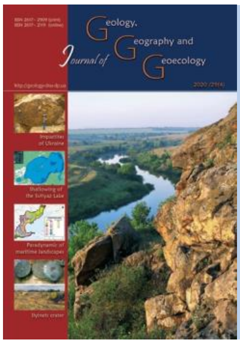

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The Ilyinets meteorite crater - geological structure unique in Europe and a promising destination for international tourism

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Abstract. The Ilyinets meteorite crater is located in Lypovets and Ilyinets districts of Vinnytsia region. It is accessible for examination in quarries near Luhova and Ivanky villages in the Sobok River valley. This site currently has the status of a geological natural landmark of local significance. The crater appeared as a result the impact of a meteorite on Precambrian surface of the Ukrainian Shield 445 million years ago. The impact of the explosion caused the formation of a typical ring structure about 8.5 km diameter and 600-800 m deep. The denudation level in the crater area is estimated at about 300-400 m. Thus, the preserved part of the crater has a diameter of about 3.2 km and is 400 m deep. Target rocks are represented mainly by granitoids of the Haisyn (Sobite) complex. The meteorite crater consists of impactites: shock-melt rocks, impact bombs, allogenic and authigenic breccia (suevite, tagamiteetc). Genesis of impactites is confirmed by the findings of stishovite, koesite, impact-type diamond, the presence of metallic and silicate spherules, planar structures in quartz, feldspars and other characteristic features. Overlap rocks are represented by sporadically distributed Devonian and widespread Quaternary sediments. Their thickness reaches 13 m, and it decreases to 3 m in the Sobok River valley. The Ilyinets meteorite crater is the most representative in Europe because it is easily accessible for examination and study, and available for sampling. Undoubtedly, it is a promising unique geological object that can attract attention of tourists around the world, as well as geoscientists interested in studying unique natural sites and phenomena in Europe and on the Earth in general.

Keywords: *Ilyinets meteorite crater, impactites, suevite, tagamite, impact bomb, tourism*

Іллінецький метеоритний кратер – виняткова геологічна споруда Європи та перспективний об'єкт міжнародного туризму

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Анотація. Іллінецький метеоритний кратер розташований в центральній частині України, на території Липовецького та Іллінецького районів Вінницької області. Він доступний для огляду в кар'єрах поблизу сіл Лугова та Іваньки в долині річки Собок. Зараз ця ділянка має статус геологічної пам'ятки місцевого значення. Кратер утворився внаслідок падіння метеориту на докембрійський фундамент Українського щита 445 мільйонів років тому. Імпактний вибух спричинив утворення характерної кільцевої структури діаметром близько 8,5 км та глибиною 600-800 м. Рівень денудації в районі кратера оцінюється приблизно в 300-400 м. Таким чином, збережена частина кратера має діаметр близько 3,2 км і глибину 400 м. Породи мішені представлені переважно гранітоїдами гайсинського (собітового) комплексу. Метеоритний кратер складається з імпактитів: ударно-розплавних порід, бомб, аллогенних та аутігенних брекчій (зювіти, тагаміти). Генезис імпактитів підтверджується знахідками стишовіту, коеситу, імпактних алмазів, наявністю металевих і силікатних сферул, планарних структур у кварці, польових шпатах та іншими мінералого-петрографічними ознаками. Породи перекриття представлені локально розвиненими девонськими та повсюдно поширеними четвертинними відкладами. Загалом потужність порід перекриття сягає 13 м, а в долині річки Собок вона зменшується до 3 м. Метеоритний кратер Іллінці є найбільш репрезентативним у Європі завдяки його доступності для огляду та вивчення, можливості відбору проб, значної кількості архівних та опублікованих геологогеофізичних матеріалів. Безперечно, це унікальний геологічний об’єкт, який може привернути увагу туристів по всьому світу, а також геологів, зацікавлених у вивченні унікальних пам’яток природи та явищ у Європі зокрема та на Землі загалом.

Ключові слова: Іллінецький метеоритний кратер, імпактити, зювіти, тагаміти, імпактні бомби, туризм

Introduction. The Earth’s surface preserves the “imprints” left by large meteorites - craters. We can assume that the famous meteorite craters are the consequences of only part of the impact events that occurred during the history of the planet. After all, under certain conditions, during the collision with the Earth, the cosmic body can form furrowed craters of insignificant depth, which quickly disappear due to the erosion and lithogenesis processes. Most known craters do not contain residues of meteorite matter. The rocks formed as a result of meteorite impact are often similar to volcanic or metamorphic, which makes it difficult to diagnose their origin.

According to modern data, about 20 thousand tons of meteorite matter enters the Earth’s atmosphere annually. More than 50 tons of space material, including meteoritic dust, falls every day. The share made up by large debris (from several kilograms to a ton) is approximately 100 tons per year. In historical times, only a comparatively small amount of cosmic debris up to 1.0-1.5 tons was recorded falling to Earth. Small (several tens of meters) craters were formed as a result.

Collisions of the Earth with celestial bodies, the size of which exceeds a few kilometers in diameter, occur on average once every million years. In this case, impact craters are formed. One of the authors of the new global plate tectonics Robert S. Dietz in 1960 proposed the special term “astrobleme” to indicate. Today this, the term is hardly used by scientists in the world. On celestial bodies, where there is no atmosphere (Mercury, Moon, Phobos, Deimos, etc.), meteorite craters, regardless of the time of formation, are stored intact. The reason for their destruction can be only the fall of later meteorites.

There are two types of meteorite craters: impact - less than 100 m in diameter and explosive - more than 100 m in diameter. The first one is the result of small meteorite falls. The second type occurs when the Earth collides with large-sized cosmic bodies. During a collision with the Earth’s surface, the meteorite`s movement sharply slows down. The rocks in the place of fall (target rocks) begin to move rapidly under the influence of a shock wave. The shock wave covers the hemispherical region below the planet’s surface and also moves in the opposite direction along the body of the meteorite. The meteorite is destroyed completely as a result of abrupt change in stretching and compression. The shock wave causes a sharp rise in temperature (over 3000 °C) and pressure (over 5 million atmospheres).The rocks heat up (partially melt) and in the center of the collision partly evaporate. The rocks formed after cooling and solidification at the bottom of the crater can be enriched with meteorite-specific chemical elements - iridium, osmium, platinum, palladium, nickel and chromium.

The plasma formation, which occurs in the process of instant evaporation of part of the matter, is accompanied by an explosion. As a result, the target rocks fly away in different directions and the bottom of the crater descends. At the bottom of the newly formed crater, there is a depression with steep edges that collapse due to gravity. The bottom of the crater is covered with rock debris thrown as a result of the collision. Breccia, a layer of debris cemented with the same material, ground to sand and dust, is formed. The impact melt buried beneath the breccia layer begins to solidify rapidly, completing the crater formation process. The processes of the meteorite craters’ formation on the Earth’s surface are described in detail in the works of E.P. Gurov (Kelley and Gurov, 2002; Gurov, 2002).

The meteorite crater consists of impact rocks called impactites: shock-melt rocks, impact bombs, allogenic and authigenic breccias (Valter et al., 2000; Kats et al., 1989).

One of the most famous, well-researched and best-preserved meteorite craters on the Earth’s surface is Arizona Crater (also called the Berringer Crater). It is located in the desert of Arizona (USA), near Winslow. The crater formed about 50 thousand years ago as a result of a collision with the Earth of iron-nickel meteorite with a diameter of 50-70 m (Artemieva and Pierazzo, 2009; Roddy and Shoemaker, 1995). The energy released during the collision ranged from 1 to 60 megatons (Kring, 2017). The meteoritic origin of the crater is evidenced by the inclusion in the rocks of the bottom of iron-nickel alloys: kamacite and taenite, which are typical of iron meteorites. Coesite and stishovite, which are formed under extremely high pressures and temperatures that occur only during high explosions, have also been identified (Shoemaker, 1987).

