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RAPID COMMUNICATION

Dating impact craters: palaeogeographic versus isotopic and stratigraphic methods – a brief case study

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Abstract

Isotopic and stratigraphic ages of the ~80 km diameter Puchezh-Katunki (Russia; 220 ± 10 to 167 ± 3 Ma) and the ~20 km diameter Obolon (Ukraine; 215 ± 25 to 169 ± 7 Ma) impact structures are associated with significant age uncertainties. As a case study, reconstructions of the palaeogeography at the time of crater formation (Late Triassic to Middle Jurassic) based on recent palaeogeographic maps help further to constrain impact ages. Palaeogeographic studies suggest that Puchezh-Katunki is older than 170 Ma and that Obolon is younger than 185 Ma. This also rules out that Obolon formed during a ~214 Ma Late Triassic multiple impact event as recently discussed.

Keywords: impact structure, dating, palaeogeography, marine impact.

1. Introduction and background

Among the around 175 impact structures currently known on Earth, the majority is still insufficiently dated (e.g. Reimold, 2007; Earth Impact Database, 2008: http://www.unb.ca/passc/ImpactDatabase; accessed on April 15, 2008). In many cases, the age of the target rock provides the only (maximum) age constraint for crater formation (e.g. the < 1.9 Ga Paasselkä impact structure, Finland; Schmieder, Moilanen & Buchner, 2008). Besides some exceptionally good ages (e.g. the 14.4 ± 0.1 Ma Ries crater, Germany (Buchner, Seyfried & van den Bogaard, 2003); the 64.98 ± 0.05 Ma Chicxulub crater, Mexico (Swisher *et al.* 1992); the 214 ± 1 Ma Manicouagan crater, Québec, Canada (Hodych & Dunning, 1992); the 682 ± 4 Ma Jänisjärvi impact structure, Russia (Jourdan, Renne & Reimold, 2008); the 2.023 Ga age for the Vredefort impact structure, South Africa (Kamo *et al*. 1996)), isotopic age data obtained from impact melt rocks and glasses are commonly of high apparent precision but of equivocal accuracy due to the use of poorly reliable chronometers (e.g. K–Ar or Rb–Sr) or over-interpretation of inaccurate or scattered dating results caused by rock alteration or post-impact thermal overprint (Reimold *et al.* 2005; Jourdan, Renne & Reimold, 2007, 2008; Renne, Jourdan & Reimold, 2007). At impact structures that lack lithologies suitable for isotopic dating, tentative stratigraphic dating commonly accounts for significant age uncertainties of up to 100 % (e.g. the 250 ± 80 Ma Kursk impact structure, Russia, or the 200 ± 100 Ma Wells Creek impact structure, Tennessee, USA). At higher levels of precision, biostratigraphic dating may yield apparently precise age data (e.g. the 167 ± 3 Ma Puchezh-Katunki impact structure, Russia, which was dated using palynostratigraphic methods by Masaitis & Pevzner, 1999), but these techniques still lack satisfactory international calibration (e.g. Pálfy, 2005). Discussing the highly variable impact ages reported for the large Puchezh-Katunki crater (Russia) and the Obolon impact structure (Ukraine), this brief and critical case study intends to emphasize palaeogeographic studies as a supporting method to test, disprove, affirm, and further constrain incoherent isotopic and stratigraphic ages of terrestrial impact structures.

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2. Impact structures

As an exemplary case study, palaeogeographic considerations focus on the Puchezh-Katunki (Russia) and Obolon (Ukraine) impact structures that are buried beneath Mesozoic to Cenozoic sedimentary rocks of the Russian Platform and the Ukrainian Shield (e.g. Masaitis, 1999).

2.a. Puchezh-Katunki, Russia

The ~80 km diameter Puchezh-Katunki crater (Russia; centred on 56°58′ N, 43°43′ E) counts among the ten largest impact structures known on Earth and even among the five largest that were generated during Phanerozoic time. The whole structure lies within Archaean crystalline and uppermost Proterozoic to Lower Triassic sedimentary rocks of the Russian Platform and is overlain by Middle–Upper Jurassic (crater lake sediments of the Kovernino Formation) and younger post-impact sediments. Impactite lithologies comprise lithic impact breccias, suevites, and subordinate impact melt rocks (Masaitis & Mashchak, 1990; Masaitis, Mashchak & Naumov, 1996; Masaitis, 1999; Pálfy, 2005). Enrichment in Os and Ir and specific interrelations of siderophile elements in suevites suggest a chondritic body as impactor for the Puchezh-Katunki structure (Masaitis & Balmasov, 1996; Masaitis, 1999). Although extensively studied and deeply drilled in the central uplift area (the Vorotilovo deep scientific well drilled 1989–1992 reached a depth of 5374 m), the Puchezh-Katunki impact structure has not yielded reliable age data (Fig. 1; Table 1). Masaitis & Mashchak (1990) and Ivanov (1994) proposed an age of 220 ± 10 Ma by stratigraphic methods, which would correspond to a Late Triassic impact age. In

