mistastin"). The other populations of ages: 6 ± 1 Ma, 11 ± 2 Ma and 23 ± 3 Ma are similar to the ages of large terrestrial craters of "Karla" ($D = 10$ km, age of 5 ± 1 Ma); "Shunak" (3 km, 12 ± 5 Ma); "Ries" (24 km, 14.8 ± 0.7 Ma); "Haughton" (24 km, 23.4 ± 1 Ma) [17]. These coincidences may indicate that, for unknown reasons, there are periods when the regular orbits of small bodies in the Solar System (in particular, in the Asteroid Belt) can be destabilized and they enter the orbits crossing the orbits of the Earth or the Moon [17]. It is possible that during the same periods, collisions of comets with the Earth were activated, for example, from the Kuiper Belt (counted for about 130,000 comets with a diameter exceeding 100 km [18]). High-speed cometary impacts can be accompanied by the effects of deep penetration into the bowels of the Earth for the material metamorphosed by the impact, or it could rebound and eject the material into space. It can be also accompanied by the effects of mantle heating, massive basalt intrusions, and surface outpourings (the traps) [19] and even (we cannot exclude) of the triggering the plate tectonics [20].

Mass extinctions of biota have been recorded five times in the geological history of the Earth [21, 22]. This is, mainly, the K-T extinction described above, then T-J (Triassic–Jurassic, 214 Ma); P-T (Permian–Triassic, $\sim$ 250 Ma); D-C or F-F (Frasnian–Famennian, 368 ± 1 Ma) and O-S (Ordovik–Silur, 445.6 Ma) events. The age of the first four extinctions corresponds (within the error) to the age clusters recorded for the lunar impact glasses (according to the Chang'e-5 mission): these are 68 ± 3, 219 ± 18, 269 ± 15, 377 ± 11 Ma. Meanwhile, the age of the oldest one lacks any match in the age clusters. The next age cluster of lunar glasses at 574 ± 12 Ma corresponds to the Vendian extinction, the so-called "Cambrian explosion" of species diversity. In this paper, an attempt is made in using Earth Impact structures catalog data (supported and updated by the author [23] for understanding how well the impact theory of mass extinction is explained by the known impact events in relation to these five established boundaries.

2. Research methods and database

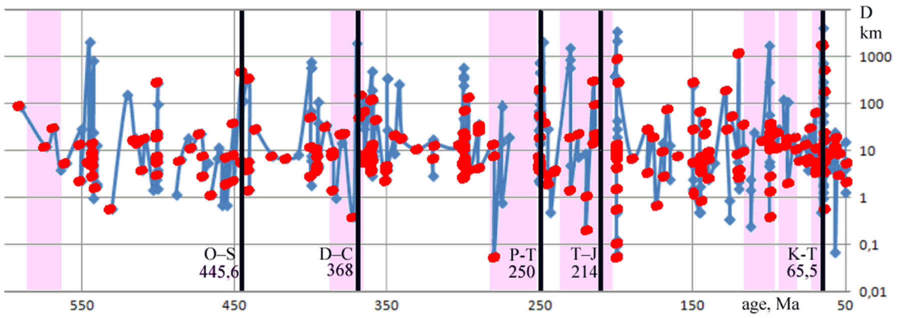
The most complete database of cosmogenic structures created and constantly updated by the author contains currently 3,300 impact structures and crater fields. Of these, 282 objects are proven (due to a large number of shock-explosive signs), 261 are probable, 2159 are potential, 556 items are questionable (only one diagnostic sign) and 42 are failure. The database is stored in a standard table with 90 attributes [24], relationally linked to 4 tables of related information: a bibliographic list, a list of pictures, a list of textual descriptions and a list of groups for multiple impacts (swarms). In a more compact version (containing only seven main attributes), the catalog is duplicated into the geoinformation system GIS-ENDDB software shell [25] and into the website-available table [23].