The Ilyinets crater is one of the most famous in Ukraine, a generally recognized structure and is on the list of confirmed impact structures found on the Earth’s surface. The Ilyinets structure has been studied by scientists since the mid-19th century. In the 1970s, geological, mineral-petrographic and geochemical evidence of its meteoritic origin was found. In 2017, the Ilyinets Impact structure was granted conservation status as a natural geosite of local importance – «the Ilyinets Crater» (the nature reserve of the Ilyinets district of Vinnytsia region). The first geological excursion to this structure took place in 1984 within the framework of the International Geological Congress.The purpose of the article is to attract the attention of geoscientists and tourists from around the world to the Ilyinets meteorite crater as a unique natural landmark and phenomena in Europe and on the Earth as a whole.

Structure of meteorite craters. Earth's meteorite craters are similar to those of the Moon, Mars, Mercury and other planets. They have a rounded shape, but their diameter is much smaller (for example, the Walgall structure on the surface of Callisto reaches 3000 km in diameter; Gurov and Gurova, 1987). Meteorite craters are diagnosed by the characteristic shaft, which acts as a rise around the depth, the presence of a central lift - a slide, a distinct radial-annular arrangement of cracks, the presence of fragmented rocks and other features.

An annular bar is a structure that surrounds the crater. The bar profile is usually asymmetrical: its inner slope is steeper than the outside. The volume of a circular bar rock for meteorite craters is usually 20-40% of the displaced rock volume.

The bottoms of the craters in the section have different shapes (flat-bottomed, cup-shaped, etc.). Their morphology is complicated by the increase in diameter. For example, the bottoms of large craters are complicated by central mound. The central mound, or central peak, is an obligatory structure that is formed in craters with a diameter of 5 to 50 km. It arises according to the laws of mechanics due to the elastic recoil of the target rocks' surface. The central mound isn't formed in craters with a diameter of more than 50 km, but such craters have central annular elevations.

Unlike the lunar craters that form and develop in a non-atmospheric environment, terrestrial impact structures immediately after their formation are destroyed by exogenous processes. Meteorite craters in Ukraine are practically not reflected in modern relief as they have formed tens and hundreds of millions of years ago. The Ilyinets meteorite crater has been affected by denudation processes for 445 million years. Therefore, as a result of erosion-denudation processes, the present size of this structure is much smaller than its original parameters. It is assumed that the size of the surface denudational section of the Ukrainian Shield in the Ilyinets structure area is approximately 300-400 m (Gurov et al., 1998).

According to the geomorphological views, the modern relief of the layer accumulative plain of the Ilyinets district began to form in the Paleogene-Neogene period. Ultimately, the modern relief was formed in the late Pleistocene, when the modern valley and complex of alluvial terraces of the Sobok River were formed.

Object of research is Ilyinets Meteorite Crater. 8 meteorite craters are known in Ukraine (Fig. 1) (http://www.passc.net; Valter, 2000; Kelley and Gurov, 2002; Gurov and Gozhik, 2006; Gurov and Nikolaenko 2017; Gurov and Nikolaenko 2017; Kats et al., 1989). The Ilyinets meteorite crater is explosive and a result of the fall of a cosmic body into the Ukrainian Shield territory 445 million years ago. As a result of the collision, a circular structure with a diameter of about 8.5 km and a depth of 600-800 m was formed. The primary relief of the meteorite crater was changed by denudation exogenous processes. At the current level of the denudation section, the outer diameter of the area of impactites' distribution is about 3.2 km. Unlike other impact structures in Ukraine, Ilyinets is not covered by a sedimentary cover and is characterized by the presence of shifted impact structures which were created as a result of the impact and explosion of the meteorite during its contact with target rocks, mainly Paleoproterozoic granitoids.

History of geological research. Until the middle of the last century, geological studies of the watershed of the Sob and Southern Bug rivers were fragmentary. The first information about the geology of the area appeared in the 1930s in works of Eichwald E.I. and Jakovitsky I.A. In 1851 Feofilaktov K.M. carried out geological surveys in the Sob river valley and identified volcanic rocks of the Ilyinets structure, which, in his opinion, were exposed to high temperature and pressure. According to petrographic studies (Tarasenko V.E, 1898), these rocks were interpreted as tuffs. From 1892 to 1915 the basins of the Ros and the Southern Bug River were explored by Sokolov M.O., Tarasenko V.E., Laskarev V.D., Luchitsky V.I., Tutkovsky P.A. They focused on stratigraphy, geomorphology and tectonic processes.

Systematic studies of this territory began in the second half of the twentieth century. During the large-scale geological mapping in 1956 Zholdak A.I., Vinogradov G.G and Ryabenko V.A. suggested the early Paleozoic age of the Ilyinets structure rocks. For the first time, they outlined the area of the development of this rock. It was also determined that it was located at the junction of Dzhuryn–Nemyriv–Ipyshets, Verkhniy Bug and Bratslav–Ladizhen regional faults. (Radzivill et al., 1986; Vinogradov et al, 1973).

In the early 70s, Masaitis V.L. (Masaitis, 1973; Masaitis, 1974) and Valter A.A. (Valter and Riabenko, 1976; Valter and Ryabenko, 1977) reported about the presence in the rocks of the Illinet structure of signs

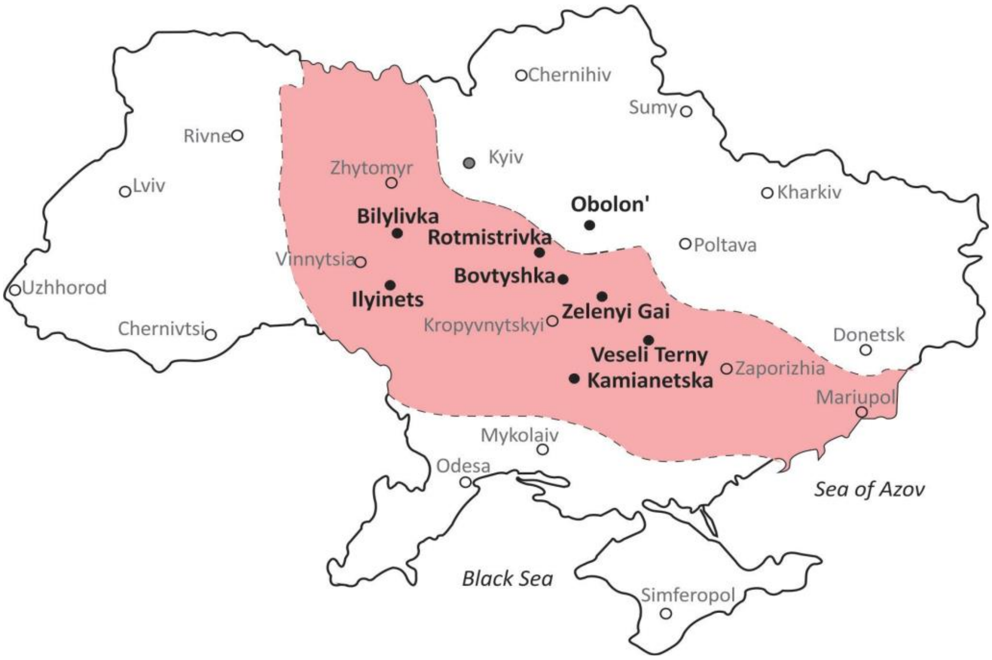


Fig. 1. Meteorite craters within the Ukrainian Shield (based on materials from Kryvodubskyi et al., 2004; Gurov et al., 2017).

of shock metamorphism. This new data led to a revision of ideas about the genesis of the structure and its attribution to the impact. A new concept of structure formation was supported by York Yu., G.K. Eremenko G.K., Polkanov Yu.O. and Nikolskyi A.P. In the 1980s, the ideas of the impact genesis of similar structures within the Ukrainian Shield were covered in the monographs and publications of Valter A.A., Ryabenko V.A.(1980, 1981, Valter et al A.A., 1982), Masaitis V.L.(1979, Masaitis et al. 1980), Gurov E.P. (1980, 1983) etc.

