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The Obolon impact structure, Ukraine, and its ejecta deposits

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Abstract–The Obolon impact structure, 18 km in diameter, is situated at the northeastern slope of the Ukrainian Shield near its margin with the Dnieper-Donets Depression. The crater was formed in crystalline rocks of the Precambrian basement that are overlain by marine Carboniferous and continental Lower Triassic deposits. The post-impact sediments comprise marine Middle Jurassic (Bajocian and Bathonian) and younger Mesozoic and Cenozoic deposits. Today the impact structure is buried beneath an about 300-meter-thick sedimentary rock sequence.

Most information on the Obolon structure is derived from two boreholes in the western part of the crater. The lowest part of the section in the deepest borehole is composed by allogenic breccia of crystalline basement rocks overlain by clast-rich impact melt rocks and suevites. Abundant shock metamorphic effects are planar deformation features (PDFs) in quartz and feldspars, kink bands in biotite, etc. Coesite and impact diamonds were found in clast-rich impact melt rocks. Crater-fill deposits are a series of sandstones and breccias with blocks of sedimentary rocks that are covered by a layer of crystalline rock breccia.

Crystalline rock breccias, conglomeratic breccias, and sandstones with crystalline rock debris have been found in some boreholes around the Obolon impact structure to a distance of about 50 km from its center. Those deposits are always underlain by Lower Triassic continental red clay and overlain by Middle Jurassic marine clay. The K-Ar age of impact melt glasses is 169 Ma, which corresponds to the Middle Jurassic (Bajocian) age. The composition of crater-fill rocks within the crater and sediments outside the Obolon structure testify to its formation under submarine conditions.

INTRODUCTION

The Obolon impact structure is situated in Ukraine at the left bank of Dnieper River, or, more exactly, in the watershed of its tributaries Sula and Khorol (Fig. 1). A morphological depression about 17 km in diameter was first found in the crystalline basement rocks by Chirvinskaya in 1947 (Chirvinskaya et al. 1968) from geophysical evidence. Extrapolating from the observed similar geophysical features of this structure compared to those of the Boltysh Depression, which contains commercial oil shale deposits, two deep boreholes (numbers 5301 and 5302) were drilled in the Obolon Depression in 1965–66 for oil shale prospecting (Vandenko and Yukhimenko 1966). Beneath the Mesozoic-Cenozoic sediments, breccia of crystalline and sedimentary rocks and tuff-like breccia were initially interpreted as products of volcanic and tectonic activity (Chirvinskaya et al. 1968).

The impact origin of the Obolon Depression was confirmed by Masaitis et al. (1976) and Valter et al. (1977) through examination of core samples from the two boreholes, in which characteristic signs of shock metamorphism were recognized. After that, the Obolon structure was included in all lists of terrestrial meteorite craters (e.g., Grieve and Robertson 1979; Grieve 1991; Gurov and Gurova 1991; Grieve et al. 1995; Poag et al. 2004; Earth Impact Database 2007; etc.). Some main features of the Obolon structure, description of shock metamorphism of the rocks, composition of impact melts, and some another data were published almost exclusively in Russian (e.g., Valter and Ryabenko 1977; Masaitis et al. 1980; Gurov et al. 1995b; Gurov and Gozhik 2006).

Several impact structures contain accumulations of various economic deposits (e.g., Grieve and Masaitis 1994; Reimold et al. 2005). Accordingly (e.g., Carpenter and Carlson 1997; Donofrio 1997; Grieve 1997), many impact structures in the petroleum-bearing basins of the USA and Canada contain commercial hydrocarbon accumulations. In this context, impact structures formed in petroleum-bearing basins can be considered as potential hydrocarbon deposits. The position of the Obolon structure in the marginal part of the Ukrainian Shield near its boundary

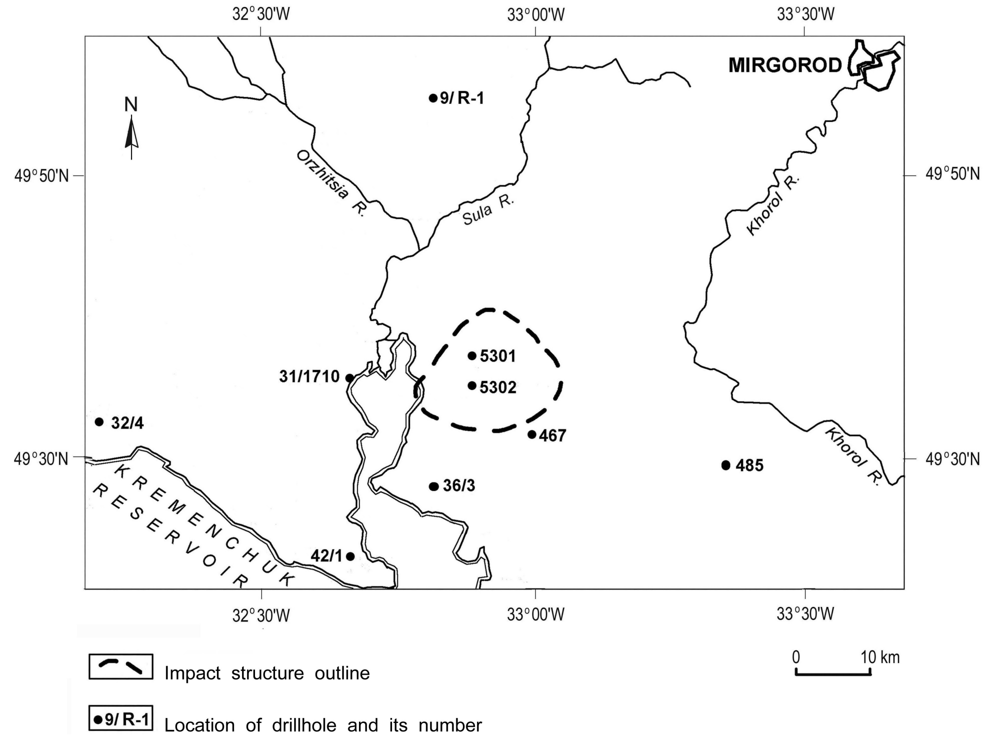

Fig. 1. Location of drillholes that penetrated the Obolon impact structure and impact deposits in the surrounding area. The crater outline shown (dotted line) follows the contours of the gravity anomaly.

with the petroleum-bearing Dnieper-Donets Depression is consistent with a probable hydrocarbon accumulation in it (Krayushkin and Gurov 1989; Krayushkin et al. 1994; Gurov and Gurova 2000).

Several years before the discovery of the Obolon Depression, Pritchina et al. (1963) described coarse clastic deposits in some boreholes in this area, at the boundary of Lower Triassic and Middle Jurassic units, which are unusual for the platform sedimentary section. That sequence of breccia, conglomerate, sand, and sandstone together with crystalline rock debris was described as tuffs, tuff breccias, and sedimentary breccias and was not studied in any detail. The location of those coarse-grained sediments around the Obolon structure, and their stratigraphic position and composition are consistent with ejecta deposits.

This paper summarizes data on the Obolon impact structure that were obtained during several decades of study and mostly published in Russian. Special attention is given to a discussion of the evidence that the crater formed within a shallow marine basin. Using unpublished archive data, the first description of ejecta and tsunami deposits around the crater is given.

MATERIALS AND METHODS OF INVESTIGATION

The structure of the Obolon crater, the composition of the impact rocks, and evidence of shock metamorphism have been studied from core samples of boreholes 5301 and 5302. This examination enabled us to re-interpret "tuffs" and "tuff breccias" that were described by Vandenko and Yukhimenko (1966) as suevites and allogenic lithic breccias. At the same time, the data of those authors on the age of the sedimentary units and on the flora and fauna are reported without modification.

The sections of boreholes, which penetrated sediments around the Obolon structure, are described using unpublished data of the State Geological Archives of Ukraine in Kiev: boreholes 467 and 485 by Pritchina et al. (1963), boreholes 36/3, 32/4, 31/1710, and 42/1 by Bezugly et al. (1960), and borehole 9/R-1 by Litvinov (1947). It is important to note that all these boreholes penetrated the coarse clastic sequence at the Lower Triassic-Middle Jurassic boundary. Some rocks, which were described by the authors mentioned above as tuffs, tuff breccias, and tuffites, were re-interpreted by us as impact-related suevites, allogenic breccias, and tsunami deposits.

A summary stratigraphic section of platform sediments in this area was compiled using data of Voynovsky and Shagan (1974) on boreholes 5301 and 5302, as well as sections of the boreholes listed above.