The GIS-ENDDB mathematical methods and software allows selecting from the Impact structures database by various attributes, obtaining the energy-frequency relationship of the impact events (to estimate the falling frequency of cosmic bodies), as well as constructing various types of distribution of the impact events parameters over time and relative to each other.

This paper describes samples from the Earths Impact structures database selecting by parameters of time (Phanerozoic age), of the crater diameter ($D \geq 50$ km), as well as of the reliability degree (0 — proven, 1 — probable, 2 — potential). At the same time, if there is no information in the literature about geophysical studies of selected structure, then its description given here uses global gravimetric data of the geoinformation system GIS-ENDDB.

3. Results

The distribution of impact events [23] that occurred during the Phanerozoic epoch is very uneven in time. The areas of event concentration, as well as



A correlation between the impact events time limits [23] (blue dots — all events, red dots — only well-proven and probable) and the boundaries of biota mass extinctions (see black vertical lines) and to the 95 % confidence intervals for the age clusters attributed to the lunar impact glasses (lilac stripes) [17]

the surge of their scale (expressed in large crater diameters), correlate well with the horizons of mass extinctions (the figure). They also correspond to the intervals of age clusters [17] obtained for the lunar impact glasses (with the exception of the oldest Cambrian-Ordovician horizon).

Let us focus on events timed to the boundaries of mass extinctions. To do this, we can limit the samples of impact structures with the known age from 50 to 490 Ma and diameter above 50 km. Only this kind of events can produce the global destructive outcomes that threaten the entire life on Earth during periods of mass extinctions. The resulting sample comprises 13 proven, 12 probable, 41 potential and 7 structures of questionable origin (such as “Richat Dome”, “Irish”, “Mississippian/Pennsylvanian”, et al.). The last 7 structures are neglected.

The final set has 66 structures, and 67 % of them belong to the boundaries of five mass extinctions within the corrected confidence intervals, proposed in paper [17] are the following: K-T (68 ± 3.02 Ma) — 11 structures, T-J (219 ± 19 Ma) — 8 structures, P-T (269 ± 19 Ma) — 14 structures, D-C (377 ± 12 Ma) — 7 structures and O-S (445.6 ± 6 Ma) — 4 structures. There are some details about these boundaries:

K-T (the boundary between the Cretaceous and Tertiary periods): the Cretaceous–Palegene extinction is the most studied and the most recent major extinction of the biota. During this extinction 68–70 % of all species were eliminated and this event accelerated the evolution of mammals. In the catalog of impact structures, this boundary includes 2 proven (“Chicxulub” and “Kara”), 1 probable (“Shiva”) and 8 potential structures (“Taclamakanskaya”, “Priaralaskaya”, “Amirante basin”, “Kilimanjaro”, “Cuban”, “Small Point”, “Muruktinskaya”, “Bering sea”) (Table 1).

T-J (the end of the Triassic period): the Triassic-Jurassic extinction is a planetary cataclysm that destroyed 90 % of marine organisms and marked

Table 1. Description of large proven, probable and potential impact structures confined to the K-T boundary (abbreviations in the table: MS — impact morphostructures, IS — geochemical and physical impact sings, GA — geophysical anomalies, SE — siderophilic elements, CU — central uplift, RU — ring uplift)