A logical consequence of the purposeful research of Ukrainian scientists and geologists was the discovery of impact type diamonds in the rocks of the Ilyinets structure. According to the results of geophysical researches, the Ilyinets gravimagnetic anomaly was revealed, the configuration of which was further detailed (Entin, 2012).

In the 1990s, the geological study of the Ilyinets structure continued at the Institute of Geological Sciences of the NAS of Ukraine under the direction of Gurov E.P. (Gurov et al., 1998). Valter A.A. published works devoted to the study of impact diamonds of Ukrainian impact structures (Valter, 1997, 1998, 2005).

Additional well drilling in 2010 (mapping works in the frame of GDP-200, M-35-XXX (Gaisyn)) gave new geological and geophysical data, as well as core materials the further petrographic and mineralogical study. In 2012, the PDRGP Pivnichgeologia together with the Institute of Geophysics of the NAS of Ukraine investigated the geophysical features of the structure and genesis of the Ilyinets structure (Entin et al, 2013). In 2015, State Enterprise "Ukrainian Geological Company" issued a set of maps on a scale of 1:200 000 territories of sheet M-35-XXX (Gaisyn). During these works, the geological and geophysical material were summarized, the contours and geological structure of the Ilyinets impact structure were specified (Prykhodko et al. 2013).

In total, within the Ilyinets structure, there are 6 outcrops of impact rocks (including 3 quarries), 58 wells, 7 of which are over 200 m deep.

Geological structure of the area. The territory of study is located on the border of Lypovets (Ivanky village) and Ilyinets (Lugova village) districts of Vinnytsia region. Following the current physical and geographical zoning, it belongs to the Podilly-Prydniprovia region of the forest-steppe zone of Ukraine. From the geomorphological point of view, the area of the Ilyinets structure is located within the layer accumulated sloping hilly-undulating alluvial-delta plain formed on Paleogene-Neogene sediments. The territory is divided by river valleys. Altitude elevations (relative to sea level) vary from 280-290 m in watersheds to 210-220 m in river valleys.

The Ilyinets meteorite crater is located 10 km west of Ilyinets in the Vinnytsia region in the Sobok valley. Visible fragments of the crater represented by typical impact rocks of various structural and textural types. These rocks are disclosed in the outcrops and quarries on the right bank of the Sobok River, on a 2 km long section between the villages of Ivanyki and Lugova.

Geological characteristics of target rocks. The Ilyinets meteorite crater is located on the boundary of

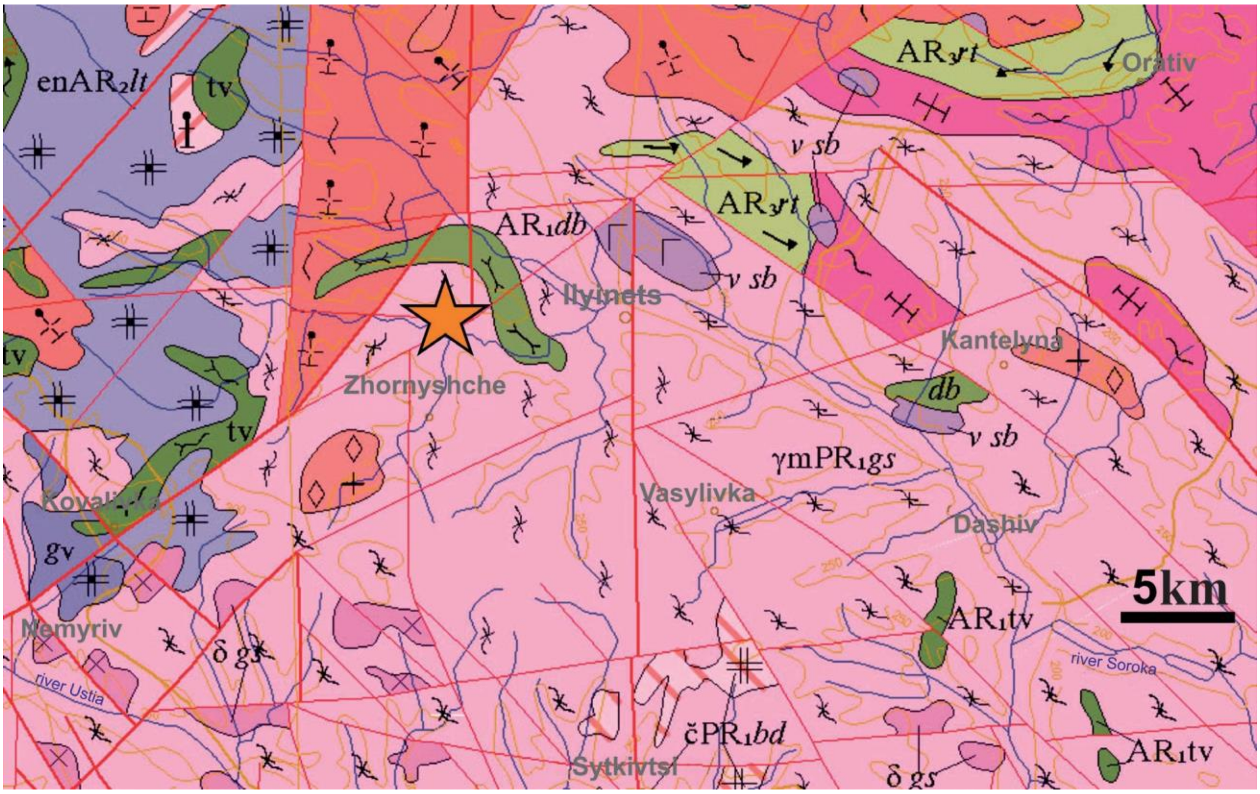


Fig. 2. Geological map of the Ilyinets meteorite crater (according to the materials of the State Enterprise "Ukrainian Geological Company"). Light pink indicates the granitoids of the Gaisyn (Sobite) complex; purple - enderbites of the Lityn complex, red - granitoids of Berdychiv complex and pink - granitoids of Uman complexes. The metamorphic rocks: light green colour - the Tyvriv sequence, green - undivided Dniester-Bug series.

two adjacent megablocks of the Ukrainian Shield- the Dnister-Bug and the Ros-Tikych (Koreliatsiina…, 2004). In its geological structure the main role is played by: Mesoarchaean enderbites of the Lityn complex and Paleoproterozoic granitoids of the Gaisyn, Uman and Berdychiv complexes (Fig. 2). The enderbites contain the remains of the crystalline schist and calciphyre of the Tyvriv sequence of the Dniester-Bug series, whereas among the granitoids - numerous, different-sized xenoliths (and remains) of undivided metamorphic formations of the Dniester-Bug and Rosyn-Tikich series are noted. The target rocks are the most common in the area of the Gaisyn (Sobit) complex granitoids.