The impact origin of the Obolon structure was confirmed by the study of samples of impactites from boreholes 5301 and 5302. Shock pressures were determined by refractive indices of shock-metamorphosed quartz, using data from Stöffler and Langenhorst (1994). To evaluate shock pressures lower 20 GPa, X-ray examination of

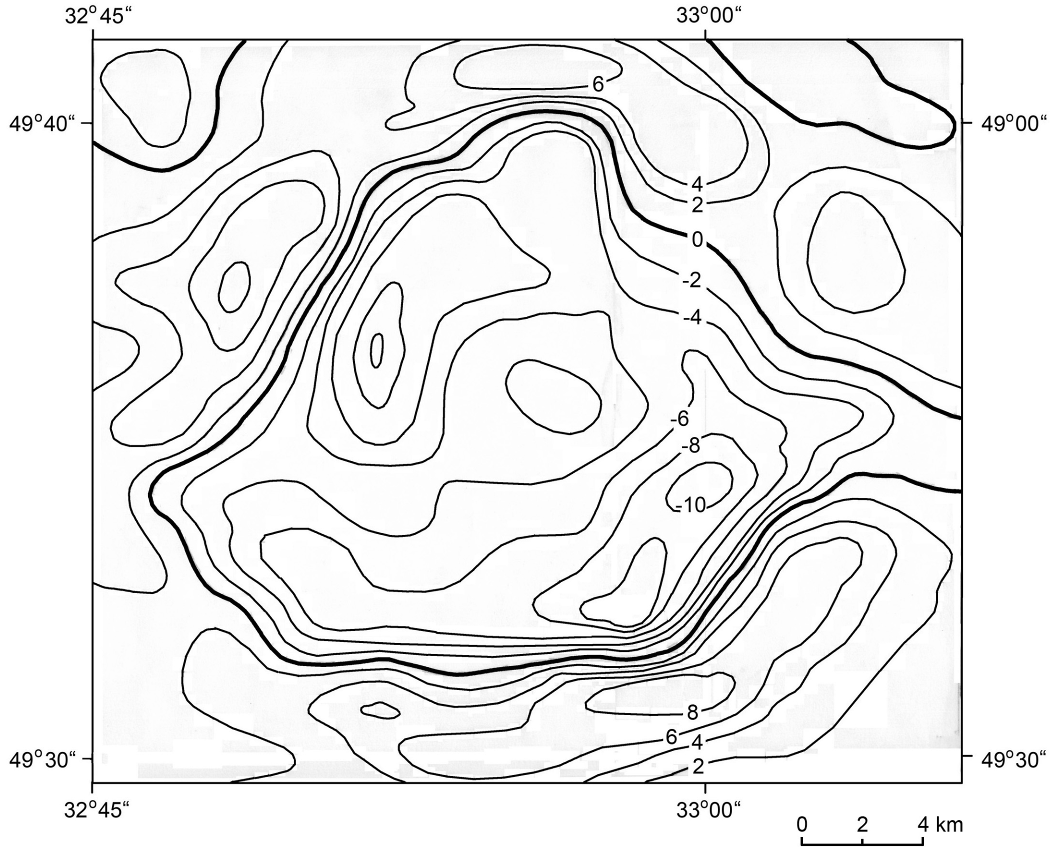

Fig. 2. Residual Bouguer gravity anomaly over the Obolon impact structure (regional values removed), after Galchenko and Kukuruza (1992). Contour interval 2 mGal.

individual quartz grains was made for the determination of their asterism grade and for comparison with experimental data (Hörz and Quaide 1973).

Coesite was confirmed by X-ray diffractometry of shock-metamorphosed quartz fractions after their partial solution in hydrofluoric acid (Gurov et al. 1980). Impact diamonds were searched for and extracted from the insoluble residuum of clast-rich impact melt rock samples from borehole 5302 after decomposition of their silicate constituents in high-temperature alkaline melt using a technique by Kashkarov and Polkanov (1970).

GEOLOGICAL BACKGROUND

Location and Size of the Obolon Impact Structure

The Obolon impact structure is situated in the northeastern marginal part of the Ukrainian Shield and is centered at 49°35′N and 32°56′E. In this region the surface of the shield dips gently towards the Dnieper-Donets Depression. As the crater is buried under thick Mesozoic-Cenozoic sediments, it has no present-day geomorphic expression and does not appear in space and aerial images.

The residual Bouguer negative gravity anomaly over the Obolon structure is −10 mGal (Fig. 2) (Galtchenko and Kukuruza 1992). The relative rise of the anomaly intensity to −4 mGal in the central part of the structure is interpreted to be due to the uplift of dense rocks of the crystalline basement forming its central peak. The minimal intensities of the anomaly to −10 mGal are located around the central rise in the E-SE-S and W-NW-N parts of the structure. Arcuate positive anomalies of up to +8 mGal occur around the negative anomaly to the E-S-E, NW and the N of it. They are interpreted as to the structural uplift of dense crystalline rocks of the crater rim. According to the parameters of the anomaly, the dimensions of the Obolon structure are about 19 km in E-W direction and 17 km in N-S direction; hence its diameter is estimated at about 18 km.

The structure of the Obolon impact site is known from two drillholes 5302 and 5301 in its western part and drillhole 467 at the SE rim (Fig. 3). The deepest part of the structure was formed in the crystalline basement rocks. The peripheral zone of the structure was formed in the platform deposits of the Carboniferous and Lower Triassic. A structural uplift of dense crystalline rocks in the rim is suggested by the presence of arcuate positive gravity anomalies around the central negative anomaly. Thick Mesozoic-Cenozoic sediments cover the Obolon structure.

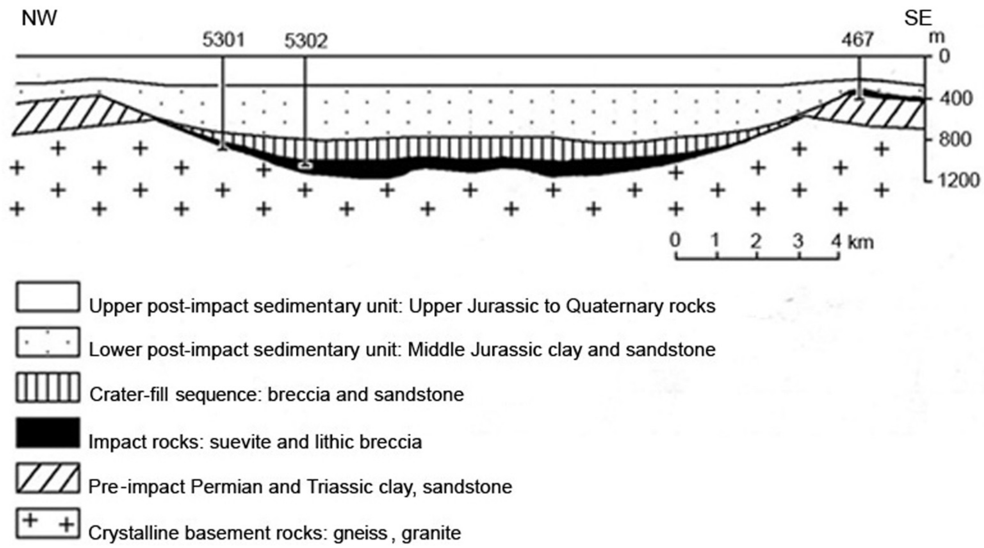

Fig. 3. Interpreted cross section of the Obolon impact structure, based on results from boreholes 5301, 5302 and 467, as well as gravity data and analogy with similar crater structures.

Crystalline Basement Rocks

The crystalline basement in this region is formed by the Precambrian gneisses and granites. They form a complex sequence of Ingul gneisses and Kirovograd-Zhitomir granitoids of Lower Proterozoic age (Voynovsky and Shagan 1974). Within the impact structure, crystalline basement rocks (gray and pinkish-gray granite) occur in borehole 5301 from the bottom of the hole at 836.7 m up to 824 m, and outside the crater in borehole 36/3 in the interval from the bottom of the hole at 452.3 m to 444.9 m.

Platform Sedimentary Rocks

During the largest part of the Phanerozoic, the northeastern slope of the Ukrainian Shield in the locality of the Obolon structure was a land and ablation region. In the Paleozoic, only since the Middle Devonian till the Bashkirian time of the Carboniferous, a significant part of the shield's territory underwent a transgression (*Atlas of Paleogeographic Maps 1960*). Through the Mesozoic, the transgression spread in the Middle Jurassic onto the northeastern part of the shield occupying the location of the Obolon structure. The maximum expansion of that marine basin was in the Middle Jurassic (Bajocian and Bathonian time), but marine sedimentation persisted till the Kimmeridgian. The following transgression during the Late Cretaceous embraced the northeastern slopes of the shield to the recent location of the Dnieper valley. The last transgression covered most part of the Ukrainian Shield in the Eocene-Oligocene (*Atlas of Paleogeographic Maps 1960*).

In the vicinity of the Obolon structure, the Precambrian crystalline basement is covered by platform formations up to 500 m thick, of which about 300 m accumulated before the impact (Fig. 4). The surface of the crystalline basement is covered by Carboniferous sediments that were drilled in borehole 36/3. That rock sequence consists of alternating clays, shales, siltstones, and sandstones with limestone interlayers. The rocks are of gray, greenish-gray, and violet color, their thickness is 9 m in borehole 36/3 (southwestern part of the area) and increases to 240 m in borehole 9/R-1 (38 km north of the crater center). The sediments contain the fauna that is characteristic for the Bashkirian Stage of the Carboniferous System (Vandenko and Yukhimenko 1966). Within the Obolon structure, those rocks are present in breccias of the crater fill as limestone and sandstone clasts and blocks with Bashkirian fauna and microfauna.

A thick sequence of the sandy-clayey Lower Triassic sediments occurs on top of the Carboniferous rocks. In the Obolon structure their debris and blocks are the main components of the crater-fill breccia. The most complete sections of the Lower Triassic sediments exist in borehole 36/3, where their thickness is 139 m, and in borehole 485, where the penetrated part of this sequence is 73 m. In borehole 467, supposedly situated on the slope of the rim, authigenic block breccias of the Lower Triassic sediments were drilled in the interval from the bottom of the hole at the depth of 402 m to the base of the crystalline rock breccia at 338 m (Figs. 4 and 6).