Name	Location	D, km	Age, Ma	Description	Discovery year
Chicxulub	Mexico	180 (600)*	66.052	MS: Ring faults, CU, RU, shifting the Moho boundary, *ejecta layers* IS: Impactites, tektites, diamonds, *concentration of SE and gold, impact quartz, impact breccia* GA: Gravity, magnetic, seismic	1978 (U. Alvarez)
Kara	Russia, Polar Urals	65	70.7 ± 2.2	MS: CU, ring trough, rounded depression, true bottom depth of 2.5 km IS: SE, diaplect minerals, diamonds, coesite, stony meteorite matter, impactites and breccias, concussion cones GA: Gravity,magnetic	1973 (V. Masaitis)
Shiva	India	450×600	65	MS: CU, 4 RU, crater-shaped depression (depth of 12 km) under lavas, the split of the lithosphere IS: Covered with the Deccan lavas GA: Gravity	1996 (S. Chatterjee)
Taclamakan-skaya	China	300	K/P	MS: Flat ellipsoid plain, thin crust with a high Moho border IS: Filled with magma GA: Shifted gravity	2008 (B.S. Zeylik)
Priaralaskaya (Aral sea)	Kazakhstan	750	Mz/Kz	MS: Oval cavity, bank, CU IS: Planar structures in quartz GA: Seismic	1988 (B.S. Zeylik)
Amirante basin	Indian ocean	300–900	∼ 65 ?	MS: Cavity, arc-shaped bank IS: Covered with the Deccan lavas GA: Gravity	1986 (C. Hartnady)
Kilimanjaro	Africa	800	66.5	MS: Arc-shaped rifts around the perimeter IS: Diamonds, SE (fossil Fe, As and others) GA: Gravity	1978 (B.S. Zeylik)
Cuban	Cuba	225	64.98	MS: Fragment of an elevated crater bank IS: Iridium (impact) layer, clastic strata GA: Gravity	1990 (B. Bohor, R. Seitz)
Small Point	USA	140	65	MS: Arc-shaped ridges around the perimeter IS: High-temperature apatite GA: Magnetic, gravity	2003 (D. Manzer, D. Abbott)
Muruktinskaya	Russia, Krasnoyarsk reg.	60	66.5	MS: Rounded basin 250 m deep GA: Gravity	2007 (S. Vishnevsky)
Bering sea	Pacific ocean	1800	65	MS: Sea basin, ring bank	1986 (V. Masaitis)

*According to magnetometric data, the Chicxulub astrobleme has a diameter of 600 km [28].

the end of the Paleozoic. The catalog offers for this boundary 3 proven ("Manicouagan", "Puchezh-Katunki", "North Caspian-Gorny Mangyshlak"), 2 probable ("South Balkhash lake", "Bizeneuille") and 3 potential structures ("Mer de Saragosse", "Solimoes basin", "Zaisanskaya") (Table 2).

P-T (the end of Perm): the Perm-Triassic extinction is the largest extinction in the history of the Earth — about 90 % of marine species (including the upper trilobites) and 70 % of terrestrial organisms disappeared. This boundary includes 2 probable ("Sevetin", "Islas Malvinas") and 12 potential structures ("Islas Malvinas-2", "Wilkes Land", "Bedout", "Dzhungarskaya", "Pricaspiyskaya", "Gulinskiy", "Bahama hot spot", "Midlands Basin", "Zapadno-Pribaikalskaya", "Tungusskaya", "Taseyevskaya", "Tungusso-Baikalskaya") (Table 3).

Table 2. Description of large proven, probable and potential impact structures confined to the T-J boundary (see abbreviations in Table 1)

Name	Location	D, km	Age, Ma	Description	Discovery year
Manicouagan	Canada	100	215.56±0.05 U-Pb	MS: CU, ring trough, RU, a system of radial-concentric faults, *ejecta layer* IS: Impactites, impact metamorphism zones, manifestations of subsequent magmatism GA: Magnetic, gravity	1967 (W. Robertson)
Puchezh-Katunki	Russia, Volga reg.	80	200 ± 3	MS: CU, ring trough, ring zone of terraces dissected by radial throgs IS: Euvites, tagamites, diplect material, coesite, SE, impact metomorphism, block breccia GA: Gravity, magnetic, seismic	1965 (L.V. Firsov)
North Caspian-Gorny Mangyshlak (North Caspian sea)	Kazakhstan	900	T-J	MS: CU, depression, concentric ring zones of stretching and compression IS: Granite layer destroyed, planar elements in quartz GA: Magnetic, seismic	1975 (B.S. Zeylik)
South Balkhash lake	Kazakhstan	285	T-J	MS: CU, depression, bank, overhangings, *ejecta layers* IS: Impactites GA: Magnetic, gravity	1975 (B.S. Zeylik)
Bizeneuille ?	France	487	215	MS: Radial-concentric cracks IS: Tremor structures in quartz GA: Gravity	1998 (R. Blanke)
Mer de Saragosse (Bermuda)	Atlantic Ocean	2250	200	MS: CU, rounded sea basin GA: Gravity	1964 (R. Gallant)
Solimoes basin	Brazil	3500	204	MS: Multi-ring basin similar to the Oriental crater on the Moon, sills IS: Covered with sediments ≥ 1 km thick, basalt sea in the center GA: Magnetic, shifted gravity, seismic	2010 (J.A. Burgener)
Zaisanskaya	Kazakhstan	400	T-J	MS: CU, depression GA: Gravity	2008 (B.S. Zeylik)