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Table 1. Impact ages for the Puchezh-Katunki and Obolon impact structures as reported in the literature (also compare Fig. 1)

Impact structure	Reported age (Ma)	Method	References
Puchezh-Katunki, Russia	220 ± 10	stratigraphic	Masaitis & Mashchak (1990) Grieve (1991) Grieve & Pesonen (1992) Ivanov (1994)
	200 ± 3**	K–Ar (suevite glass)	Masaitis & Pevzner (1999)
	~ 180–200	stratigraphic	Firsov (1973) Ivanov (1992)
	183 ± 5**	K–Ar (suevite glass)	Grieve (1987) Masaitis & Pevzner (1999)
	167 ± 3*	palynostratigraphic	Masaitis (1999) Masaitis & Pevzner (1999)
	> 170	palaeogeographic	this study
Obolon, Ukraine	215 ± 25	stratigraphic	Masaitis *et al.* (1980) Grieve (1987; 1991) Spray, Kelley & Rowley (1998)
	169 ± 7*	K–Ar (suevite glass)	Masaitis (1999) Valter *et al.* (2000)
	< 185	palaeogeographic	this study

*currently accepted as impact age in the Earth Impact Database (April 15, 2008); http://www.unb.ca/passc/ImpactDatabase.
**see also Pálfy (2005) for discussion.

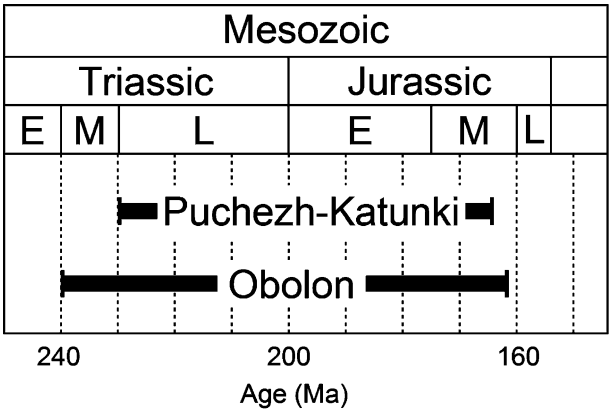


Figure 1. Impact age ranges for the Puchezh-Katunki and Obolon structures, compiled from the literature (compare Table 1).

contrast, K–Ar isotopic dating of impactites by Masaitis & Pevzner (1999) resulted in ages of 200 ± 3 Ma and 183 ± 5 Ma, which suggest impact ages respectively at the Triassic–Jurassic transition or for the Lower Jurassic (the latter would also correlate with the first stratigraphic age estimations of ~ 180–200 Ma for Puchezh-Katunki given by Firsov, 1973). Masaitis (1999) and Masaitis & Pevzner (1999) reported a Middle Jurassic age of 167 ± 3 Ma for Puchezh-Katunki obtained by palynostratigraphic studies of the oldest crater lake deposits. A discussion of the impact age of the large Puchezh-Katunki structure and its possible relation to Mesozoic extinction events is given by Pálfy (2005), who concluded that 'the possibility cannot be ruled out that the Puchezh-Katunki impact is coeval with either the end-Triassic or the Early Jurassic (Pliensbachian–Toarcian) extinction'.

2.b. Obolon, Ukraine

The ~ 20 km Obolon crater (Ukraine; centred on 49°35′ N, 32°55′ E) is located within Carboniferous to Lower Triassic sedimentary rocks that overlie Early Proterozoic crystalline rocks of the northeastern Ukrainian Shield (Donets Graben region). The impact structure, with a deep central annular basin, a flat central uplift, local depressions, and gentle outer slopes, is covered by up to 500 m of Middle Jurassic to Cenozoic sedimentary rocks. Core drilling recovered lithic breccias and suevites in the annular trough of the structure. Small particles of taenite and kamacite found in suevite were interpreted as remnants of the Obolon impactor (Valter & Ryabenko, 1977), probably an iron meteorite (Grieve, 1991; Grieve & Pesonen, 1992). Enrichment in Cl and Br in impact glasses (Gurov & Gurova, 1995), together with an inverted sombrero structure and the presence of poorly graded 'resurge breccia' deposits in the central crater basin, indicate a shallow marine Obolon impact scenario (Valter, 2002). Stratigraphic dating by Masaitis *et al.* (1980) suggested a most likely Late Triassic age of 215 ± 25 Ma for the Obolon impact structure (see also Grieve, 1987, 1991; Spray, Kelley & Rowley, 1998). K–Ar ages of suevite glass samples, in contrast, yielded a Middle Jurassic age of 169 ± 7 Ma (Masaitis, 1999; Valter *et al.* 2000; Fig. 1; Table 1). Spray, Kelley & Rowley (1998) proposed that the Obolon crater could be part of a semi-global-scale impact crater system (together with the impact structures of Manicouagan, Québec, Canada; Lake Saint Martin, Manitoba, Canada; Red Wing Creek, North Dakota, USA; Rochechouart, France; as well as possibly Wells Creek, Tennessee, USA, and Newporte, North Dakota, USA) that formed during a Late Triassic multiple impact event ~ 214 Ma ago (see Table 2).