The Lower Triassic sediments are represented by a sequence of alternating clays, sands and sandstones. They have characteristic motley colors from red and brick-red to light gray. Due to the prevailing red color of the rocks, their clasts are easily recognized in the breccias. The rock sequence rarely contains traces of chara algae and ostracodes. Vandenko and Yukhimenko (1966) described traces of the Lower Triassic chara algae in blocks of breccias from borehole 5301, which may be correlated with the Lower

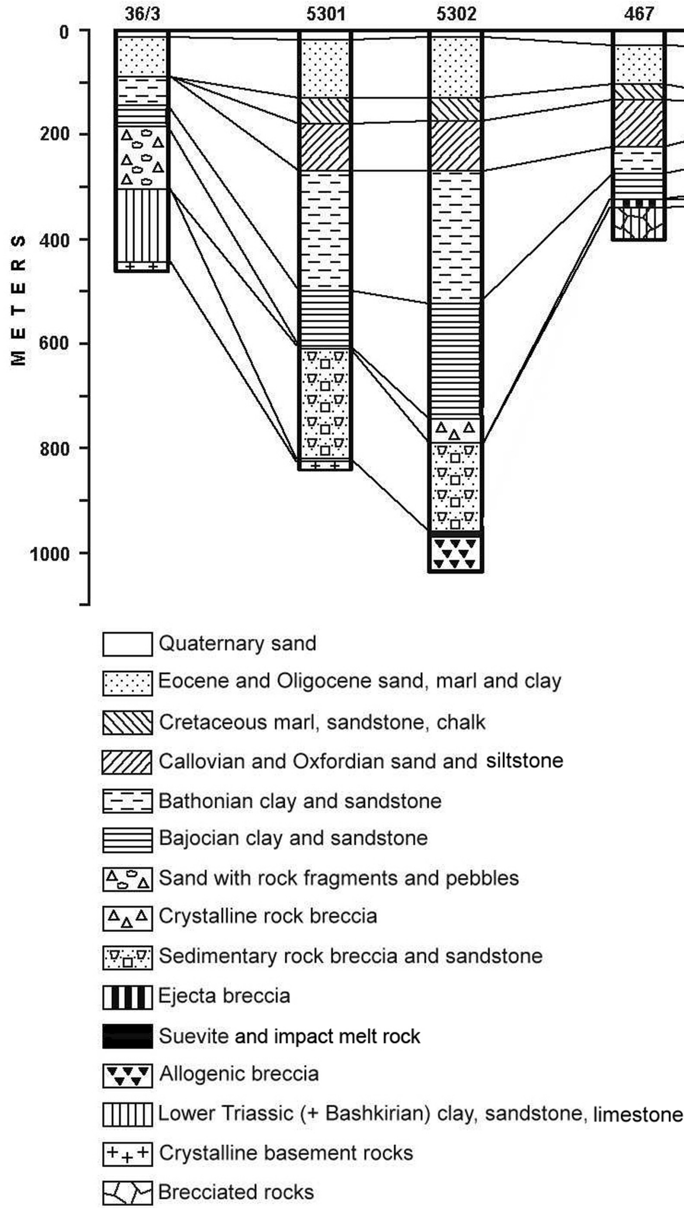

Fig. 4. Regional correlation of drillholes that penetrated the Obolon impact structure (5301 and 5302) and impact deposits in surrounding areas (36/3, 467 and 485).

Triassic algae of the Russian Platform: *Stenochara shaikini* S a i d., *Moslavichara retunda* S a i d., *Porochara triassica* G r a m b., *Lotochara acuta* S a i d., *Cuneatochara acuminata* S a i d., *Auerbachichara bascuntschakiensis* K i s. According to Voynovsky and Shagan (1974), the Lower Triassic sediments are continental deposits, which accumulated in lakes, river valleys, and temporary streams.

Post-Impact Sedimentary Strata

The post-impact sediments of the Obolon structure are Middle Jurassic marine deposits covering the breccias. The breccias of the crater fill in borehole 5302 in the interval from 747 m are overlain by a basal sand and sandstone sequence with inclusions of crystalline rock debris. Above, in the interval of 732–523 m, a sequence of gray clays with sandstone interlayers occurs. The rocks have clear horizontal lamination. The sequence contains Middle Jurassic (Late Bajocian) macro- and microfaunal fossils as described by Vandenko and Yukhimenko (1966): the Middle Jurassic marine microfauna *Ammodiscus baticus* D a i n., *Ammobaculites sp., Trochammina aquamataformis* K a p t. were found in the interval 727–726 m; the late Bajocian microfauna was described from the interval of 630.7 to 524.1 m: *Ammobaculites agglutinantis* O r b., *Ammodiscus incertu*s (O r b.), *Trochammina aquametaformis* K a p t., *Glomospira gordialis*

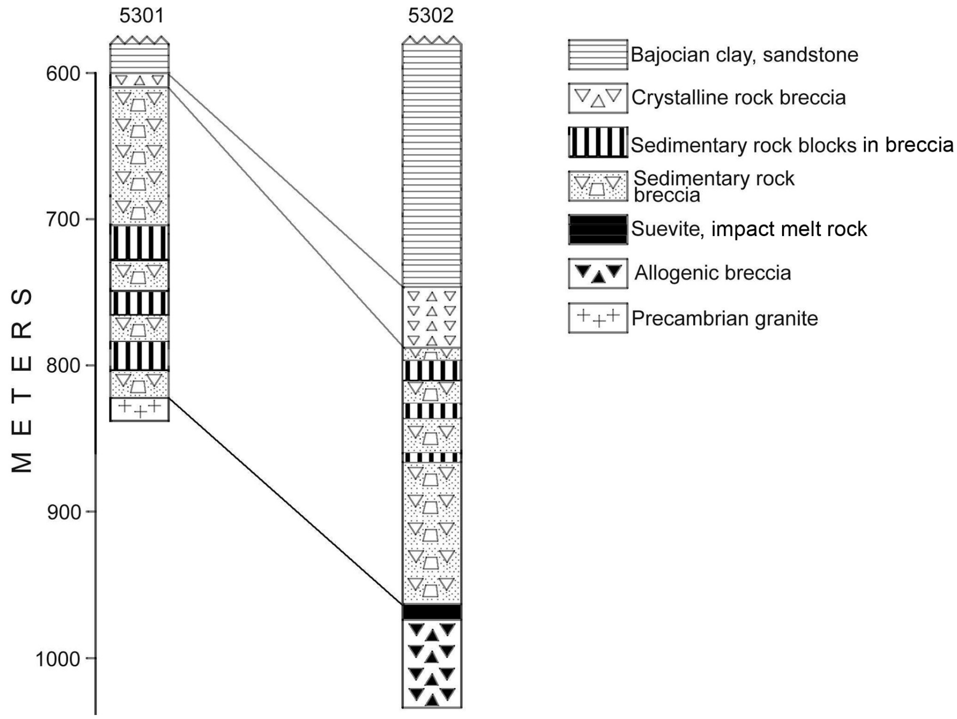

Fig. 5. Detailed correlation diagram of drillholes within the Obolon impact structure showing impactites and crater-fill deposits.

(P a r k. et J o n.). The Late Bajocian or Late Bajocian-Early Bathonian marine macrofauna was determined in the interval 633-631.5 m: *Parkinsonia doneciana* B o r i s s., *Mellagrinella doneciana* B o r i s s., *Nucula cf. andorae* O r b. The Middle Jurassic clays and siltstones occur in borehole 5301 in the interval of 602–498 m (Fig. 4). The marine microfauna was described from the interval 576–575 m in the lower part of the strata: *Ammodiscus baticus* D a i n., *Ammodiscus varians* K a p t., *Trochammina aquamataformis* K a p t.

The Bathonian sediments conformably occur on the surface of the Bajocian rocks. They are penetrated in boreholes 5302 (depth of 523–274 m) and 5301 (498–272 m). It is necessary to note that the Bajocian-Bathonian contacts usually are not well defined in the area and were determined approximately. The Bathonian sediments are dark gray clays and silty clays, with subordinated presence of sandstones. Besides, thin limestone interlayers are distributed throughout the clays. Abundant Bathonian guide faunal remains in the rocks were described by Vandenko and Yukhimenko (1966), including macrofauna: *Pseudocosmoceras michalskii* (B o r i s s.), *Pseudocosmoceras masarovichi* M o u r a c h., *Meleagrinella doneciana* (B o r i s s.), and microfauna: *Haplophragmoides canariensis* (O r b.), *Ammodiscus varians* K a p t., *Lenticulina mironovi* (D a i n.), *Lenticularia obesa* K a p t.

Even though the basement of the Middle Jurassic sediments in borehole 5301 is 146 m higher than in borehole 5302, the surface of the Bathonian rocks occurs at equal depths in both boreholes—at about 272–274 m. Therefore, more rapid accumulation of the post-impact sediments is observed in the central, deeper part of the structure.

The Bajocian and Bathonian sediments are conformably overlain by a Callovian sequence of silty sandstones and siltstones with poorly preserved faunal remains. The thickness of the Callovian sediments reaches 38 and 36 m in boreholes 5301 and 5302, respectively. In the vicinity of the Obolon structure those sediments are present everywhere. In borehole 485, the Callovian sediments are represented by 14 m thick clays. In borehole 36/3 in the southern part of the territory under consideration, the sediments of this age are absent, as the marine basin in that time began to retreat northeastward. But in borehole 9/R-1 to the north of the Obolon structure the Callovian sediments reach a thickness of 70 m.