Table 3. Description of large probable and potential impact structures confined to the P-T boundary (P-P — Pre-paleozoic–post-paleozoic, see other abbreviations in Table 1)

Name	Location	D, km	Age, Ma	Description	Discovery year
Sevetin (Southern Bohemia)	Czech Repub. and Slovakia	58	277–228	MS: CU, depression, *ejecta layers* IS: Molten rocks, SE, impact metamorphism in quartz, *impacts* GA: Gravity	1987 (S. Vrana)
Islas Malvinas (South Atlantic G.A.)	Atlantic Ocean	200	P-T	MS: Rounded basin IS: Impact breccias ? GA: Magnetic, gravity, seismic	1992 (M.R. Rampino)
Islas Malvinas 2	Atlantic Ocean	100	P-T	MS: Double with the previous one IS: Impact breccias ? GA: Gravity, linear magnetic anomalies	2015 (A. Mikheeva)
Wilkes Land	Antarctica	243	~ 250	MS: Basin in ice cover and in subglacial topography, marginal structures IS: Tektites (australites) GA: Gravity	1962 (exploration work)
Bedout (Bedu)	Australia	180	251.1 ± 4 Ar	MS: CU, depression IS: Shock metamorphism GA: Gravity, seismic	1998 (J. Gorter)
Dzhungarskaya	Kazakhstan	750	P-T	MS: CU, depression GA: Gravity	2008 (B.S. Zeylik)
Pricaspiyskaya	Kazakhstan	800	PZ-MZ	MS: Depression IS: Caspian nuclear, granite layer removed GA: Gravity, seismic	1978 (B.S. Zeylik)
Gulinskiy	Russia, Siberia	50	251	MS: CU, semicircular bank, rift crack IS: Cones of destruction, kimberlites GA: Gravity	1972 (N.Z. Evzikova)
Bahama hot spot	Bahamas	70	251	MS: Depression, radial dikes position GA: Gravity	1992 (R. Deitz, J. McHone)
Midlands Basin	Great Britain	90	275 ± 15	MS: Ring of hills around CU	2004 (R. Stratford)
Zapadno-Pribaikalskaya	Russia, Siberia	900	250	MS: CU, sills, depression (Angara nuclear), arc-shaped rift zone IS: Covered with lava of trap formation GA: Magnetic, gravity	1978 (B.S. Zeylik)
Tungusskaya	Russia, Siberia	600	250	MS: CU, depression, arc-shaped gorst and deep fault IS: Covered with lava of trap formation GA: Magnetic, gravity	1978 (B.S. Zeylik)
Taseyevskaya	Russia, Siberia	320	P-P	MS: CU, depression, arc-shaped gorst and deep fault IS: Covered with lava of trap formation GA: Magnetic, gravity	1978 (B.S. Zeylik)
Tungusso-Baikalskaya	Russia, Siberia	1600	P-P	MS: Ellipsoid depression, sills IS: Covered with lava of trap formation GA: Magnetic, gravity	1978 (B.S. Zeylik)

D-C or **F-F** (the end of the Devonian period): the Devonian extinction is one of the largest extinctions of flora and fauna in the Earth history. The first (and strongest) peak of extinction occurred at the beginning of the Famenian Century — the last century of the Devonian period, when almost all the jawless species disappeared suddenly. We can count for this boundary 3 proven ("Siljan Ring", "Woodleigh", "Alamo Breccia"), 1 probable ("Taihu") and 3 potential structures ("Yuzhnosinegorsk", "Olenek rise", "Sredne-Sibirskaya") (Table 4).