This view was supported by Bezborodko M.I., Polovinkina Yu.I., Tkachuk L.G., Usenko I.S., Goodwill M.M. At the same time, Slenzak O.I. said for the first time that the sobite has an intermediate position between the charnokite and the migmatites of the Kirovograd complex. Lisak A.M. and Pashchenko G.M. believe that the sobite forms not one, but two separate formations, namely sobite (diorite, granodiorite, plagiogranite) and Uman (biotite porphyry granite). Shcherbakov I.B. proposed to define the Gaisyn complex, which consists of the association of genetically united rocks from charnokite to normal two-feldspar granites: diorites - quartz diorites - granodiorites (tonalites) - amphibole-biotite granites - biotite granites - pink aplite-pegmatoid granites (Shcherbakov, 1975; Shcherbakov, 2005). Usually, all kinds of rocks are usually present within one outcrop. So it is very difficult to determine any patterns in their spatial distribution. These granitoids are spread over an area of over 4000 km^2 and extend along the valleys of the rivers Sob, Southern Bug, in the upper reaches of Ros and Roska. Structurally, they are located in the area of the junction of the Rosyn-Tikych and Dnister-Bug megablocks.

The rocks of the complex are massive, from medium to coarse-grained, even-grained and porphyric. In the outcrops the rocks looks like typical magmatic formations. This impression is intensified by the presence of diverse, often rounded, xenoliths. They are represented by the rocks of the Dniester-Bug series: pyroxene-containing amphibolites, two-pyroxene-plagioclase crystalline schist, calciphyre, ferruginous quartzites, and rarely garnet-biotite plagiogneisses. In granites porphyroblasts are represented by potassium feldspar, and in the more basic rocks - plagioclase with a characteristic steel-grey, almost black colour. Aplite-pegmoid granites contain typically granulite blue-grey quartz.

To determine the time of the Gaisyn complex formation, the monazite from the granite quarry

Fig. 3. Rocks from a quarry in Nyzhcha Kropyvna village: 1) porphyry-shaped granite; 2) xenoliths of crystalline shale in granites (Stepanyuk et al., 2017)

in the Nyzhcha Kropyvna village on the left bank of the Southern Bug River was dated by the uranium-lead isotope method (Stepaniuk et al., 2017). The quarry is located 25 km southwest of Ilyinets Crater. The dated amphibole-biotite inequigranular grained (to porphyropic) granites (Fig. 3) have gradual transitions with different grades of K-feldspathization diorite-like rocks and granodiorites. The studied rocks contain numerous crystalline xenoliths, rarely amphibolites. The sizes of the crystalline schist bodies range from a few centimeters to several meters, and their shape is usually angular. The whole rock association looks like eruptive breccia, the cement of which is pink porphyry-like granite similar to the Uman one.

The Gaisyn complex granites were formed about 2.05 billion years ago (Stepaniuk et al., 2017). Due to the fact that the monazite crystals are spatially confined mainly to the microcline, the obtained age value characterizes the granite formation process sufficiently. The obtained isotope date is in good agreement with the time of formation of two-feldspar granites of the Uman complex of the Rosyn-Tikiych megablock.

Geology of the Ilyinets meteorite crater. The Ilyinets meteorite crater is the oldest and most eroded crater among the known impact structures of the Ukrainian Shield (Fig. 1). In its section, four major rock complexes are distinguished (Prykhodko et al., 2013): basement, coptogenic, filling and overlaps (Fig. 4). In the lower and lateral parts of the crater are rocks of the basement complex. They are represented by an autogenous breccia - brecciated rocks that have undergone shock metamorphism. With depth, they gradually turn into cataclased rocks and gradually into undisturbed rocks. The basement complex is overlain by a coptogenic one. The coptogenic complex, which was created by the explosion, consists of allogeneic breccia and impactites (from the bottom up). Allogeneic breccia is a displaced rock that is bedded on an authigenic breccia. It consists mainly of altered metamorphism of the target rocks fragments.

The target rocks were the above-described granitoids of Gaisyn type. It is likely that the crystalline rocks had a clayey weathered crust since allogeneic breccia contains solid inclusions of baked clay.

Impactites complete the coptogenic complex and, depending on the glass content, are divided into suevite (glass up to 75%) and shock-melt rocks (glass up to 100%). Allogenic breccia, which almost doesn’t contain glass, accounts for more than 60% of the volume of coptogenic rocks. The suevite lies on it with allogenic lenses and fragments of autogenous breccias. There are single shock melt lenses among the suevite, with a thickness from a few centimeters to 46 meters. These rocks are sometimes related to tagamites by analogy with the rocks found near Tagami Mountain in the Popigai River Basin.

The coptogenic complex rocks are overlain by the lenses of the Devonian mudstone and eluvium, formed of a cemented mass of suevite, fragments of mudstone and brecciated rocks of the foundation. One of the lenses of mudstone reaches 3.7 km in length and is oriented in the latitudinal direction (Fig. 4).

