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Catalog and database on the Earth impact structures*

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Abstract. An Expert Database on the Earth Impact Structures (EDEIS) has been compiled and is being maintained in the Tsunami Laboratory of the Institute of Computational Mathematics and Mathematical Geophysics of SB RAS in Novosibirsk. The database has been developed on the basis of the catalog of Earth impact structures that was being maintained in the Department of Mathematical Problems of Geophysics of ICMMG SB RAS since 1990. In addition to fully validated craters, the database contains also the data on the proposed structures whose impact origin is still needed to be confirmed. For any structure, the degree of confidence in the impact origin is reflected by its validity index V, that can adopt the following values: 4 (confirmed), 3 (probable), 2 (possible), 1 (suspected) and 0 (rejected). The latter relates to the structures, whose once proposed impact origin was later disproved by additional studies. Classification of structures over the validity index is based on some sort of expert judgment and reflects the availability of impact criteria found at four different levels: morphological, geological, petrological and mineralogical. Currently, the database contains 1082 structures, among them 206 structures with $V = 4$, 186 structures with $V = 3$, 501 structures with $V = 2$ and 75 structures with $V = 1$. In addition to the main parametric table, the database in its current version contains over 3200 photos and maps, 860 textual descriptions and 1145 bibliographical references.

1. Introduction

The history of the search and investigation of impact craters on the Earth begins with the Barringer (alternative names are Meteor, Canyon Diablo, Coon Mountain) crater located near Flagstaff, Arizona, USA. The large near-circular depression among the flat deserted area was well known to inhabitants, but until 1905 considered as a paleo-volcanic crater resulted from a volcanic gas explosion. Daniel Barringer, an American mining engineer, was the first to propose meteorite origin of this structure based on the presence of iron particles in and around the crater [4]. However, discussions on the crater genesis continued until 1960 when Eugene Shoemaker, a US geologist and planetary scientist, could finally confirm Barringer's hypothesis [26]. The key element of its proof was the presence of the mineral stishovite, a rare form of silica found only in places where quartz-bearing rocks have been severely shocked by an instantaneous overpressure. This

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mineral cannot be created by volcanic action; the only possible mechanism of creating stishovite is through an impact event. Shoemaker's discovery is considered to be the first definitive proof of an extraterrestrial impact on the Earth's surface. It gave an impulse to a systematic search and study of impact craters on the Earth by now resulted in more than 200 identified and confirmed craters of different size and age. Among them, the Barringer Crater remains the most visually impressive due to its size (1.2 km) and depth (170 m), absence of vegetation cover and geologically young age (49,000 years BP).

2. Earlier catalogs of meteorite craters

Catalogization of impact structures identified on the Earth surface is an important instrument for evaluation of frequency of impacts and for studying the comet and asteroid hazard. Up to present, there are more than 50 catalogs and databases containing parametric and descriptive data on the impact structures discovered on the Earth. Their full list can be found in the "Impact" Section of the Web-Encyclopedia on Natural Hazards supported by the Tsunami Laboratory of the ICMMG SB RAS (http://tsun.sscc.ru/nh/).

To the best of the authors' knowledge, the first compilation of circular structures, suspected to be the impact craters, was presented in 1933 by L. Spenser [27]. At that time, his list contained only the eight structures (Meteor, Odessa, Kaali, Campo del Suelo, Podkamennaya Tungusska, Murgab, Henbury, Wabar), accompanied by detailed description of their basic, mostly morphological features.

Soon after, another survey of 13 craters was published by I. Astapovich, a Russian astronomer [2]. His compilation contains all the eight craters listed in [27] but includes five additional structures (Bosumtwi, Gwarkuh, Haviland, Gulf of Mexico, North Carolina). In concluding remarks of his paper, I. Astapovih mentions Tswang (South Africa) and Lonar (India) but indicates to them as examples of circular depressions on the Earth surface caused by other reasons (e.g. an explosion of volcanic gas). At present, both structures are considered as fully proved meteoritic craters and both are included in the Canadian Earth Impact Database [28].

Basically, the same set of 11–13 structures were included in several further compilations published in the next 30 years [6, 16, 19, 15]. It is interesting to note that the site named "Podkamennaya Tunguska", with the coordinates corresponding to the 1908 bolide explosion, was included to all earlier catalogs despite the fact that the craters from this explosion have never been found.