The surface of the Middle Jurassic sediments in the crater is covered by sandy-clayey rocks with limestone interlayers characterized by a Late Jurassic (Oxfordian) fauna. It completes the Jurassic stage of the regional history and marks the regression period of the marine basin.

The platform section in the region of the Obolon structure continues upward through the Cretaceous deposits 52–43 m thick in boreholes 5301 and 5302, consisting of marls, clays, sandstones, and chalk. Eocene-Oligocene sands, clays and marls occur above, with a thickness of 107–111 m within the crater and 72–110 m in the boreholes closest to it. The section is completed by loose Quaternary sediments ranging in thickness between 17 and 35 m.

Geology of Boreholes within the Obolon Structure (5301, 5302)

The inner structure of the Obolon crater is interpreted from the sections of the boreholes 5301 (6 km northwestward of the crater center), 5302 (4 km westward of the center), and 467. The latter is presumably situated on the outer rim slope, 9.4 km southeastward from the crater center (Figs. 1 and 3). The interpretation is based on the following observations: borehole 5301 penetrated impact rocks to the crater basement. Borehole 5302 was terminated near the crater floor: in its deepest part, from about 1004 m to the borehole bottom at 1033 m, crystalline rock breccia was penetrated. This breccia contains large gneiss clasts with low-pressure shock metamorphic effects and almost devoid of impact melt. The presence of a central peak was derived from the gravity data, and the structural symmetry was assumed based on comparison with other, similar impact structures. Thus, it was assumed that the eastern part of the crater has about same depth and cross section as its western part.

The deepest central part of the Obolon impact structure was formed in the crystalline basement rocks represented by Precambrian gneisses and granites. The average composition of the crystalline basement rocks of the crater target was calculated from the relative content of different rock type debris in core samples of allogenic breccias and suevites of borehole 5302. These data show that biotite gneisses and granite gneisses prevail; their content reaches about 65% by volume of the target composition. Other rock types in the crystalline target are as follows: biotite and garnet-biotite granites and gneiss granites—14%, pegmatoid and leucocratic granites—14%, and melanocratic crystalline schists—7%.

The periphery of the structure formed in sedimentary rocks of the platform cover consisting of the Middle Carboniferous and Lower Triassic sedimentary sequences. The thickness of the pre-impact sedimentary cover was 143 m in the section of borehole 36/3 (17 km to SSW from the crater center) and increased up to 723 m in borehole 9/R-1, 38 km north of the center of the structure. From those data, at uniform subsidence of the Precambrian basement surface to the northeast, the initial thickness of the sedimentary cover rocks in the impact point was estimated at about 300 m.

Borehole 5302 penetrated allogenic breccias, clast-rich impact melt rocks, and suevites in the interval from 1033 m (bottom of the hole) to 963 m (Fig. 5). The lower portion of the section, to a depth of 974 m, comprises lithic breccias of crystalline rocks with thin interlayers of suevites at 1028, 1017, and 1005 m, in which the content of small glass particles reaches several volume percent. The breccias consist of clasts of gneisses, granite gneisses, granites, and crystalline schists, as well as individual fragments of sedimentary rocks. Dimensions of clasts and blocks in breccia range from centimeters to several meters, with clasts from tens of centimeters to 1 m dominating. A prevailing presence of coarse breccias in the basal part of the borehole section is evidence that those rocks are close to the contact with the underlying authigenic breccias of the true crater floor. Rocks and minerals in the breccias show abundant signs of shock metamorphism, including shatter cones in boulders of gneisses and granites.

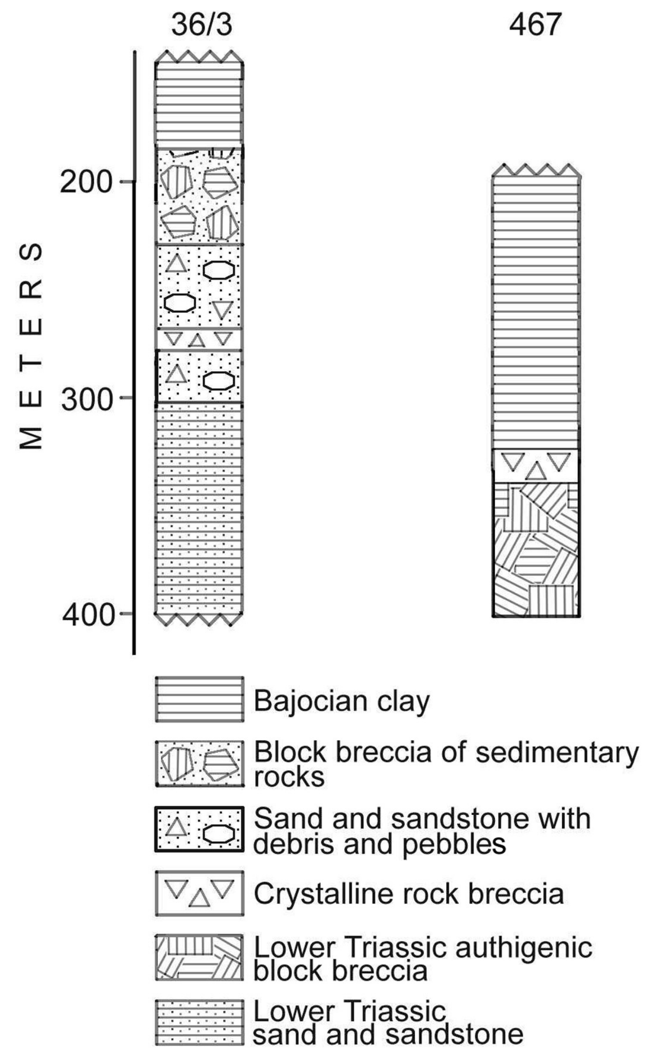

Fig. 6. Detailed correlation diagram of drillholes outside the Obolon impact structure, showing ejecta and tsunami deposits.

Clast-rich impact melt rocks and suevite breccias with 15–20 vol% of a melt or glass component occur above the lithic breccias in the interval between 974 and 963 m. Xenoliths of biotite and garnet-biotite gneisses and granite gneisses up to 5 cm in diameter, dominate the clast-rich impact melt rocks and suevites. Vesicular melts or glasses form inclusions of irregular shape; their dimensions vary from millimeters to 2–3 cm. Lithic breccias of crystalline and sedimentary rocks occur on the top of basement granites in the interval of 824–804 m in borehole 5301.

Above the allogenic breccias and suevites, post-impact filling rocks occur at 963–788 m in borehole 5302 and 804–610 m in borehole 5301 (Fig. 5). Post-impact rocks that fill the Obolon crater form a very specific sequence without any analog in all the impact craters of the Ukrainian Shield and most other known impact structures. They comprise inequigranular sandstones with subordinate layers of breccia, pebbles, and gravel, and blocks of sedimentary rocks. Clasts and blocks of the Lower Triassic rocks, including brick-red clays and gray sandstones, are abundant in the composition of coarse-grained clastic material. The sizes of the clasts and blocks vary between decimeters and tens of meters. Large blocks of clays and sandstones occur in borehole 5301 in the intervals of 821–816, 804–782, 772–767, 728–704 m and others, and in borehole 5302 in the intervals of 865–859, 836–826, 810–797.6 m. Rocks in the blocks and debris are intensely crushed and fractured. Numerous gliding planes are observed in the clays. Fragments of crystalline rocks are present in the breccias in subordinated quantities within local zones up to 2 m thick. The clasts are cemented by clastic and sandy material with fine-grained matrix of clayey and carbonate composition. 1–2 PDFs are rarely observed in quartz grains in breccias from borehole 5302 and 5301. The post-impact crater-fill comprises wash-back material composed of brecciated sedimentary target rocks with minor amounts of shocked fallout crystalline rocks and minerals.

Besides angular clasts, gravel and, rarely, pebbles are present within the breccia. Gravels in the cement are represented by rounded and semi-rounded grains of quartz, chert, and quartzite. In borehole 5302, an admixture of gravel is observed in the intervals of 910–908, 837 m, and a few other levels.

The Lower Triassic motley clays and sandstones and the carbonate-terrigenous Carboniferous sedimentary rocks in part were the main source material for forming the breccias. The imprints of Early Triassic chara algae were described by Vandenko and Yukhimenko (1966) in the rocks from borehole 5302 at the depths of 848.3, 842.9, 833, 829, 810.8, and 806.0 m. The Middle Carboniferous microfauna was determined in limestone clasts from borehole 5301 at the depths of 805 and 773 m: *Pseudostafella gorskyi* R a u s., *Eostafella paraprotvae* R a u s., *Ammodiscus compactus* B r a z h. et P o t., *Millerella carbonia* G r o z d. et L e b.

A comparative study of the breccia sequence of the filling rocks from the two boreholes demonstrates that blocks prevail in the marginal part of the crater in borehole 5301, and closer to the crater's center, in borehole 5302, sandstones and sandy breccias dominate. This sandstone-breccia sequence was the result of material deposition from the dense suspension submarine flow of the material that was ripped up and washed into the crater.