O-S (the end of the Ordovic): the Ordovician-Silurian extinction was the third (in terms of the percentage of extinct genera) and the second (in terms of the number of living organisms lost). We can notice "a spike in the number of Ordovician age terrestrial craters" [17], although the maximum of them was considered a diameter of 30 km [22]. Nevertheless, there are several

Table 4. Description of large proven, probable and potential impact structures confined to the D-C boundary (see abbreviations in Table 1)

Name	Location	D, km	Age, Ma	Description	Discovery year
Siljan Ring	Sweden	52	380.9±4.6 Ar	MS: Ring trough (lakes), CU, overhangings, *ejecta layers* IS: Diaplect quartz, allogeneic breccia, impactites, *microspherules, fossil Ni* GA: Gravity, magnetic, seismic	1971 (N.B. Svensson)
Woodleigh	Australia	120	364±8	MS: CU, multi-ring structure IS: SE, diaplect glasses, planar structures in quartz GA: Gravity, magnetic	2000 (A.J. Mory)
Alamo Breccia	USA	150	367, 382.1±3	MS: CU fractured, *ejecta layers* IS: Breccias, planar structures in quartz, *Ir-anomaly* GA: Gravity	1995 (H. Leroux)
Taihu	China	70	365	MS: Round Lake, *ejecta layers* IS: Impact metamorphism, planar structures in quartz, coesite, SE, *Ir-anomaly* GA: Gravity	1990 (Fu Chengyi et al.)
Yuzhnosinegorsk depression	Russia, Primorye	100	Mid. Devonian – Early Carbon	MS: Oval depression, broken plate structure IS: Surfacing structures of Fe, microspherules, diamonds GA: Gravity, magnetic	2013 (V.A. Tselmovich)
Olenek rise	Russia, Siberia	500	Late Devonian	MS: Round shape, mosaic fault network, *ejecta layer* IS: Rocks similar to rocks of Popigai crater, *diamonds* GA: Gravity, magnetic, seismic	2007 (K.K. Khazanovich-Wulf)
Sredne-Sibirskaya	Russia, Siberia	4500	D-C	MS: Fragments of concentric circles IS: Similarity of ores mineralogy in Sudbury and Norilsk GA: Gravity	2008 (B.S. Zeylik)

Table 5. Description of large proven, probable and potential impact structures confined to the O-S boundary (see abbreviations in Table 1)

Name	Location	D, km	Age, Ma	Description	Discovery year
Ishim (Tengiz)	Kazakhstan	350	O-S	MS: CU, depression, grabens, ring folds — ring reefs, centrifugal overhangings, crust thinning IS: fracture cones, quartz isotropy, planar systems, breccias GA: Gravity, magnetic	1974 (B.S. Zeylik)
Lukanga	Zambia	52	400±100	MS: Swampy depression IS: Diaplect quartz, allogeneic breccias, impact glasses GA: Magnetic	1985 (S. Vrana)
Pribalhash-Iliyskaya (Balkhash lake)	Kazakhstan	480 (700×600)	End upper ordovician	MS: CU, depression, RU, thinning of the granite layer, ring intrusions IS: Melange (breccia), destruction cones, jadeites, planar structures, ores GA: Gravity, magnetic	1975 (B.S. Zeylik)
unnamed/Iraq (#050427-1)	Iraq	115	444	MS: Semi-elliptical ring structure GA: Gravity	1998 (M.W. Ibrahim)

structures with size $D \geq 50$ km related to this mark in the Catalog [23]: 1 proven ("Ishim"), 2 probable ("Lukanga" and "Pribalhash-Iliyskaya") and 1 potential structures ("unnamed/Iraq (#050427-1)" (Table 5).