The essential step in extending this initial list was made by E. Krinov, a Soviet astronomer, who published in 1962 a list of 14 confirmed and 10 suspected craters [18]. Two years later, R. Barringer, in response to the recommendation of the Meteoritical Society, compiled and published a list of meteorite craters "officially approved as such by the Society" [5]. The list contained 27 proved structures listed in the order of the year of identification and was accompanied by a list of 13 structures indicated as suspected craters and an additional list of 12 "large fall sites" containing, in particular, the "Podkamennaya Tunguska" site.

Just one year after, the first compilation of all (or most) of earlier published data on impact structures was made by O'Connel [23] as a result of extensive screening of large set original publications (more than 700) related to meteoritic structures on the Earth. His list contained the descriptive (but structured) data on 116 structures proved or suspected as being meteorite craters.

The first detailed parametric catalog of confirmed and suspected meteorite craters appeared in the book "Explosive craters on the Earth and planets" [7]. The table of parametric data on 115 structures, presented in this book, contained eight fields. V. Fel'dman [8] has elaborated one of the most informative catalogs for 122 confirmed impact structures. His parametric table includes 13 fields having in addition to the basic parameters (coordinates, diameter, depth, age) also the data on geophysical anomalies, shock metamorphism and the presence of meteoritic material.

Several parametric catalogs containing tabulated data on 80–115 structures were compiled and published in the two last decades of XX century [20, 9, 12, 17, 11, 10]. C. Hamilton was the first to post a parametric table of 147 impact structures in Internet [14].

3. From descriptive catalogs to parametric databases

Further progress in compilation of data on the Earth impact structures was associated with converting the parametric catalogs into databases, where data are kept in the active form and can be easily searched and retrieved by complex criteria. The first impact database with global coverage accessible through the Internet was created by the Planetary and Space Science Center (PASSC) of the University of New Brunswick, Canada, in 2003 [30]. In its early version, the PASSC database contained data on 163 structures whose impact origin was acknowledged by database compilers as being confirmed by adopted criteria. At present, the PASSC Earth Impact Database contains 178 structures [28] and is considered by majority, but far not all of members of the impact community as the most authoritative source of information on the meteorite craters on the Earth.

Another approach was used by J. Moilanen [21] who compiled the parametric list of 653 of probable, possible and discredited structures and posted it in Internet. This was the first attempt to assemble the diverse data related to the proposed impact structures on the Earth scattered in different publications. A similar approach was used J. Raymon who in 2005 presented his own compilation of 390 structures with different degree of confidence about their impact origin. Later his compilation was extended up to 896 structures, it is accessible on Internet and continues to be constantly updated [25]. Some experts in the planetary science consider such compilation as a non-critical assemblage of diverse and not fully reliable data related to impacts, while others believe such data anthology to be the useful source of information, anyhow circulating in the scientific literature, Internet and mass media.

The Expert Database on the Earth Impact Structures (EDEIS), described in this paper, has been created and is being maintained by the Tsunami Laboratory of the Institute of Computational Mathematics and Mathematical Geophysics (ICMMG) of SB RAS as a part of project of studying impact generated tsunamis. The important part of this project was the compilation of the data on oceanic impact structures, however, systematization of the data on terrestrial craters found on the Earth was also in the focus of consideration. The EDEIS was created on the basis of the initial catalog of impact structures developed by V. Petrenko and Z. Lyapidevskaya in the Department of Mathematical Problems of Geophysics of ICMMG SB RAS [1, 24]. Initially, it included parametric data on 125 structures, most of them at that time being considered as confirmed meteoritic craters. In addition, the catalog was supplied by a list of 110 probable structures. Since then, a considerable extension of the catalog was made by means of including the data, widely scattered in the literature, on suspected structures whose impact origin is still under investigation.

4. Criteria of identifications of impact craters

As is known [9, 13, 17, 20, 32], the full set of evidences for proving the impact genesis of a suspicious structure includes the study of the four groups of criteria found at different spatial levels:

(1) Morphological criteria discovered on macro-spatial level (10^2–10^5 m): a circular form, the presence of an edge wall, the central uplift (for a complex structure) and associated craters, characteristic diameter/depth ratio, inconsistency with local geological settings, limited drainage area and inconsistency with local hydrographic network (for crater lakes).