3. Discussion

Although the Puchezh-Katunki and Obolon impact craters have been well investigated (core drilling, petrography and geochemistry of impactites, sedimentology, geophysics; see Masaitis, 1999, for summary), both structures are associated with significant age uncertainties. At the large Puchezh-Katunki impact structure, results of stratigraphic dating (220 ± 10 Ma), isotopic dating of impact glasses (200 ± 3 Ma and 138 ± 5 Ma), and palynostratigraphic dating of the lowermost crater lake sediments (167 ± 3 Ma) cover a range of uncertainty of 66 Ma (Fig. 1; see also Pálfy, 2005, for discussion). The same obviously holds true for the Obolon crater (215 ± 25 to 169 ± 7 Ma), which is associated

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Table 2. Proposed members of a Late Triassic (~ 214 Ma) impact cluster as postulated by Spray, Kelley & Rowley (1998)

Impact structure	Diameter (km)	Age (Ma)	Dating method	Reference
Manicouagan, Québec, Canada	100	214 ± 1*	U–Pb (zircon from melt rock)	Hodych & Dunning (1992)
Lake Saint Martin, Manitoba, Canada	40	219 ± 32	Rb–Sr (melt rock)	Reimold *et al.* (1990)
Rochechouart, France	24	214 ± 8*	^{40}Ar–^{39}Ar laser fusion (pseudotachylite)	Kelley & Spray (1997)
Red Wing Creek, North Dakota, USA	9	210 ± 10	stratigraphic	Koeberl, Reimold & Brandt (1996)
Obolon, Ukraine (see discussion)	20	215 ± 25	K–Ar (suevite glass)	Masaitis *et al.* (1980) Spray, Kelley & Rowley (1998)
Wells Creek, Tennessee, USA	12	200 ± 100*	stratigraphic	Grieve (1991)
Newporte, North Dakota, USA	3.2	~ 500	stratigraphic	Koeberl & Reimold (1995)

*currently accepted as impact age in the Earth Impact Database (April 15, 2008); http://www.unb. ca/passc/ImpactDatabase.

with an age uncertainty of 78 Ma (Fig. 1; see Table 1 for variable impact age data reported in the literature and references).

Different environmental (continental or marine) conditions basically influence the development of structural and sedimentary features at terrestrial impact sites (e.g. Dypvik & Jansa, 2005) and can be used to constrain the timing of an impact event. According to palaeogeographic maps by Ziegler, Scotese & Barrett (1983) and Golonka (2000, 2007), most parts of the Russian Platform and the Ukrainian Shield were continental during Triassic and Early Jurassic time; marine sediments were deposited from Bajocian or Bathonian (~ 170 Ma) time onwards in this region (e.g. Ziegler, Scotese & Barrett, 1983; Pálfy, 2005). An exception was the Donets Graben, which was already flooded in Early Toarcian time (~ 180–185 Ma; Krymholts, 1972; Ziegler, Scotese & Barrett, 1983; Pálfy, 2005; Fig. 2). At Puchezh-Katunki, crater lake sediments up to ~ 200 m in thickness (e.g. Masaitis, Mashchak & Naumov, 1996; Pálfy, 2005) suggest that the impact structure formed under continental conditions. The palaeogeographic framework is in general conflict with the recent palynostratigraphic dating results for the Puchezh-Katunki crater (167 ± 3 Ma corresponding to Bajocian–Bathonian time; Masaitis & Pevzner, 1999; see also Pálfy, 2005 for discussion), as this age would imply a marine impact scenario (Fig. 2). The lacustrine (i.e. continental) crater sediments of the Kovernino Formation, in contrast, rather support a Late Triassic to early Middle Jurassic minimum age (> 170 Ma) of the Puchezh-Katunki impact structure. Stratigraphic dating of the Obolon impact structure suggested an age of 215 ± 25 Ma (corresponding to Middle Triassic to Early Jurassic time; Masaitis *et al.* 1980; see also Spray, Kelley & Rowley, 1998). Impacts into marine targets are characterized by specific (mostly soft) rock deformation behaviour and submarine sedimentary processes involved in crater formation (such as deposition of 'resurge breccia'; Sturkell, 1998; Ormö & Lindström, 2000; King *et al.* 2002; Dypvik, Burchell & Claeys, 2004; Poag, Koeberl & Reimold, 2004; Dypvik & Jansa, 2005). From the fact that Obolon is a marine impact structure (Gurov & Gurova, 1995; Valter, 2002), a Late Triassic crater formation under continental conditions is unlikely. Thus, from a palaeogeographic point of view, marine ingression in the Donets Graben at ~ 180–185 Ma (Ziegler, Scotese & Barrett, 1983; Pálfy, 2005; Fig. 2) provides an Early Jurassic maximum age (< 185 Ma) for the Obolon impact structure. This also precludes that the Obolon structure could be a member of the putative ~ 214 Ma Late Triassic multiple impact system postulated by Spray, Kelley & Rowley (1998). Further field work and refined isotopic dating of suitable materials (e.g. ^{40}Ar–^{39}Ar dating of least-altered impact melt rocks and glasses; high-resolution U–Pb dating of zircons grown in impact melt rocks) will be necessary to obtain more accurate and representative impact ages for both impact structures.