The reason for a smaller number of large structures at O-S boundary compared to the other time boundaries may be from inaccurate dating the traces of very old events: impact structures, stratigraphic boundaries, glasses of distal ejecta, etc. [22]. The large structures had been poorly preserved compared to the smaller craters due to the large scale and complexity of the processes they trigger. The small impact craters dating back to the Ordovician extinction are dated much better: "Kardla" (D = 7 km, ∼ 455 Ma), "Lockne" (7.5–13.5 km, 455 Ma)(+"Granby" (3 km, 466 Ma), and "Tvaren" (2 km, 458 Ma) supposed to be connected by a single asteroid shower [26]), "Rock Elm" (6 km, 455–430 Ma), "Pilot Lake" (6 km, 445 ± 2 Ma). Although these well-proven small-impact events could not affect the deterioration of ecological situation [27] and cause the mass extinctions, but they in addition to big impact structures could manifest as a surge in impact activity at O-S boundary (comparable to the other four major extinction boundaries). The number of small impact structures dated to the Ordovician end is greater or comparable to the number of small proven impact craters of other time boundaries. These structures are the following: "Flynn Creek" (3.6 km) — for D-C; "Araguainha Dome" (40 km) and "Arganaty" (20 km) — for P-T; "Rochechouart" (23 km), "Saint Martin" (24 km), "Obolon" (15 km) and "Red Wing Creek" (9 km) — for T-J, and also "Boltysh" (40 km), "Manson" (35 km), "Eagle Butte" (10 km), "Vista Alegre" (9.5 km) [27], and perhaps also "Silverpit" (8 km) — for K-T boundary. Stratigraphic data also indicate that the Ordovician extinction is most likely associated with an impact event [11].

Therefore, the data presented in Tables 1–5 show that each of the five major extinction boundaries is well provided with large ring structures having more than one diagnostic attribute of its impact origin: 44 impact structures, and 8 of them are reliably-proven. This means that the factor of impact, in contract to other options, has a sufficient evidence for participation in the mass extinction of the Earth's biota. However, the unambiguous proof of the impact theory of extinctions can be found through reclassifying of features "probable" and "potential" to the well-"proven" category. But as the traces of craters of this scale are often erased by tectonic and erosive processes (or covered by lavas of magmatism), the most promising way to solve this problem is to search for the distal ejecta of the events considered, which were buried in stratigraphic layers. Note that, only 8 of the 44 big structures (see Tables 1–5), attributed to the biota extinction boundaries, have enough data on geochemical and physical data on ejections (highlighted in tables by italic font).

Conclusion

This paper does not claim that the impact theory of mass extinctions has been proven unequivocally. There are certain difficulties for this. In particular, they are associated with the poor knowledge of large shock structures, many of which were discovered in the last century, but have not yet been thoroughly investigated from the shock metamorphism aspects. The second reason is the poor preservation of astroblems in conditions of permanent geological activity of the Earth interior (sometimes activated by the impact itself or by an accompanying cosmic factor), erasing geomorphological traces of large (but short-term) impacts. The geochemical evidence preserved in deep stratigraphic layers (and the physical evidence: inclusions of impact materials from cosmic impact) confirming the hypothesis may be more convincing, especially by considering in addition to Ir-anomalies for identifying the impact ejections also the complete set of siderophilic anomalies with relative values comparable to the known meteorites composition [29]. However, the search and investigation of the ejections of large impact events is not currently the traditional task of the scientific community studying the Earth impact craters, and such observations are very incomplete (sufficient only for the K-T boundary). In addition, the non-chondritic impactors may not create noticeable geochemical anomalies, and the findings of impact materials might be close to the background of the daily sedimentation of cosmic matter [29]. Finally, high-speed cometary bodies and, conversely, low-speed meteorites (so-called "sluggish" explosions, such as "Boltysh", "Kara", "Puchezh-Katunki" [30]) may not create distal behind-the-crater ejections at all.