(2) Geological criteria discovered at a spatial level of 10^{-1}–10^2 m: ejecta layer, breccias, pseudotachylite, shatter cones, radial faults, presence of melt sheets and dykes.

(3) Petrological criteria discovered at a spatial level of 10^{-4}–10^{-2} m: high-pressure metamorphism of rocks and minerals, a disordered structure of grains, the presence of plagioclase feldspar, etc.).

(4) Mineralogical criteria discovered at a micro-spatial level (10^{-6}–10^{-5} m): planar deformation structure (PDFs), shocked quartz, micro-spherules of different types (silicate, magnetite, carbon), translucent amorphous C, splash in Fe, Ni, Cr content, Iridium anomaly.

Normally, the process of proving the impact origin of a structure should include the investigation made on all the four levels: starting with the initial identification on maps or satellite images (level 1), through the field geological study at level 2 followed by laboratory analysis at levels 3 and 4. However, for too many structures this process is limited to the first, second or third levels, thus leaving some degree of uncertainty on the impact origin of a structure. In the EDEIS, this uncertainty is reflected by the validity index V varying from 4 (confirmed on all four levels), through 3 (probable) and 2 (possible) to 1 (suspected). Therefore, the classification of structures over the validity index is based on some sort of expert judgment and reflects the availability of impact criteria found at the above four levels. In the EDEIS, kept in the constantly updated state, this classification is continuously changing, thus reflecting availability of new data.

5. Content of the current version of the EDEIS database

Currently, the database contains a parametric catalog of 1082 structures, among them 206 structures with the validity index $V = 4$, 186 structures with $V = 3$, 501 structures with $V = 2$, 75 structures with $V = 1$, and 114 structures with $V = 0$. The last group of records includes the structures whose impact origin has once been proposed, but further investigation demonstrated a clear evidence against the impact genesis. We keep these rejected structures on the list, because information about them is somehow circulating in literature and on Internet. In addition to the main parametric table, the database contains over 3200 photos and maps, 860 textual descriptions and 1145 bibliographical references.

For each structure, the main table contains the basic parametric data on geographical location, diameter, depth of depression, estimated age, etc., as well as additional data on availability of further impact criteria, degree of erosion, geophysical anomalies, finding meteorite body remnants, etc. Each structure is provided with bibliographical references to the original publications, catalogs and web-sites that list this particular structure.

Estimation of the age of crater formation is one of the most difficult tasks in the crater research. Only few large meteorites having potential for cratering (such as Wabar, Sikhote Alin', Carancas) were witnessed during their fall thus providing the exact dates of crater formation. For the dating of all other impacts, various direct and indirect methods of geological, paleontological, dendrochronological, archeological dating should be used. Application of

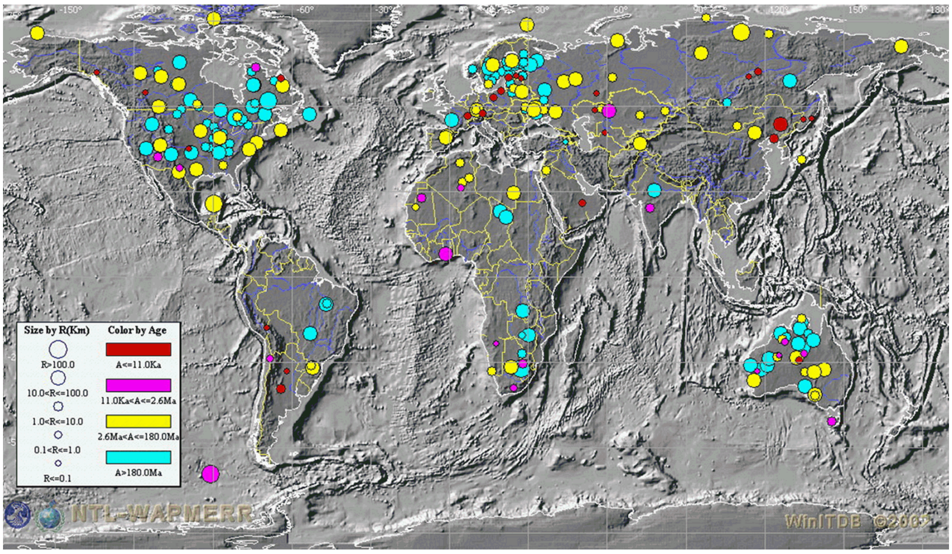


Figure 1. Geographical distribution of 206 impact structures having age estimates and the validity index V=4. The size of circles is proportional to the crater diameter, the density of the grey tone corresponds to the four groups of age (as shown in the inserted legend)