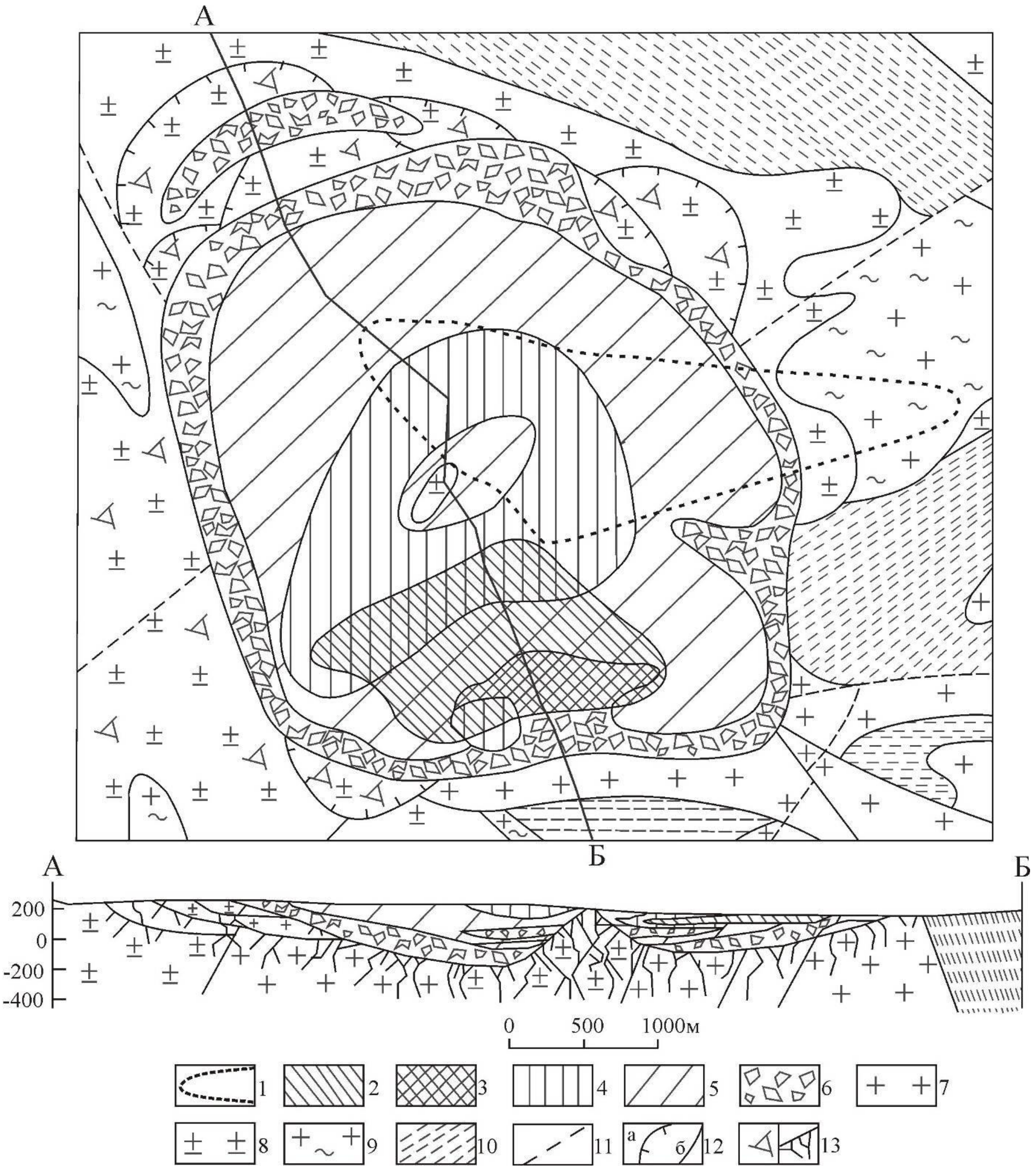


Fig. 4. Schematic geological map (without Cenozoic sediments) and the section of the Ilyinets impact structure (Masaitis et al., 1980).

Symbols: 1 - boundaries of the area of distribution of Devonian clays, mudstones, and siltstones; 2, 3 - distribution of shock-melt rocks (2 - under suevites and Cenozoic sediments. 3 - under Cenozoic sediments); 4 - crystal-vitroclastic suevites; 5 - vitro-crystalloclastic suevites; 6 - allogeneic breccia; 7 - aplite-pegmatoide granites; 8 - biotite granites; 9 - diorites, quartz diorites, granodioites (tonalites), plagiogranites; 10 - gneisses and crystalline schist; 11 - faulting of uncertain morphology; 12 - predicted drifts (a - on the map, b - on the section); 13 - shock fracture (a - on the map, b - on the section).

The Neogene (Miocene) rocks lie on the filling complex. They are represented by secondary kaolins, clays, sands, on which the Quaternary deposits formed. The rocks' average volume of the overlapping complex at the watershed (in the central part of the structure) is 13 m, in the valley of the Sobok River, it decreases to 3 m.

Mineral-petrographic features of impactites. Rocks and minerals undergo impact metamorphism and shock melting in the process of impact cratering. The impact nature of rocks and structures formed by them is considered to be confirmed by the presence of signs of shock-metamorphic origin (Gurov, 2002). The most important features of shock metamorphism are the short duration of its influence and the creation of ultrahigh pressures and temperatures that are not reached in endogenous processes.

A.A. Valter (Valter et al., 1982) found that the rock and mineral composition of an authigenic (unmoved) breccia fully corresponds to the foundation rocks' composition, which lies below, and in the central part of the structure, small brittle material accounts for approximately 50% of the composition of the authigenic breccia.

An allogenic breccia is a relocated impactite. It consists of target rock fragments, cemented with a fine-grained mass of minerals grains with signs of impact metamorphism of varying degrees. The allogenic breccia in the Ilyinets Crater lies, with a gradual transition, on authigenic breccia and fills an annular trough with a diameter of approximately 3.2 km. Unlike authigenic, allogeneic breccia is a heterogeneous accumulation of clumps and fragments of various compositions, which indicates the removed nature of these formations.

In the cross-section of the Ilyinets structure from the bottom up, the size of the fragments in allogenic breccias gradually decreases, separate particles and pancake-like fragments of glass appear with the inclusion of fragments of rocks and minerals with clear signs of shock metamorphism. The rocks change into suevites (Fig. 5), which in unaltered form have a grey colour with a greenish or bluish tone. The colour of the suevites changes from pale yellow to brown as a result of weathering. These rocks are strong, breccia texture, sporadically porous and cavernous due to glass alkalinisation. The yellow-white molten glass fragments of the various forms (up to 8 cm) can be observed against the background of pale-yellow fine-grained mass. The suevites contain a significant amount of brecciated granite rubble, rarely gneiss sizes from 1-3 mm to 10-20 cm. The fragments of minerals are represented by feldspars, quartz, amphiboles, and pyroxenes, sometimes garnet. These fine-grained minerals also form the cementitious mass of the rock. In addition to a glass of irregular shape, the suevites contain the inclusion of «aerodynamic» shape, the so-called «bombs» (Gurov, 2009). Their sizes vary from 1-2 to 10-13 cm in diameter; form - droplet-shaped, spherical, sometimes spindly. There are peculiar longitudinal furrows and ribs on the sur- face. Usually «bombs» have a zonal structure: the inner core is composed of relicts of clay or crystalline rocks; the outer shell has a crystalline structure with inclusions of fine-grained fragments; contacts with the core are clear, irregular, wavy or toothed (Fig. 6).

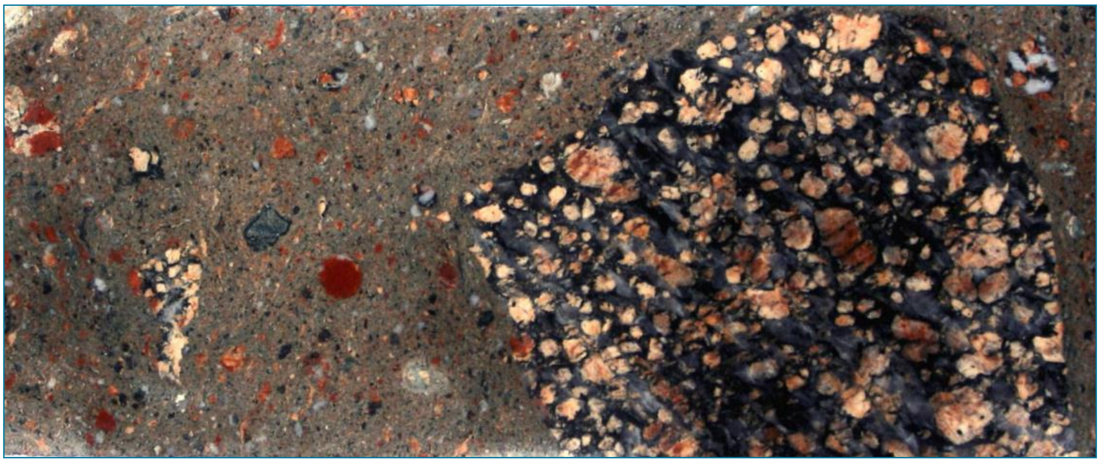


Fig. 5. Suevites of Ilyinets structure, the polished core of 9D drillhole (depth 121.2 m). Core diameter is 76 mm (Prykhodko et al., 2013).