Thus, the impact theory is still only a working hypothesis, and it is very important to collect all the arguments pro/contra this theory. The data from the Earths Impact Structures catalog [23], if possible, contain the most comprehensive supporting data that convince that the impact factor plays a major role in global catastrophes causing the mass extinctions of organisms. At least, unlike other factors, cosmic impacts have sufficient evidences of its mandatory involvement in the mass extinction of the Earth biota.

References

[1] Alvarez W., Alvarez L.W., Asaro F., et al. Current status of the impact theory for the terminal Cretaceous extinction // Geological implications of impacts of large asteroids and comets on the Earth / Eds. L.T. Silver, P.H. Schultz.— 1982.—Vol. 190.—P. 305–315.—(Geological Society of America; Special Issue).

[2] Alvarez W. Comparing the evidence relevant to impact and flood basalt at times of major mass extinctions // Astrobiology.— 2003.— Vol. 3.— P. 153–161.

[3] Goderis S., Tagle R., Belza J., et al. Reevaluation of siderophile element abundances and ratios across the Cretaceous-Paleogene (K-Pg) boundary: Implications for the nature of the projectile // Geochimica et Cosmochimica Acta.— 2013.—No. 120.—P. 417–446.

[4] The K/T boundary of Gams (Eastern Alps, Austria) and the nature of terminal Cretaceous mass extinction / Ed. A.F. Grachev.—Geophysical Center RAS; Geological Survey of Austria, 2009.—DOI: 10.2205/2009-GAMSbook.

[5] Barash M.S. Factors Responsible for Catastrophic Extinction of Marine Organisms at the Mesozoic-Cenozoic boundary // Oceanology.—2011.—Vol. 51, No. 4. — P. 640–651 (Original Russian text published in Okeanologiya. — 2011.—Vol. 51, No. 4.—P. 683–695).

[6] Keller G. Micropaleontology in Multi-Disciplinary Research: Applications to OAE2 and KTB // Geological Society of India. Special publication.– 2013.– No. 1.–P. 1–23.

[7] Korchagin O.A., Tselmovich V.A. Cosmic particles (micrometeorites) and nanospheres from the boundary layer of clay between the Chalk and Paleogene (K/T) of the Stevens-Klint section, Denmark // Dokl. RAS.—2011.— Vol. 437, No. 4.—P. 520–525 (In Russian).

[8] Napier W.M. The influx of comets and their debris // Accretion of Extraterrestrial Matters Throughout Earths History / Eds. B. Peucker-Ehrenbrink, B. Schmitz.—Dordrecht: Kluwer, 2001.—P. 51–74.

[9] Grachev A.F., Korchagin O.A., Kollmann H.A., et al. A new look at the nature of the transitional layer at the K/T boundary near Gams, Eastern Alps, Austria, and the problem of the mass extinction of the biota // Rus. J. Earth Sciences. — 2005. — Vol. 7. — ES6001.

[10] Muraveynik Yu.A. Degassing of the exploding Earth and the deep structure of Eurasia // Degassing of the Earth: geodynamics, geofluids, oil, gas and their parageneses. – Moscow: Geos, 2008. — P. 324–325 (In Russian).

[11] Lefebvre B., Makhlouf Y., Nardin E., et al. Impact of the Boda Event (Late Ordovician) on High-Latitude Peri-Gondwanan Faunas: An Echinoderm Perspective // STRATI-2013. First Intern. Congress on Stratigraphy. Springer Geology / Eds. R. Rocha, J. Pais, J.C. Kullberg, S. Finney. — 2014.