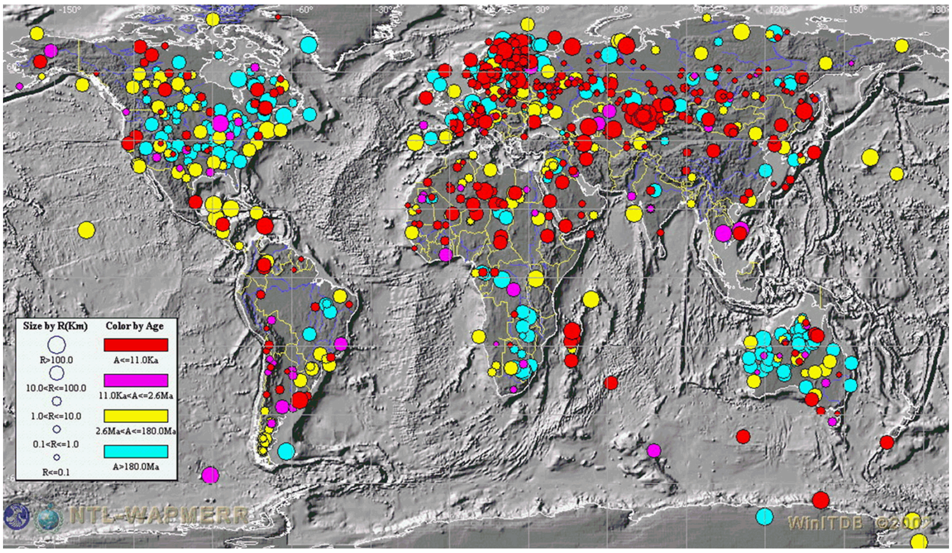


Figure 2. Geographical distribution of 418 structures having age estimates and the validity index $V = 3$, 2, and 1. The size of circles is proportional to the crater diameter, the density of the grey tone corresponds to the four groups of age (as shown in the inserted legend)

different dating techniques to a particular structure quite often gives somewhat different dates. A good example of such a difficultly is the Kaali group of craters. Despite more than 80-year history of investigation, the date of their formation still varies from 800 to 400 BC [3] with the existence of at least one alternative date of 1500 BC [29].

In the EDEIS, from 968 structures the having validity index $V = 1$–4, only 624 (that is 64 %) have assigned age values. Variation of fraction of the dated structures over the groups with different validity index ($V = 4$— 100 %, $V = 3$— 73 %, $V = 2$— 52 %, and $V = 1$— 28 %) clearly reflects the degree of detalization of crater investigation. The geographical location of 624 impact structures, having the age estimates is shown in Figure 1 for structures with validity $V = 4$ and in Figure 2 for structures with validity $V = 3$, 2, and 1. The background maps on both figures are built with the use of mapping system built-in in the WinITDB graphic shell [31]. Two facts are worthwhile to be noted on these figures: (1) geographical pattern of confirmed and proposed impact structures on the Earths surface is generally the same; (2) the spatial distribution of impact craters on the Earth is rather uneven reflecting geological conditions on the surface and the level of geological mapping of the territory.

6. PDM_IMP graphic shell

The earlier version of the database, initially constructed on the basis of DBMS DBASE III, in 2005 was converted into the DBMS MS Access and is provided with a specially developed user interface — PDM (Parametric Data Manager) graphic shell (Figure 3). This graphic shell provides a fast and efficient handling of parametric data (retrieval, listing, editing, sorting, processing and analysis) and gives an access to another type of information— tables, textual descriptions, graphic images, bibliographical references.