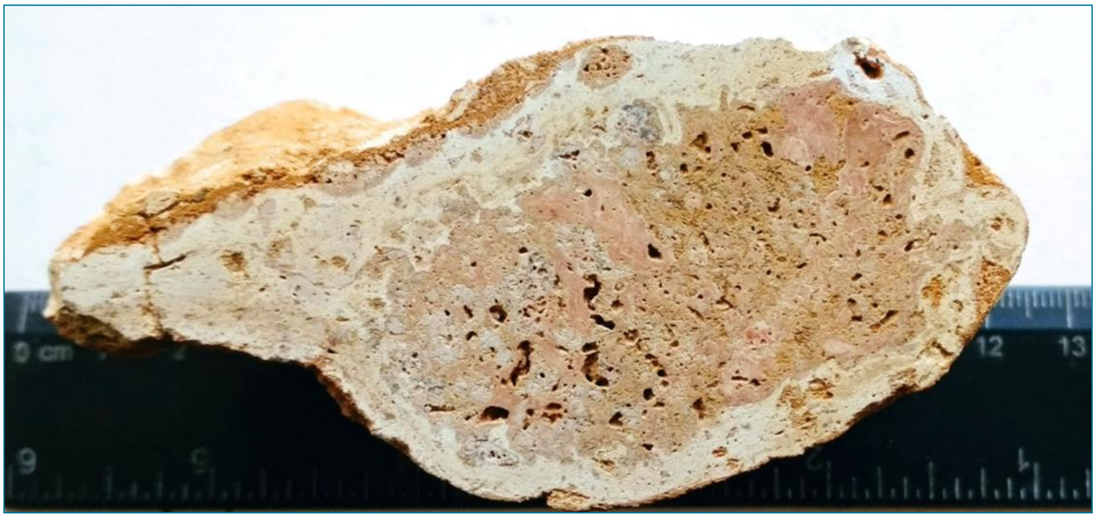


Fig. 6. The elongated “bomb” from the thickness of the Ilyinets crater. Longitudinal cutting, 6×13 cm bomb. Sample from the Gurova E.P. collection.

Shock-melt rocks are solid glassy and massive, mostly black. The colour changes to brown as a result of weathering. Due to high glass content (up to 90%), they have an aphanitic texture. Previously, they were described as andesidacites and felsite porphyry. These rocks are developed in three locations of the Ilyinets structure.The central one is on the slopes of the central elevation, close to the contact with the brecciated target granites. The eastern locations are among the suevites of the eastern depression filled with mudstone. The third is the southern one. The cross-sections of the central locations show that the shock-melt rocks lenses have a steep fall. In the southern one, they form a subhorizontally-oriented oval-shaped formation body, up to 1.5x1.1×0.035 km. The contacts of shock-melt rocks with surrounding rocks are gradual and dim. The shock metamorphism leads to changes in the mineral composition of rocks and their textural and structural features. This process also causes the appearance of planar (thin parallel) fissures similar to cleavage in the minerals (Gurov, 2002). The planar fissures have been found in quartz, feldspars, biotites, amphiboles of allogenic breccias (Valter et al., 1982; Gurov et al, 1998). Destruction cones, diaplectic and molten glass, spotty anisotropization of minerals, bands of biotite, geochemical anomaly of iridium, etc. are also observed (Valter , 2008).

In the granitoid and gneiss fragments of the authigenic breccia upper horizon, the porphyroclastic structures appear, which are caused by the spread of intensively deformed large grains of quartz and feldspar in fringes composed of small mica aggregate or newly formed quartz. .

Valter A.A. (Valter et al., 1982) estimated the impulse pressure of feldspar-sanidine transformations at 40-50 GPa (400-500 kbar) and the temperature at 1500 ° C. The predominant orientation of the angles between the planar element poles and the optical quartz axis (omega factor) indicates a shock at a peak pressure of 16-20 GPa (Masaitis et al.,, *1980*).

The comparison of the average composition of impact and basement rocks shows that the content of impact and molten rocks is characterized by a decrease in the content of silica, ferrous iron, magnesium, calcium and sodium, and increase of oxide iron and potassium (Prykhodko et al., 2013). The most significant is the difference in the content of alkalis and iron. The degree of iron oxidation increases from the basement to shock-melt rocks, in other words from the bottom up. In the shock-melt rocks, the content of disthene, corundum, and graphite, characteristic of high-dimensional and restorative conditions of mineral formation, increases in comparison with granites and suevites.

The ore hydrothermal minerals (chalcopyrite, pyrite, galena, sphalerite, molybdenite), as well as non-metallic ones (barite and fluorite), are distributed regularly in all varieties of both coptogenic and sedimentary complexes. The next hydrothermal processes are likely to occur after the completion of formation of both complexes and are associated with the Cimmerian tectonic-magmatic activation of the southwestern margin of the Eastern European Platform.

Metal and silicate spherules were found in the rocks of the Ilyinets structure. These particles, even in shape and size, have a different composition, type of inclusions and impurity elements. Among the spherules were found: those which are strongly magnetic, hollow inside. They can consist of magnetite, magnetite-iocyte, iocyte and magnesioferrite-iocyte; magnetic with a spherical core of native iron and a shell composed of iocyte or glass saturated with skeletal crystals of manganese ulvospinel; silicate glass containing inclusions of skeletal crystals of magnetite, alumochromite, spinel, iocyte. The cogenite micron-size inclusions are present in native iron.

The isotopic age of the Ilyinets structure molten rocks, which underlies allogeneic breccias, is 445 million years (corresponding to the Ordovician) according to the 40Ar /39Ar method (Pesonen et al., 2004) and the results of paleomagnetic studies performed by scientists at the University of Helsinki. This age is considered to be the most reliable. Earlier definitions (1972) of the K-Ar method in the IGFM (now IGMR NAS of Ukraine) indicate the age of the Ilyinets meteorite crater rocks to be about 400 million years (Radzivill et al., 1986).

Geological and touristic route to the Ilyinets meteorite crater. Here we present the developed route of the geological excursion within Vinnytsia region, the top object of which is the geological natural monument “Ilyinets Crater”.

The geological excursion is designed for one day and consists of 4 observation points. The last stop can be used as an extra.

1 – Kalnyk village. Flooded granite quarry

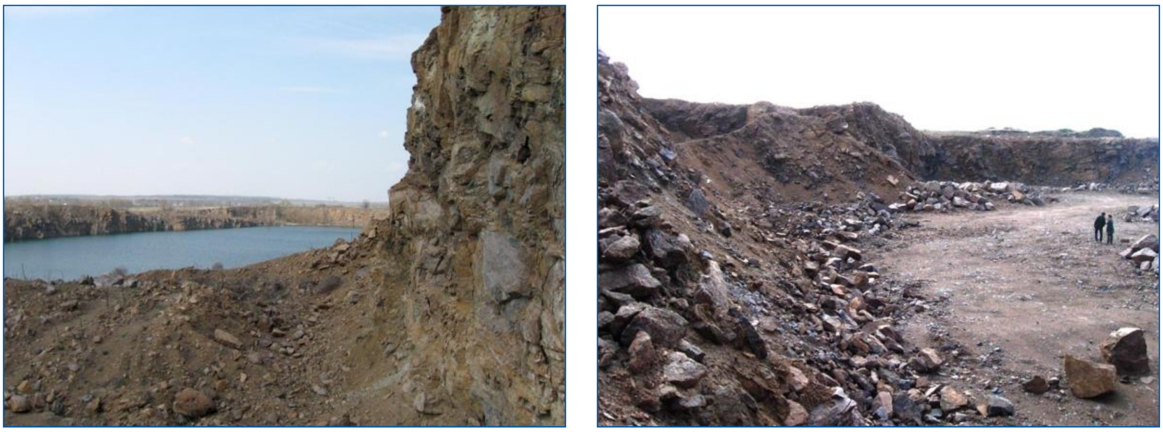
The quarry is located on the left bank of the River Sob on the eastern outskirts of Kalnyk village and about 20 km to the east of Ilyinets Crater (Fig. 7). The Paleoproterozoic granitoids of the Gaisyn complex, typical representatives of the target species, are revealed there.

In the 1960s granite was mined in the quarry. Now the quarry is no longer worked and is flooded (Fig. 8 A). Two ledges of shallow excavation in its southeastern part remain available for study (Fig. 8B),

Fig. 7. Kalnyk granite quarry in Google satellite image. The arrows indicate the observation points and their number.

where probably after the completion of the industrial production granites were mined in a small amount for local needs.