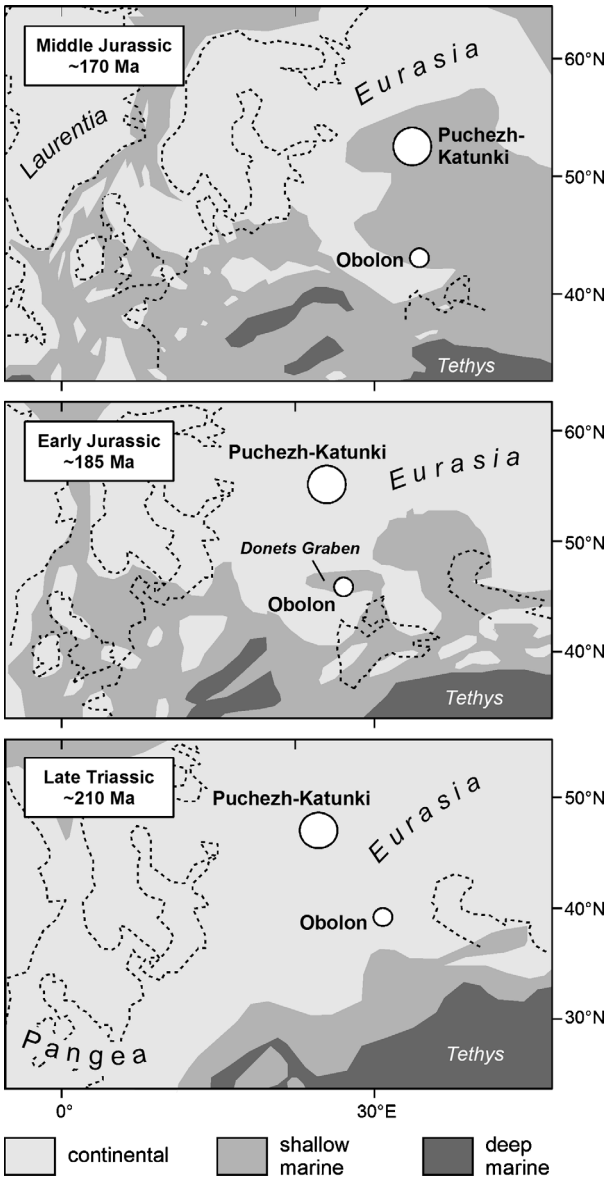


Figure 2. Palaeogeographic map of Eurasia in Late Triassic, Early Jurassic, and Middle Jurassic time (modified from Golonka, 2000, 2007) and the positions of the Puchezh-Katunki and Obolon impact structures (Mollwide projection).

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4. Summary and conclusions

In addition to isotopic and stratigraphic dating, palaeogeographic studies can be an appropriate method to check and further constrain possible formation ages of terrestrial impact structures. The available isotopic and stratigraphic ages of the Puchezh-Katunki and Obolon impact structures are highly incoherent and associated with age uncertainties of up to 66 Ma for Puchezh-Katunki (220 ± 10 Ma to 167 ± 3 Ma) and 78 Ma for Obolon (215 ± 25 Ma to 169 ± 7 Ma), respectively. Palaeogeographic reconstructions, according to Late Triassic to Middle Jurassic palaeogeographic maps by Ziegler, Scotese & Barrett (1983) and Golonka (2000, 2007), suggest that the continental Puchezh-Katunki crater is older than 170 Ma and that the marine Obolon impact structure is younger than 185 Ma. Furthermore, these observations rule out that the Obolon impact structure formed during a ~ 214 Ma Late Triassic multiple impact event as recently discussed. This work underlines that the chronological data for impact craters and impact stratigraphic correlations (e.g. as listed in the Earth Impact Database) should not be applied without careful examination of the original literature.

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