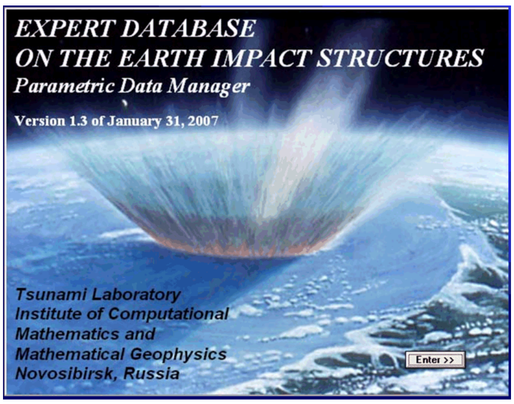


Figure 3. Headpiece of the PDM_IMP graphic shell

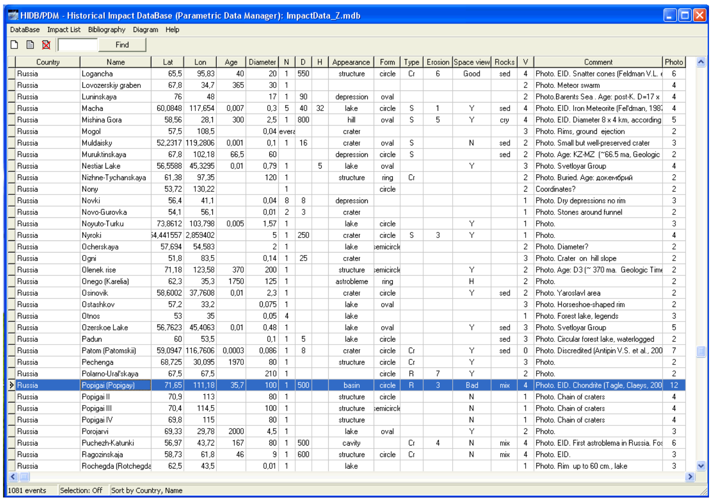


Figure 4. The main screen window of the PDM graphic shell shows a parametric list of the impact structures with their basic parameters. By default, craters in this list are sorted in the order of their countries of origin and the crater names. Clicking the headline of any column allows one to re-sort the listing by this parameter in ascending or descending order

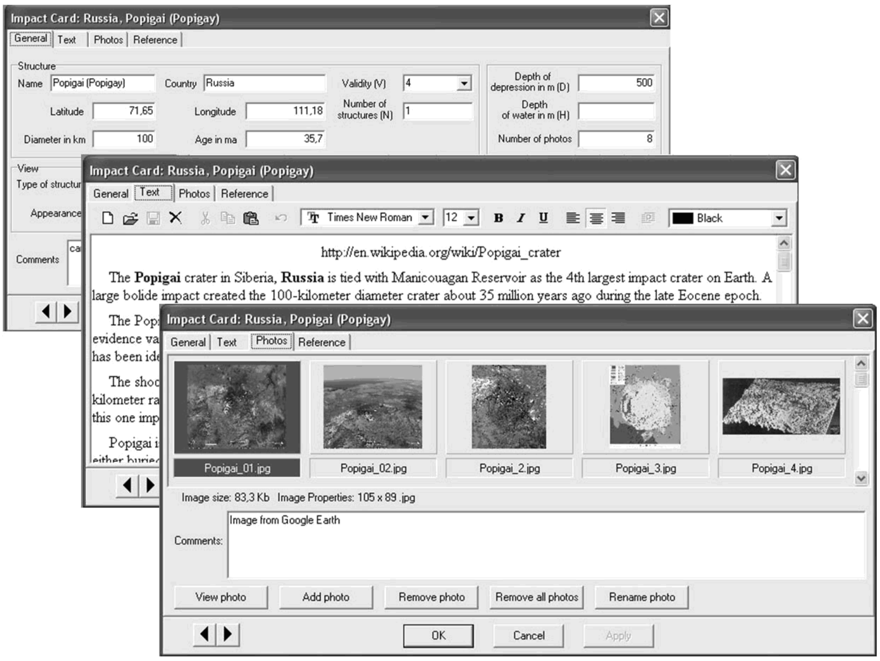


Figure 5. Additional dialog windows provide detailed parametric data, textual description and graphic images for the selected structure (in this example, for the Popigai crater in the north Siberia)