[12] Schulte P., Alegret L., Arenillas I., at al. The Chicxulub Asteroid Impact and Mass Extinction at the Cretaceous-Paleogene Boundary // Science. — 2010. — Vol. 327, No. 5970. — 1214-8.

[13] Premovic P.I. Experimental evidence for the global acidification of surface ocean at the Cretaceous-Palaeogene boundary: the biogenic calcite-poor spherule layers // Intern. J. Astrobiology. — 2009. — Vol. 8, No. 3. — P. 193–206.

[14] Molina E. Evidence and causes of the main extinction events in the Paleogene based on extinction and survival patterns of foraminifera // Earth-Science Reviews. — 2015. — Vol. 140. — P. 166–181.

[15] Thibault N., Gardin S. The calcareous nannofossil response to the end-Cretaceous warm event in the Tropical Pacific // Palaeogeography, Palaeoclimatology, Palaeoecology. — 2010. — Vol. 291. — P. 239–252.

[16] Molina E. The Global Boundary Stratotype Section and Point for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic): auxiliary sections and correlation // Episodes. — 2009. — Vol. 32, No. 2. — P 84–95.

[17] Long T., Qian Y., Norman M.D., et al. Constraining the formation and transport of lunar impact glasses using the ages and chemical compositions of Change-5 glass beads // Science advances. — 2022. — Vol. 8, Iss. 39. — eabq2542.

[18] Petit J.M., Kavelaars J.J., Gladman B.J., et al. The Canada-France Eclpitic Plane survey — full data release: The orbital structure of the Kuiper Belt // The Astronomical J. — 2011. — Vol. 142. — Iss. 4. — P. 131.

[19] Burgener J.A. The Amazon Basin is a multi-ring impact basin. — 2015. — (Preprint; DOI: 10.13140/RG.2.1.1333.1042).

[20] Price N.J. Major Impacts and Plate Tectonics. — London: Routledge Press, 2001.

[21] Lisov I. Craters, craters, craters. . . // Cosmonautics News. — 1998. — Vol. 8, Iss. 7. — P. 42 (In Russian).

[22] Racki G. The Alvarez impact theory of mass extinction; limits to its applicability and the "great expectations syndrome" // Acta Palaeontologica Polonica. — 2012. — Vol. 57, Iss. 4. — P. 681–702.

[23] Mikheeva A.V. Web-site "The complete catalog of the Earths impact structures. 3300 records" [Electronic resource]. — 2022. — URL: labmpg.sscc.ru/index1.htlm (application date: 31.10.2022).

[24] Petrenko V.E. Catalogs and data banks for impact craters // Proc. ICM&MG SB RAS. Ser. Mat. models. in Geophysics. — Novosibirsk, 1998. — Iss. 5. — P. 161–180 (In Russian).

[25] Vazhenin A.P., Mikheeva A.V., Dyadkov P.G., Marchuk An.G. The software using digital databases and GIS interface for detecting geodynamic structures // New Trends in Intelligent Software Methodologies, Tools and Techniques / Ed. H. Fujita. — IOS Press, 2017. — P. 576–592.

[26] Dypvik H., Plado J., Heinberg C., et al. Impact structures and events — a Nordic perspective // Episodes. — 2008. — Vol. 31, No. 1. — P. 107–114.

[27] Barash M.S. Interaction of the Reasons for the Mass Biota Extinctions in the Phanerozoic // Okeanologiya. — 2013. — Vol. 53, Iss. 6. — P. 825–837 (In Russian).

[28] Portnov A.M. Golden shower of astroblems // Nature. — 2021. — Vol. 2. — P. 15–24 (In Russian).

[29] Grieve R.A.F. Extraterrestrial impact events: the record in the rocks and the stratigraphic column // Palaeogeography, Palaeoclimatology, Palaeoecology. — 1997. — Vol. 132. — P. 5–23.

[30] Interaction of meteoritic matter with the Earth / Ed. Yu.A. Dolgov. — Novosibirsk: Nauka, 1980 (In Russian).