Accessory minerals are apatite, zircon; secondary. Secondary minerals are actinolite, chlorite, carbonate, graphite.



A B

Fig. 8. General view of a granite quarry near Kalnyk village. A - view from item 1-2 on the flooded main part, B - excavation.

In the excavation walls, a typical granite-like association outcrops: biotite-amphibole diorites and granodiorites, amphibole-biotite tonalites and plagiogranites, biotite two-feldspar and aplite-pegmatite and aplite-pegmatite granites.

At the entrance to the excavation in a small ledge (point 1-1, N49°02'15'80 «E29°24'39'50»), grey biotite-amphibole, biotite diorites, tonalites, plagiogranites are massive, medium-grained, replaced by two-feldspar granites. These granites are pinkish-grey and often with spotted structure due to the microcline inclusions. The change occurs in two ways. The first (the most common) is a relatively uniform shadow replacement. The second one is the unequal enrichment of microcline and quartz with the formation of migmatitic rocks, in which the melanosome is represented by poorly modified plagio- and leukosoma - two-feldspar granitoids. Mineral composition of granitoids: plagioclase-oligoclase, quartz, biotite, amphibole, microcline of replacement.

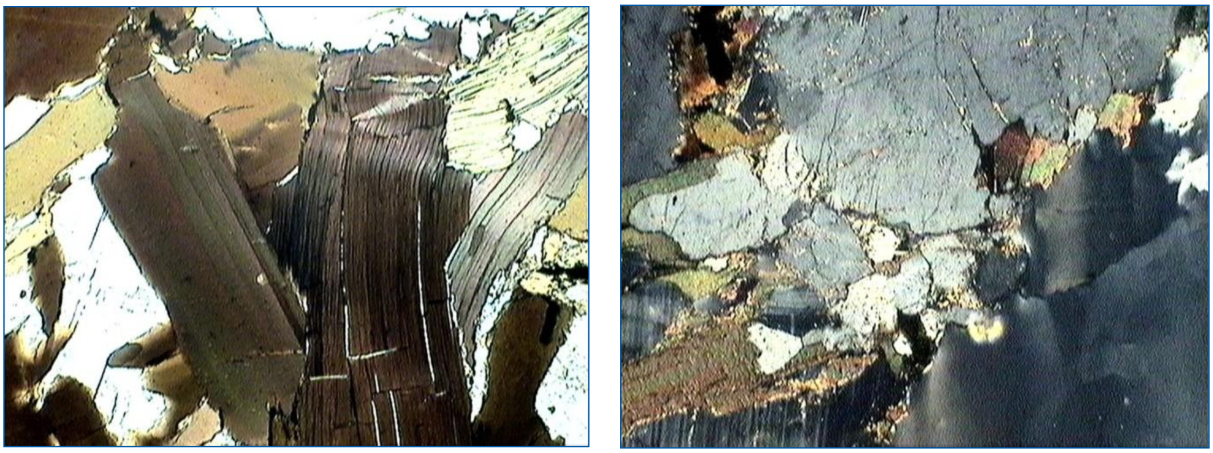
There are several stages of retrograde metamorphism granite transformation under P-T conditions from amphibolite to green-shale facies. In the early stages, there was the rock crushing, which was accompanied by recrystallization of the mineral grains' contact zones during interclass sliding under conditions of compression and filling of biotite with apatite mineralization of cracks under stretching conditions. Quartz was deformed, plastic in compression areas and granularized in shear areas, decomposing into sub-basins most often with a serrated (suture) contact surface. The wavy extinction attests to the dynamic nature of the restoration of quartz subgranular.

In the next stages of tectonic transformation, the rock-forming minerals - plagioclase, quartz, biotite, amphibole, are deformed intensively (Fig. 9). A network of cracks, kink bands, grain breaks, and recrystallization of grain contacts are formed. Carbon dioxide solutions actively penetrated the cracks, which led to the crystallization of calcite and graphite, as well as the replacement of green amphibole by chlorite and actinolite.

Some grains of clinopyroxene are noted in some places. More intense sign of graphitization and carbonation also occurs sometimes. The graphitization reveals in cracks in virtually all grains of rock-forming minerals and is accompanied by carbonation. Graphite, calcite, and chlorite form crusts around the accessory minerals, or pseudomorphically replace them.

Two-feldspar biotite granites (Fig. 9) with coarse-grained and porphyric-like structure contain tectonized inclusions of quartz-feldspar composition, fringed by linear-elongated biotite aggregates, thereby making their structures look lepidogranoblastic. Feldspars are cataclastic, internally cracked, characterized by deformation of the polysynthetic twin of plagioclase and the formation of a spotty microcline lattice and its deformation. Biotite occurs on cracks and deformation bands in the feldspars. On the contact of microcline with plagioclase myrmekite occurs. Quartz is deformed plastically with the formation of deformation bands and subsequent decay of the grains into sub-grains under dynamic restoration. Further transformation of granites occurs with the appearance of crack formation, quartz recrystallization, deformation and rupture of biotite plates, local redistribution of microcline, carbonate cracking and a small amount of graphite.

On the opposite side of the excavation wall (point 1-2, N49 ° 02’18,10 «E29 ° 24’44,00») massive, porphyritic, sometimes unclear striped, grey-pink and pink biotite, amphibole-biotite medium-grained granite and granodiorites outcrop (Fig. 10 A). Porphyropic inclusions of individual grains microcline or its aggregates reach 4-5 cm. Among the granites, there are single inclusions of dark grey diorite and crystalline schist, which look like melted ovals up to 25×15 cm in size (Fig. 10 B). These rocks form the main background of this part of the quarry.



A B

Fig. 9. The character of micro-deformations in biotite plagiogranites (point 1-1).

Here and further in the photo the size of the long side of the shot is 1.43 mm; never crisscrossed.

Amphibole-biotite granites and granodiorites consist of plagioclase, microcline, quartz, biotite,

A B

Fig. 10. Granites and granodiorite (biotite and amphibole-biotite, point 1-2).

secondary chlorite, graphite, calcite, accessory apatite, and zircon. Hypidiomorphic-granular texture with maximal plagioclase idiomorphism relative to potassium feldspar and quartz is featured. There are elements of rock-forming minerals deformation, intergranular recrystallization in the form of micromyrmekite aggregates at the boundaries of plagioclase and K-feldspar grains. The rock-forming mineral grains are deformed, characterized by wavy attenuation and the presence of bands of deformation, bending of twin growths of feldspars and biotite plates, granulation of quartz grains. There is a system of parallel healed cracks traced by microinclusions similar to planar fractures (Fig. 11).

In the east wall of the excavation (point 1-3, N49 ° 02'16,10 «E29 ° 24'43,10»), pink-brown two-feldspar granitoids are revealed. In this rock there are different morphologies of grey relic bodies up to 1.5 meters in size, which are composed of altered and tectonized amphibole-biotite crystalline gneisses (Fig. 12). The crystalline schist is grey, dark grey with a greenish tinge, fine-grained. On the edge of the relic, a biotite rim is often observed. According to the geologists of the Pravoberezhna GRE, relics (up to 2-3 m) of carbonate-silicate rocks (from calciferous to scapolite-diopside rock) were also observed in the of the flooded part of the quarry.