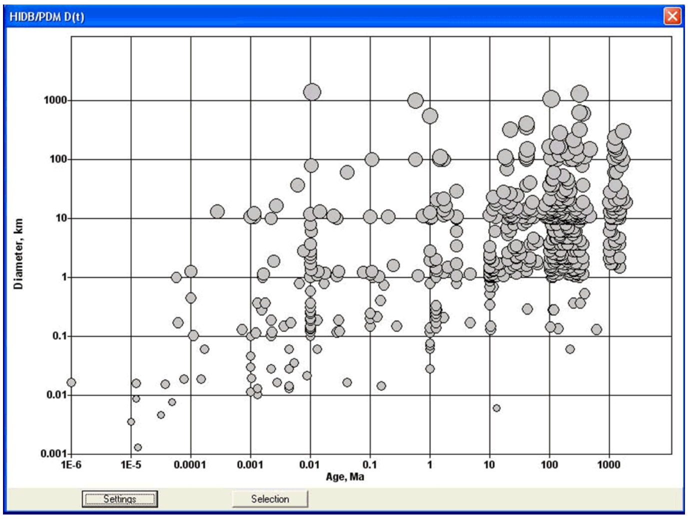
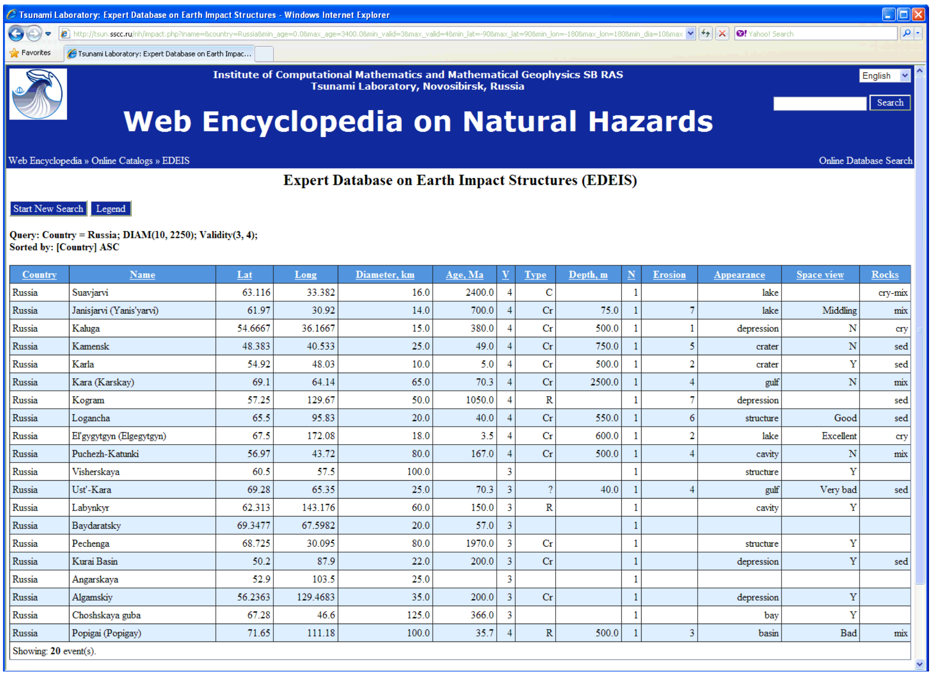


Figure 6. An example of the data processing system built-in the PDM_IMP graphic shell: distribution of the crater diameters over the age



Expert Database on Earth Impact Structures (EDEIS)

Start New Search | Legend

Query: Country = Russia; DIAM(10, 2250); Validity(3, 4);
Sorted by: [Country] ASC