The accumulation of the breccia sequence of sedimentary rocks occurred by fallback, mass wasting, and washing of the ejected and seismically disturbed target rocks by resurge waves back into the crater. The dominating role of fallback and mass wasting of sedimentary rocks from the crater walls and rim is clearly traced in the section of borehole 5301, in which some sandstone and clay blocks reach up to tens of meters in size. Accumulation of coarse-grained clastic rocks in craters due to slumps and avalanches following the resurge waves and tsunamis (fallback and washing of the brecciated material into the crater from slopes and rim under action of resurge waves) directly after their forming is the most important filling process for impact structures originating in shallow marine basins (Dypvik et al. 2004). For example, the structure-fill breccias with target-rock blocks are important components of the filling complex in the Wetumpka impact structure in the USA that formed in the Late Cretaceous on a shallow shelf (King et al. 2004). The generation of direct and resurge tsunami waves at formation of impact structures in marine conditions is also described by Matsui et al. (2002).

Breccias of crystalline basement rock debris cover in the Obolon structure a sequence of block-bearing sandstones and sedimentary rock breccias. In borehole 5302, 41 m thick breccia of crystalline rocks occurs in the interval of 788–747 m, and in borehole 5301 its thickness decreases to 8 m at the interval 610–602 m (Fig. 5). This breccia consists of clasts of biotite gneisses, granite gneisses, granites, quartz, and feldspar grains, as well as debris of intensely altered glasses substituted by clayey matter. Rock fragments in breccia vary from dense and not fractured to intensely cataclased and brecciated. Angular clasts prevail, but on rare occasions they are weakly rounded. In smaller quantities, the breccia contains debris of sandstones, green clays, also rounded gravel grains of quartz and quartzites. Limestone clasts with the Middle Carboniferous fauna are present in the breccia from both boreholes. The maximum size of clasts reaches 10 cm. The cement of these breccias is fine-grained sandy-clayey material that is sulfidized in a few places. A microscopic examination of thin sections of crystalline rocks from the breccia revealed signs of shock metamorphism in the form of PDFs in quartz and kink bands in biotite.

Middle Jurassic post-crater sediments cover the top of the breccia in the crater. In the base of this sequence in borehole 5302, a basal layer of inequigranular polymictic sandstones with inclusions of crystalline rock fragments occurs in the interval of 747–735 m. Above, in the interval of 735–523 m, a uniform sequence of gray, brown, and greenish clays and siltstones occurs. In borehole 5301, Bajocian clays and siltstones form the interval of 602–498 m. The Bajocian and Bathonian sediments are conformably covered by a Callovian sequence of silty sandstones and siltstones of 36–38 m thickness. The Callovian sediments in the crater are overlain by Oxfordian sandy-clayey rocks, which mark the regression period of the Jurassic marine basin.

The post-impact deposits in the Obolon structure continue upward through the Cretaceous sedimentary rocks 52–43 m thick consisting of marls, clays, sandstones, and chalk. They are overlain by Eocene to Oligocene sands, clays, and marls with a total thickness of about 110 m. The section is topped by Quaternary sands, clays, and loess with a thickness of 35 m.

Geology of Boreholes with Impactites outside the Obolon Structure (467, 485, 36/3 and Others)

Outside the Obolon structure, coarse-grained ejecta deposits were found in boreholes up to 50 km from the crater center (Figs. 1 and 6). In all of these boreholes, coarse clastic sediments, which are related to the Obolon impact, occur above the motley-colored Early Triassic clays and beneath a sequence of clays and sandstones with a guide fauna that places them in the Middle Jurassic (Bajocian and Bathonian stages).

A layer of crystalline rock breccia occurs at the Lower Triassic-Bajocian boundary in borehole 467 that is situated at the rim of the crater (Fig. 6). The intensively deformed Lower Triassic red clays with sandstone interlayers that form the lowest part of the borehole section in the interval from 401.8 to 338.0 m are converted into the autochthonous breccia. The block of brecciated brick-red clay with lamination inclined to about 45° to the horizon occurs at the base of the section to the depth 360.5 m. Above, in the interval of 360.5–338.0 m, breccias are found that consist of large clasts and blocks of intensely fractured red and bluish-gray clays, with gliding planes of various directions. The clays contain traces of the Early Triassic charophytes.

In the interval of 338.0–324.0 m breccias of crystalline basement rocks occur. Pritchina et al. (1963) described them as tuffs and tuffites. The breccias consist of angular fragments of gneisses, granites, and vesicular glasses, as well as grains of quartz, feldspars, and less common biotite and garnet. Some fragments of chert and limestone are observed. The breccia cement is of clayey and fine-grained clastic composition. Above these breccias, in the interval of 324–226 m, a sequence of alternating clays, mudstones, siltstones, and sandstones, with Bajocian and Bathonian mollusk and brachiopod fossils were described. The composition of these breccias, the presence of vesicular glasses, and their occurrence at the Early Triassic-Middle Jurassic sequence, indicates that they are Obolon impact ejecta.

Ejecta were also found in borehole 485 (Fig. 4). From the bottom of the hole at a depth of 400 m up to 327 m, wax-red and gray clays with thin sandstone interlayers occur. Dislocations are observed in the clays as rare gliding planes and fractures. Pritchina et al. (1963) described traces of the Early Triassic chara algae in the interval from 374.1 to 373.1 m: *Stellatochara dnjeprovica* S a i d., *Stellatochara dneproviformis* S a i d., *Praechara donetziana* S a i d.

Above these sediments, in the interval of 327–317.8 m, a layer of alternating inequigranular sands and sandstones occurs that contains quartz, gneiss, and granite pebbles in its lower part. This layer is interpreted as tsunami deposits. Over, in the interval of 317.8–298 m, intensely deformed blocks of motley clays with gliding planes occur, which are interpreted to represent the product of submarine mass wasting. In the interval of 298–295 m, tuff-like breccias occur, which consist of crystalline rock debris, quartz, and intensely weathered glasses cemented by dark green clayey-chlorite material. Those breccias are interpreted to be suevitic ejecta.

A sequence of grey clays with sandstone layers occurs over the breccias in the interval of 295–257 m. Directly above the contact with breccias, the microfauna of the Late Bajocian-Early Bathonian exists. The overlying section of the Mesozoic-Cenozoic sediments is typical for the whole region.

A complicated sequence of coarse-grained sediments occurs in borehole 36/3 (Fig. 6). Bezugly et al. (1960) note that the sequence of red and brick-red sandstones and clays is covered in the interval of 302–291.5 m by weakly cemented inequigranular sandstones and sands with debris, pebbles, and gravel of crystalline rocks and quartz. Large rock clasts are most abundant in the lower part of the layer at 302–299.9 m. The interval of 291.5–279.5 m consists of weakly deformed blocks of clays, mudstones, and sandstones with gliding planes. Breccias consisting of gneiss and granite fragments, as well as quartz and feldspar grains, occur in the interval 279.5–267.5 m. Apart from crystalline rocks, clasts of clays and marl are present in small quantities in the basement of the breccia horizon. Above, in the interval of 267.5–185.5 m, a sequence of sands and weakly cemented sandstones occurs. The unit contains blocks of intensely fractured clays (mainly in the intervals of 242.9–239.5 m, 228.4–185.5 m) that are intercalated with crystalline rock debris (intervals of 267.5–263.0 and 254.0–242.9 m). Formation of the thick sequence of coarse-grained clastic rocks (interval of 302–185.5 m) was a complex process, in which material transportation and accumulation by tsunami waves predominated, whereas submarine mass wasting phenomena had a subordinate role. The layer of crystalline rocks breccias in the interval of 279.5–267.5 m was formed due to deposition of ballistic ejecta. This layer consists of angular clasts of gneiss, granite, and some other rocks of the crystalline basement. In the upper part of the sequence, large blocks of the fractured Triassic red clays and sandstones are present those accumulated through their sliding from the crater rim. Submarine sliding processes play an important role at forming shallow marine impact structures (e.g., Claeys et al. 2002; Norris and Firth 2002; Dypvik et al. 2004).

In the interval of 185.5–91.1 m, a sequence of alternating clays and sandstones of Middle Jurassic age occurs. Its basal layers contain fragments and pebbles of crystalline rocks. The upper part of the borehole section consists of the Paleogene sands and marls and Quaternary sediments.

In borehole 42/1, situated southwest of the crater center, the Lower Triassic motley sediments are covered in the interval of 137.5–84.0 m by a sequence of coarse-grained and inequigranular sands and sandstones with numerous fragments and pebbles of crystalline rocks, less often clasts of limestones, clays, brown coal, and some other rocks. Fragments of crystalline rocks are most abundant in the intervals of 137.5–131.7 and 121.7–110.3 m. The uppermost part of the sequence in the interval 90.4–84.0 is formed by coarse-grained sandstones with a conglomerate layer at its top. Besides angular fragments, the sequence contains also pebbles and gravel of crystalline rocks. This coarse-grained section is considered to be the result of tsunami activity and ejecta deposition. Over the top of this sequence, gray clays of the Middle Jurassic occur.

In borehole 32/4, a layer of coarse-grained sand with pebbles and angular clasts of crystalline rocks and chert occurs in the interval of 202.4–201.35 m. Boulders of motley-colored clays with gliding planes rest over, up to the depth of 179.2 m. They are covered by a sequence of alternating clays and sandstones of the Middle Jurassic age.

In borehole 31/1710 at the boundary of the Lower Triassic and Middle Jurassic at the depth of 230.4 m, the impact-related coarse-grained rocks are absent.