Biotite granites have a porphyritic texture, the bulk being medium-grained, hypidiomorphic-granular with plagioclase idiomorphism to quartz and the development of a myrmekite at the microcline and plagioclase grains contacts of microcline and plagioclase (Fig. 13). The quartz, as well as feldspars, is characterized by wavy attenuation and decays into sub-grains with a specific contact surface. The mineral composition of the rock (%): plagioclase –35, microcline – 35, quartz –28, biotite, chlorite, graphite – 2, calcite, apatite, zircon.

The biotite crystalline schist and plagiogneiss are modified to varying degrees. The rock's texture is lepidoblastic, with porphyroblastic elements. Mineral composition (%) is: porphyroclast mesoperthitic - 24; main mass: plagioclase - 34, quartz - 15, biotite - 25, chlorite, calcite, graphite - 1, apatite, zircon.

As was shown, the rocks at the micro level show intense multistage tectonic transformations, some of

Fig. 11. Signs of planar fracture in feldspars and quartz (point 1-2).

Fig. 12. Pink-brown two-feldspar granitoids with relict of amphibole-biotite gneisses and crystalline schist (point 1-3).

Fig. 13. Biotite granites in thin-section (point 1-3).

which may be related to the impact events that led to the formation of the Ilyinets Crater. Particularly important in this regard are the above-mentioned elements of planar structures, which in the Kalnyk quarry require further study.

2 – Luhova village, Geological monument of nature «Ilyinets Crater»

We can get acquainted with the peculiarities of the geological structure of the southern part of the Ilyinets meteorite crater in quarries and natural outcrops, study a variety of the impactites' structural and textural types.

Near **Luhova village** on the left bank of the Sobok River in quarries shock-metamorphosed rocks are exposed (Fig. 14, 15). Geographic coordinates of main quarry N49 ° 06'00,04 «E29 °06'24,66».

It should be noted the impactites were mined as rubble stone for local needs up to the 1960s. Now the outcrops of the Ilyinets structure rocks are a geological monument of nature and protected by law.

It is believed that a massive meteorite under the pressure of 5000 - 8000 atmospheres and at temperatures above 3000°C crashed into the Earth's crust to a depth of 800 m and exploded. In this case, the target rocks partially melted, split apart, sintered and formed a new complex of rocks - impactites.

The different types of impact rocks are formed at various stages of the impact process and in diverse parts of the impact structure. The peculiarities of the composition and structure of such rocks depend on their original location and distance from the center of impact, the composition and structure of the tar-

Fig. 14. General view of the impactites' quarry, which can be a part of the Geosite

Fig. 15. Spherical impactites' body in the quarry near Luhova village

get, the type of material movement in the cratering process, and the final position of rocks in the impact structure (Gurov, *2002*).

Allogenic breccias and tufts (Fig. 16A), including "bombs", appear on the surface of the workings and quarries. The rocks underwent hypergenic transformations, which are confirmed by the presence of manganese, ferruginous and clay minerals, zones of silicification and mylonitization (Fig. 16B).

The meteorite crater circular bar was destroyed by further exogenous and endogenous processes and is not expressed in modern relief.

3 – Luhova village, place of millstone production

A site with traces of Chernyakhiv culture and signs of stone millstone production (Fig. 17) was found in the Ilyinets meteorite crater (Khavliuk, 1980; Klimovskii and Gurov, 2011). The researchers found marks of picks in ancient workings, numerous finds of millstones and defect millstones. Also, an almost six-meter layer of production waste from this activity was left. So there is no doubt about the functional purpose of the open object. The large-scale mining here was begun in the III BC by tribes of Chernyakhiv culture. Probably, with a slight interruption, it lasted until the pre-Rus time. The locals mined impactites and granitoids for making millstones - paired stone circles used in mills for grinding grain into flour (Fig. 18). The opening of the Ilyinets quarry was important for studying the history of production and economy of the ancient settlements of the region.

4 – Ivanky village, Geological monument of nature «Ilyinets Crater»

Here we can find out about the geological structure features of the boundary part of the crater (N49° 06'04,72" E29° 04'41,78") in the quarry near the village Ivanky on the banks of the River Sobok (Fig. 19). Also, we can study impactites, their mineralogical, structural and textural features and hypergene changes.

The quarry revealed shock-metamorphosed rocks, which belong to the lower complex of the Ilyinets structure impactites. They are represented by allogenic breccia and suevites (Fig. 20).

Over millions of years, the crater was destroyed

A

B

Fig. 16. Impactites and its hypergene alterations

Fig. 17. Stone mining site of the 3rd century AD (the Chernyakhiv culture).

Fig. 18. Ancient millstones, which are made of suevites

Fig. 19. General view of the quarry near Ivanky village

by tectonic and denudation processes. These processes continue at the present stage. Therefore, fragments of a meteorite crater can only be distinguished in quarries and, occasionally, in outcrops. Everywhere, the suevites have undergone significant secondary alterations and have acquired various shades of yellow, brownish, and brown.

Conclusions. It should be noted that in contrast to other impact structures of Ukraine, which are covered with a thick layer of rocks, the Ilyinets meteorite structure is opened by quarries of the Chernyakhiv culture stone mining. Such works revealed the crater's southern edge, so we can observe the internal compounds of cosmogenic origin structure. This allows us to see not only the geological history of this point on the Ukrainian Shield but also to touch the history of the region.

The geological route was developed to present

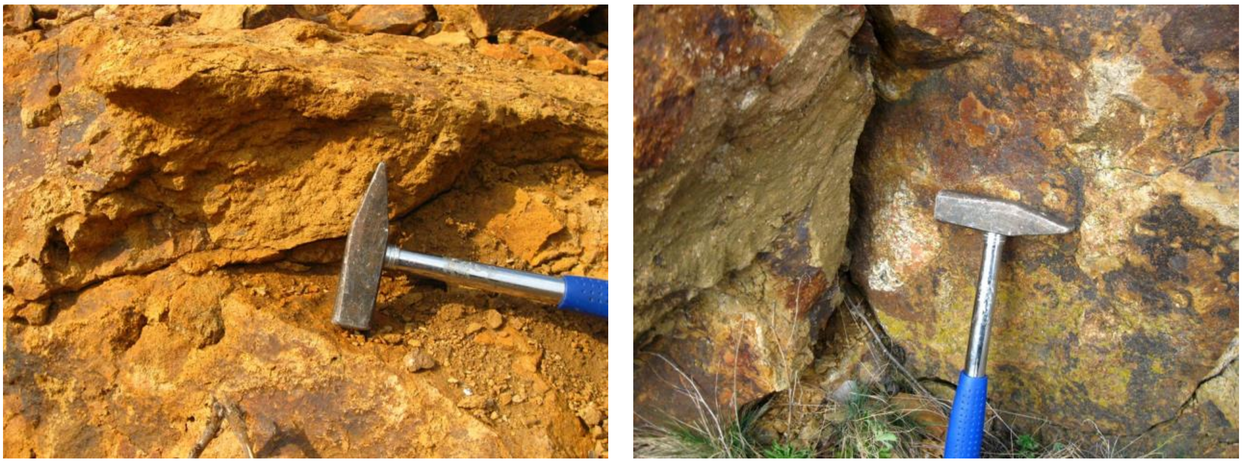


Fig. 20. Impactite outcrops in the quarry walls near Ivanky village. The rocks are varying in degrees of hypergene alteration

geological objects in chronological order. The geological excursion will allow visitors to learn about meteorite craters in general; to feel the threats posed to our planet by cosmic bodies; to touch the secrets of the Ilyinets Crater, which will allow us to learn the geological history of our planet and the universe. At the end of the route we will look at the millennial prints of the Chernyakhiv culture, traces of which were found on the edge of the Ilyinets structure.

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