Country	Name	Lat	Long	Diameter, km	Age, Ma	V	Type	Depth, m	N	Erosion	Appearance	Space view	Rocks
Russia	Suavjarvi	63.116	33.382	16.0	2400.0	4	C		1		lake		cry-mix
Russia	Janisjarvi (Yanis'yarvi)	61.97	30.92	14.0	700.0	4	Cr	75.0	1	7	lake	Middling	mix
Russia	Kaluga	54.6667	36.1667	15.0	380.0	4	Cr	500.0	1	1	depression	N	cry
Russia	Kamensk	48.383	40.533	25.0	49.0	4	Cr	750.0	1	5	crater	N	sed
Russia	Karla	54.92	48.03	10.0	5.0	4	Cr	500.0	1	2	crater	Y	sed
Russia	Kara (Karskay)	69.1	64.14	65.0	70.3	4	Cr	2500.0	1	4	gulf	N	mix
Russia	Kogram	57.25	129.67	50.0	1050.0	4	R		1	7	depression		sed
Russia	Logancha	65.5	95.83	20.0	40.0	4	Cr	550.0	1	6	structure	Good	sed
Russia	El'gygytgyn (Elgegytgyn)	67.5	172.08	18.0	3.5	4	Cr	600.0	1	2	lake	Excellent	cry
Russia	Puchezh-Katunki	56.97	43.72	80.0	167.0	4	Cr	500.0	1	4	cavity	N	mix
Russia	Visherskaya	60.5	57.5	100.0		3			1		structure	Y	
Russia	Ust'-Kara	69.28	65.35	25.0	70.3	3	?	40.0	1	4	gulf	Very bad	sed
Russia	Labynkyr	62.313	143.176	60.0	150.0	3	R		1		cavity	Y	
Russia	Baydaratsky	69.3477	67.5982	20.0	57.0	3			1				
Russia	Pechenga	68.725	30.095	80.0	1970.0	3	Cr		1		structure	Y	
Russia	Kurai Basin	50.2	87.9	22.0	200.0	3	Cr		1		depression	Y	sed
Russia	Angarskaya	52.9	103.5	25.0		3			1				
Russia	Algamskiy	56.2363	129.4683	35.0	200.0	3	Cr		1		depression	Y	
Russia	Choshskaya guba	67.28	46.6	125.0	366.0	3			1		bay	Y	
Russia	Popigai (Popigay)	71.65	111.18	100.0	35.7	4	R	500.0	1	3	basin	Bad	mix

Showing: **20** event(s).

Figure 7. Web-version of the EDEIS (http://tsun.sscc.ru/nh/impact.php) provides a remote access to all the volume of parametric data on the Earth impact structures

The main screen window shows the parametric list of impact structures containing the basic set of the quantitative information related to a particular structure (Figure 4). By default, they are sorted by their geographical location and structure's name. The user can easily re-sort the list (in ascending or descending order) by clicking on header of any column in the table. Double-click on any line in the table opens additional dialog windows with more detailed data and information available for this structure (Figure 5). As an example of the data processing system built-in the PDM shell, Figure 6 shows the distribution of crater diameters over the age of formation.

The full version of the database contains about 400 Mb of data and information and is distributed on a CD-ROM. The Internet version, providing the access to the main parametric catalog, can be found at http://tsun.sscc.ru/nh/impact.php. Figure 7 shows the main screen with the list of parametric data retrieved from the database by an user request.

7. Conclusion

The EDEIS database described in this paper is one of the most complete sources of parametric and descriptive information on confirmed and possible impact structures on the Earth. It grew up from the parametric catalog of Earth craters that was being maintained in the Department of Mathematical Problems of Geophysics of SB RAS since 1990.

The word "expert" in the title of the database reflects its main feature—involvement of the expert judgment for classification of structures over the validity index. This index varies from 4 to 1 and reflects the degree of confidence that a particular structure has an impact origin. Any conclusive finding retrieved from the analysis of parametric data included into the database, should be made on the basis of structures having validity index 4 and 3. The structures with validity 2 and 1 are kept in the database as indicators to circular morphological features on the Earth surface that require further investigation.

The history of the Earth craters identification and study shows that quite often it is an extended and complicated process where long debates are involved. It is known, for instance, that the final verification of an impact origin for the Barringer crater required almost 50 years, for the Tswang crater — more than 70 years. Even for the most recent Carancas meteorite in Peru, whose passage over the sky on September 15, 2007 was watched by hundreds of people and was recorded by seismic and infrasonic stations, there was some period of candid discussions about correctness of association of 15m in diameter and 3m deep hole on the surface with the observed meteorite downfall. Taking into account all the complications and difficulties involved in the crater identification, we do believe that many of craters from the last two groups (possible and suspected) collected within the EDEIS will be gradually transferred in the first groups (confirmed and probable).

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