In borehole 9/R-1, located to the NNW of the crater center, the pre-impact sedimentary formations of the Middle Carboniferous and Lower Triassic occur from the surface of crystalline rocks at the depth of 1433 m up to 710 m. Above, from 710 to 617 m, Bajocian sediments occur those are represented by inequigranular sands containing in the basal part of the sequence rare pebbles of crystalline rocks and quartz, and also fragments of brown coal and shells. Pebbles and clasts in sands are the only traces of the Obolon impact in the sedimentary section of that borehole. Upwards in the section, those rocks are replaced by a clay and sand sequence up to 85 m thick with a Bathonian fauna. The Upper Mesozoic and Cenozoic sediments in this area consist of Callovian and Oxfordian clays and sands (interval 532–345 m), Cenomanian glauconite sands (345–286 m), Turonian to Santonian chalk (286–157 m), Paleogene sands and marls (157–20 m), and Quaternary sands.

Therefore, Obolon impact ejecta are recognized at distances of up to 50 km from the crater center. They are represented by crystalline rock breccia and suevites, tsunami deposits (sand and sandstone formations with fragments and pebbles of crystalline rocks), and submarine mass wasting breccia formations consisting of large clasts and blocks of sedimentary rocks.

SHOCK METAMORPHISM

The rocks and minerals of the Obolon structure show numerous signs of shock metamorphism that confirms its impact origin (Masaitis et al. 1976, 1980; Valter et al. 1977; Gurov and Gurova 1991; Gurov and Gozhik 2006).

Macroscopic shock evidences are shatter cones, which are present in large clasts of crystalline rocks from the allogenic breccia. One core in drillhole 5302 intersected three shatter cones at the depth 1023.5 m. The parts that are cut in the core are 3, 7, and 9 cm in size. The original cones were somewhat larger. The cones were fairly rough and had a striated surface.

Microscopic shock metamorphic effects are observed in thin sections of the rocks of the impactites. Quartz in clast-rich impact melt rocks, suevites and lithic breccias from boreholes 5302 and 5301 contain a variety of shock effects, ranging from basal PDFs in allogenic breccia to diaplectic glasses, and to recrystallized melt glasses in suevite.

The lowermost shock pressures are recognized in gneiss and granite clasts from the sequence of allogenic breccia (borehole 5302, depths 995, 997, 998, 1004, 1017 m). The clasts of crystalline rocks are intensely cataclased; intersecting zones of fine-grained breccias are often seen in them. Quartz has undulated extinction in all examined rock varieties. The basal orientation of PDFs prevails in quartz (Fig. 7a), whereas other orientations are less common. A histogram of the frequency distribution of indexed PDFs in quartz from allogenic breccia is shown in Fig. 8a. The binning angle on the histogram is 5 degrees. The frequency distribution of the PDFs was normalized to 100%. Shock pressures, which were determined applying the method by (Hörz and Quaide 1973), for quartz grains from gneiss and granite clasts are as follows: at 1017 m—5–12 GPa, 1004 m—5–10 GPa, and 997 m—5–8 GPa. Kink bands are widespread in biotite from the rocks of that interval. Garnet is intensely fractured.

Moderate to high shock pressures were determined for rocks and minerals in clast-rich impact melt rock and suevite from the interval of 974–963 m. Quartz contains numerous PDFs (Fig. 7b), amongst which the $\{10\bar{1}3\}$ orientations dominate, whereas $\{10\bar{1}2\}$, $\{10\bar{1}4\}$and some others are less common (Fig. 8b). The number of systems in quartz grains varies mostly between 2 and 6 and reaches up to 10 in some individual grains. Lechatelierite is not preserved in the suevites, but is transformed into mosaic quartz aggregates. Coesite was found in moderately shocked quartz from a granite fragment from a depth of 973 m. Quartz has reduced refractive indices: $n_e = 1.544$, $n_o = 1.535$, birefringence 0.009 that by diagram in Stöffler and Langenhorst (1994) testifies that the mineral was shocked to pressure of about 25 GPa. The coesite content in this quartz is estimated as about 10% (Gurov et al. 1980).

Feldspars have reduced refractive indices and birefringence up to their complete isotropization and transformation into diaplectic glasses (Fig. 7c). One to two PDF sets rarely occur in feldspar grains with low birefringence. Potassium feldspar melt glass is of vesicular and fluidal structure. Kink bands occur in biotite. Garnet is intensely fractured (Fig. 7d).

Biotite and garnet-biotite gneisses of Obolon basement contain graphite. Studies of the composition of clast-rich impact melt rock heavy fraction found individual grains of

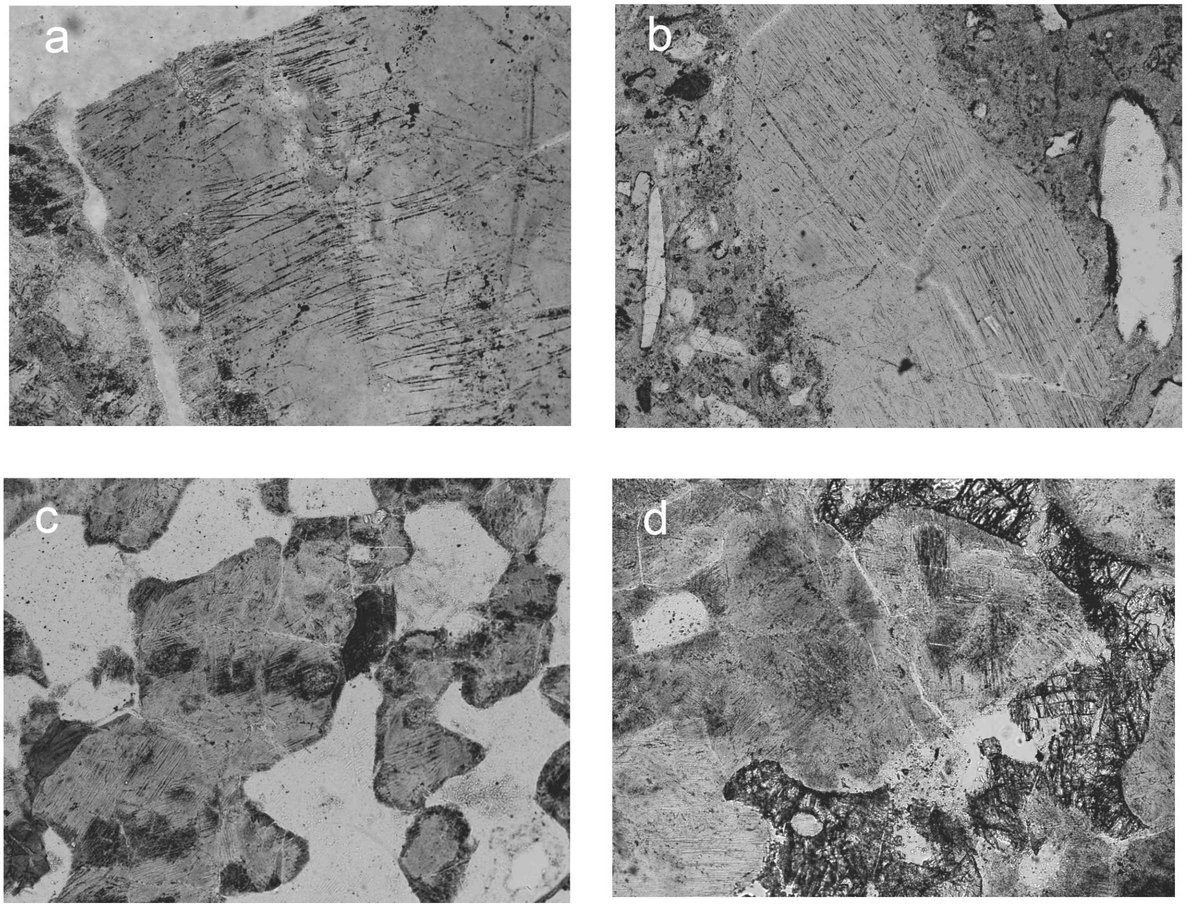

Fig. 7. Microphotographs of some shocked minerals of the Obolon structure. a) Two sets of PDFs in quartz from the gneiss clast in allogenic breccia. The decorated basal set is dominant (drillhole 5302, 1017 m depth, 1.13 mm wide, plane-polarized light). b) Numerous sets of PDFs in quartz from suevite (drillhole 5302, 973 m depth, 1.13 mm wide, plane-polarized light). c) Shocked granite clast from suevite. Quartz grains with numerous sets of PDFs and feldspar transformed into transparent diaplectic glass (drillhole 5302, 973 m depth, 0.60 mm wide, plane-polarized light). d) Fractured garnet and quartz with PDFs in shocked granite clast from suevite (drillhole 5302, 973 m depth, 0.60 mm wide, plane-polarized light).

impact diamond (Gurov et al. 1995a). The mineral is of gray color, grains are 0.1–0.2 mm in size, and their tabular shape is inherited from the initial graphite crystals. X-ray measurements of individual diamond grains confirm the microaggregate structure and complex phase composition with prevailing phase of cubic diamond (interplanar spaces 0.206, 0.126, 0.107 nm) and less abundant lonsdaleite phase with interplanar spaces 0.219 and 0.192 nm.

Shock metamorphic effects in minerals are recognized in the rocks from the crater-fill unit of sandstones and breccias of sedimentary rocks. Quartz with PDFs is observed in sandstones (intervals 948, 908, 870 m) and gneiss clast (interval 988 m) from the crater-fill rock complex in drillhole 5302. In crater-fill rocks of drillhole 5301, quartz with PDFs is present at the intervals 780.5, 773, and 740 m.

In overlying crystalline rock breccia (drillhole 5302, interval of 780–746 m and drillhole 5301, interval 610–602 m), quartz with PDFs is observed in clasts of shock-metamorphosed crystalline rocks as well as in individual grains of the matrix.

IMPACT MELT ROCKS

Impact melt rocks in the Obolon structure are represented by a local zone of clast-rich impact melt rocks and suevites in allogenic breccias from borehole 5302. Suevites occur in the interval 973–972 m, while clast-rich impact melt rocks occur at the interval 971–963 m. The boulder of biotite-garnet gneiss, about 1 m in diameter, is situated at the contact between clast-rich impact melt rocks and suevites in the interval 972–971 m. Vesicular glasses occur in crystalline rock breccias in the ejecta sequence that is penetrated by boreholes 467 and 485 outside the impact structure.

Clast-rich impact melt rocks are gray and greenish-gray dense rocks with abundant xenoliths of crystalline rocks that are dominated by gneisses, granitic gneisses, and their minerals. The elongated and curved particles of vesicular impact glass form rare clasts in impact melt rock.

Clast-rich impact melt rocks contain devitrified glass with

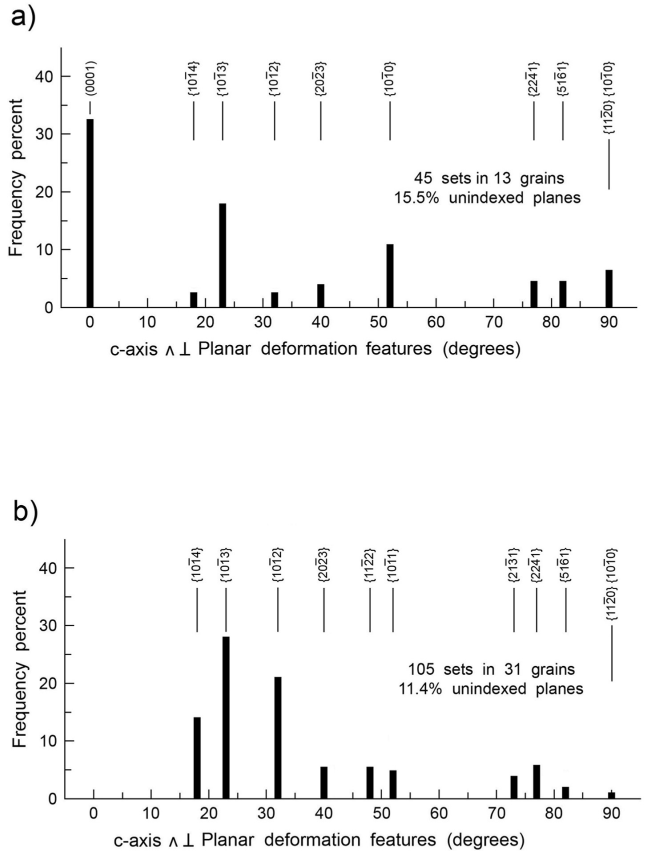

Fig. 8. Frequency histograms of angles between the c-axis and poles of PDFs in quartz (in per cent). a) Gneiss clast from allogenic breccia, drillhole 5302, 1017 m. b) Suevite, drillhole 5302, 973 m. The binning angle is 5 degrees. The frequency distribution of the PDFs was normalized to 100%.

fluidal structure that has, in thin sections, greenish-gray and grayish-brown color. Variously recrystallized glasses form spherulitic and sheaf-like aggregates of quartz-feldspar composition (Figs. 9a and 9b). Clasts comprise crystalline rocks and minerals, mainly quartz and rarely feldspars, biotite, and garnet (Fig. 9c). Prismatic pyroxene crystallites, mainly replaced by chlorite, occur in a few devitrified glass fragments (Fig. 9d). Replacement of glass by chlorite, montmorillonite, and zeolite is observed in some of the thin sections.

Glass fragments and particles are abundant in suevites from the interval 973–972 m, where their content reaches up to 20–30 vol%. Rare glass particles occur also in some zones and interlayers in allogenic breccia from borehole 5302 (intervals 1004–1005 and 1017 m). Glasses form irregular particles from parts of a millimeter to 2–3 cm in size (Fig. 9e). They have bubbly structures and rare mineral inclusions. Fresh glass is isotropic and transparent, and its color is from light brown to colorless. Perlitic structures are characteristic of the glass (Fig. 9f). Replacement of glass by green chlorite is a common alteration.

A comparison of the impact melt rocks composition with composition of several types of basement crystalline rocks shows their resemblance with gneisses and granitic gneisses from allogenic breccias, in which content of that rock type is about 65% (Gurov et al. 1997). The composition of clast-rich impact melt rocks and gneisses from the borehole 5302 is given in Table 1. There are some distinctions in the content of MnO, K_2O, and P_2O_5. An increased content of chlorine in impact melt rocks is noted (Gurov and Gurova 1995) and may represent derivation from marine water that covered the target surface at the time of the impact. Due to evaporation of water, impact melts were enriched with the elements dissolved in the sea water. Chlorine and sodium enrichments in impact melts from the Eltanin submarine impact event in the southern Pacific Ocean were reported by Margolis et al. (1991). Higher chlorine concentrations in underground water within breccia pores was described from the Chesapeake Bay impact structure (Poag et al. 2004).

AGE

The age of the Obolon impact event was constrained by geological data to be later than Early Triassic but earlier than Middle Jurassic (Masaitis et al. 1980), or as Middle Jurassic (Valter et al. 1977). Lower Triassic sediments with characteristic fossil assemblages occur below the ejecta deposits in, e.g., boreholes 467 and 485. The boulders and clasts of sedimentary rocks with the Early Triassic chara algae are a constituent of the crater-fill breccia.

The breccia horizon in the Obolon crater is covered by marine sediments with faunal remains that indicate them to be of Middle Jurassic (Bajocian) age. Outside of the crater, the Middle Jurassic (Bajocian and Bajocian-Bathonian) sediments cover the ejecta in boreholes 467 and 485, or tsunami deposits that are represented by sands with breccia and conglomerate breccia interlayers in boreholes 36/3, 41/2, and 32/4. Middle Jurassic rocks are not recognized in underlying pre-impact sediments, crater-fill rocks and ejecta. The structural features of the impact breccia and crater fill in the Obolon structure, as well as the coarse clastic composition and stratigraphic position of the surrounding sediments, testify to its forming in a shallow marine basin. Paleogeographic data (*Atlas of Paleogeographic Maps 1960*) indicate that the marine transgression onto the northeastern slope of the Ukrainian Shield began in the Middle Jurassic (Bajocian). Therefore, the geological evidence confirms that Obolon formed during Bajocian times.

The isotope ages of Obolon impact melt rocks (K/Ar data) vary from 160 ± 30 Ma (Masaitis et al. 1980) to 215 ± 25 Ma (Grieve 1991). Using the K-Ar method, the most recent age determinations were made at the Institute of Geological Sciences, Ukraine, for two core samples of impact melt rocks and one sample of feldspar melt glass (Gurov et al. 1995b, 1997). According to these data, the isotope age of the Obolon structure impact melt rocks is 169 ± 7 Ma (Table 2). This age

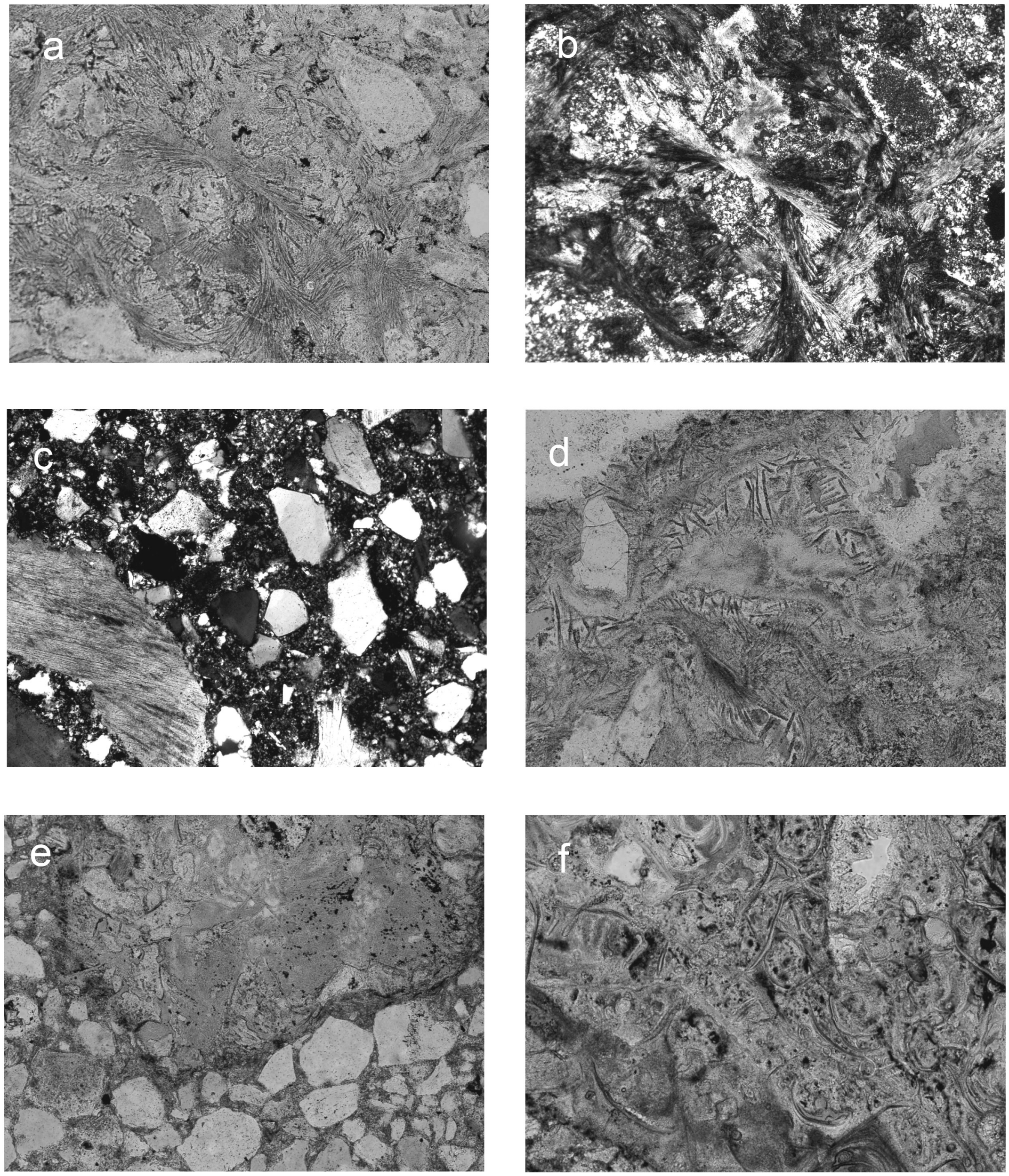

Fig. 9. Microphotographs of clast-rich impact melt rocks and glasses. a, b) Sheaf-like structures of devitrified glass in clast-rich impact melt rock. Matrix is partly recrystallized into fine-grained quartz-feldspar aggregates, drillhole 5302, 969 m depth, 1.13 mm wide; (a) plane-polarized light, (b) cross-polarized light. c) Clast-rich impact melt rock with abundant mineral clasts in devitrified glass matrix. Quartz grain, 0.8 mm long, with numerous sets of PDFs (drillhole 5302, 965 m depth, 1.13 mm wide, cross-polarized light). d) Glass recrystallization in clast-rich impact melt rock. Long prismatic crystallites are pyroxene substituted by chlorite (drillhole 5302, 969 m depth, 1.13 mm wide, plane-polarized light). e) Particle of fluidal glass in suevite. The central part of the particle is replaced by chlorite (drillhole 5302, 973 m depth, 1.60 mm wide, plane-polarized light). f) Perlitic structure of glass particle partly substituted by chlorite (dark grey) (drillhole 5302, 963 m depth, 1.13 mm wide, plane-polarized light).

of the glasses confirms the geological age of the structure and its forming during the Bajocian of the Middle Jurassic.

CONCLUSIONS

The Obolon impact structure is situated at the northeastern slope of the Ukrainian Shield near its boundary with the Dnieper-Donets Depression. The structure was formed in crystalline rocks of the Precambrian basement covered by the Carboniferous and Lower Triassic platform sediments of the total thickness of about 300 m. The impact structure and its coarse-grained clastic ejecta deposits are covered by Middle Jurassic (Bajocian and Bathonian) marine deposits, whose accumulation is connected to the

Table 1. Major (wt%) and trace (ppm) element concentrations measured in 10 samples of clast-rich impact-melt rocks and crystalline target rocks from borehole 5302* into the Obolon crater.

Depth (m)	965	965a	968	973cr	977	988	990	1011	1025	1028
wt%	CRIMR	CRIMR	CRIMR	IG	Gneiss	Gneiss	Gneiss	Gneiss	Granite	Granite
SiO_2	59.89	61.61	57.82	59.59	59.47	60.94	58.80	65.86	71.33	72.55
TiO_2	0.57	0.60	0.59	0.77	0.79	0.77	0.85	0.58	0.60	0.72
Al_2O_3	16.45	15.99	17.25	16.87	18.22	14.04	17.59	12.80	13.13	11.72
Fe_2O_3	6.62	6.49	7.43	7.11	7.84	9.81	9.51	7.05	3.49	6.41
MnO	0.05	0.03	0.05	0.09	0.09	0.09	0.11	0.05	0.02	0.08
MgO	3.31	2.87	3.48	4.02	4.01	5.45	4.33	4.31	2.16	2.78
CaO	2.34	1.12	2.35	0.68	1.97	2.078	2.19	2.82	1.51	0.87
Na_2O	1.55	2.11	1.68	1.88	1.83	2.00	2.16	2.59	3.05	1.78
K_2O	4.49	4.36	4.38	3.49	1.93	1.75	2.11	1.41	3.75	2.07
P_2O_5	0.23	0.15	0.13	0.11	0.11	0.06	0.08	0.08	0.10	0.10
S	0.03	0.12	0.03	0.04	0.02	0.08	0.02	0.02	0.01	0.03
Cl	0.09	0.26	0.10	0.25	0.02	0.13	0.07	0.11	0.03	0.08
H_2O	0.84	0.87	0.86	0.19	0.71	0.27	0.48	0.27	0.18	0.18
LOI	3.35	3.21	3.66	4.73	2.79	2.33	1.51	1.86	0.44	0.44
Total	99.80	99.80	99.80	99.80	99.80	99.80	99.80	99.80	99.80	99.80
ppm										
Ni	40	68	<20	66	67	78	68	46	<20	55
Cu	34	54	53	118	58	13	36	71	14	27
Zn	80	713	184	117	117	799	106	79	48	233
Ga	11	13	32	20	<10	<10	<10	<10	<10	<10
Rb	171	145	173	157	113	102	122	68	115	79
Sr	194	168	186	320	255	275	258	292	332	257
Y	30	28	27	17	16	<10	17	<10	<10	12
Zr	196	280	205	273	156	186	153	162	141	287
Nb	<20	<20	<20	<20	<20	36	<20	<20	<20	<20
Pb	36	86	46	28	15	27	13	17	26	36
Th	25	25	24	22	<10	11	13	11	<10	11
Ba	870	897	839	796	425	328	419	429	1569	840
La	62	39	66	50	54	42	53	35	36	24
Ce	107	83	100	89	84	66	101	51	75	34
Nd	27	25	24	21	20	22	26	<20	22	<20

*XRF analyses were made by V. V. Zagorodniy at Kiev State University.
CRIMR—clast-rich impact melt rocks; IG—impact glass. LOI—loss on ignition. All Fe as Fe_2O_3.

Table 2. Isotope age of impact melt rocks of the Obolon structure* (Gurov et al. 1995b, 1997).

Drillcore	Depth (m)	Sample characteristic	K (wt%)	$Ar_{rad.}$ (ng/g)	Age (Myr)
5302	965	Impact melt rock	4.03	49.3	169 ± 5
5302	973-1	Impact melt rock	3.90	47.2	167 ± 6
5302	973-2	Feldspar melt glass	10.04	125.5	172 ± 5

*Analyses were made at the Institute of Geological Sciences, National Academy of Sciences of Ukraine, using mass spectrometer MI-1330. Analyst M. M. Vischniak.

Middle Jurassic transgression onto the northeastern slope of the shield.

The impact formations in the Obolon structure are represented by allogenic lithic breccias and clast-rich impact melt rocks of total drilled thickness over 70 m. Shock metamorphic effects in impact rocks are observed in the form of PDFs in quartz, diaplectic as well as melt glasses of feldspars, coesite, impact diamonds, and rare shatter cones. The products of impact melting in the Obolon impact structure are clast-rich impact melt rocks and glasses in suevites. The composition of impact melt rocks is close to those of gneisses and granite gneisses of the crystalline basement. A higher content of chlorine in the impact melt rocks may be related to impact into marine basin and inclusion marine water.

The crater fill at Obolon consists of a sequence of breccias of sedimentary rocks and coarse-grained sandstones, up to 175 m thick, that is covered by crystalline rock breccias with up to 41 m thickness. Such a succession of the crater filling is interpreted to be the result of accumulation of fallback, sliding and washing into the crater of the sedimentary part of the target before the deposition of the ballistically emplaced ejecta (mainly of crystalline rocks) with their subsequent washing into the crater by resurge tsunami waves.

A coarse-grained sequence at the Lower Triassic and Middle Jurassic boundary around the Obolon impact structure up to a distance of 50 km from its center are ejecta and tsunami deposits. They are represented by breccias of crystalline rocks, sands, and sandstones, and also by conglomerates and conglomerate breccias. The composition and texture of the impact rocks and breccias of the crater fill, and the distribution and texture of the surrounding coarse-grained clastic ejecta sequences suggest that Obolon formed in a shallow marine basin.

The geological age places the Obolon impact event after the Lower Triassic and before the Bajocian stage of the Middle Jurassic; the age determined by the K-Ar method is 169 Ma, corresponding to the crater formation during the Middle Jurassic (Bajocian).

Of the about 175 impact structures recognized on Earth (Earth Impact Database [2008]), five craters are completely (Mjølnir, Montagnais) or partially (Chicxulub, Chesapeake Bay, Neugrund) below the ocean surface. Submarine formation is identified with various grades of reliability for about 20 further impact structures (e.g., Dypvik et al. 2004). The Obolon structure is an addition to the list of craters that formed in a shallow marine basin.

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