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KARST-COLLAPSE TECHNOGENIC EARTHQUAKE SEPTEMBER 30 (29), 2017 IN STEBNYK (WESTERN UKRAINE) AND MAN-MADE PROVOKED PROCESSES AT STEBNYK POTASSIC MINE

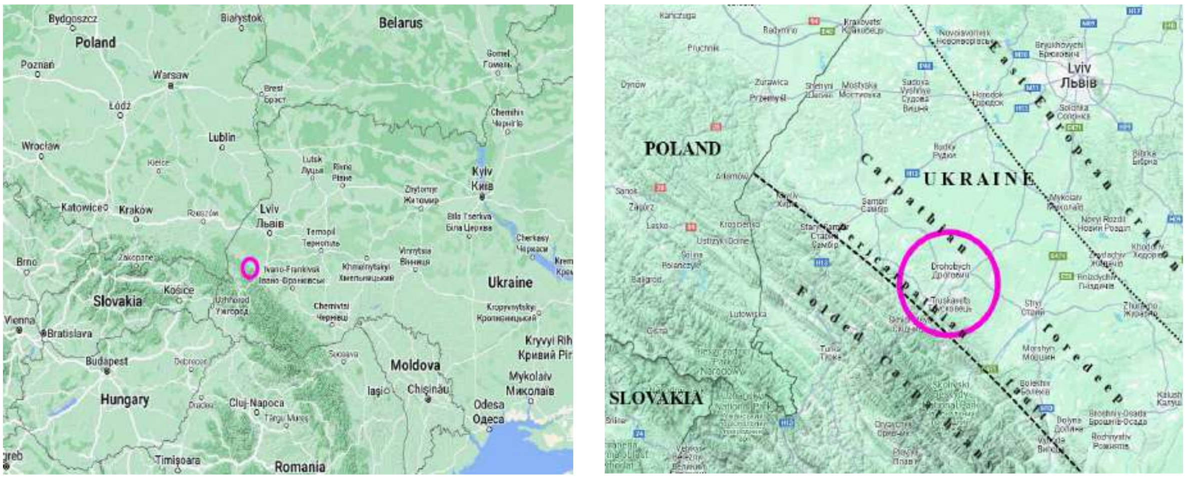
The purpose of the work is a comprehensive analysis of the causes, characteristics and consequences of the karst-collapse technogenic earthquake that occurred on September 30, 2017 at 00:46 local time (September 29, 2017 at 21:46 GMT) in the city of Stebnyk in the area of the Mine No. 2 of the Stebnyk MCE “Polymineral”, its analysis in connection with technogenically provoked dangerous geological processes (in particular, with the formation of karst sinkholes) at the Stebnyk potash mine (Ukrainian Precarpathians). Methodology. The research methodology combines a comprehensive analysis of seismic, geological and other data in the Stebnyk potash deposit area, including specifying the localization of local earthquake foci, estimating the parameters of seismic sources, using for this purpose developed approaches and methods, adapted known and specially created computer and GIS technologies and their variants, developed appropriate software tools. Results. The modern seismic activation (2014–2024) of the Boryslav-Stebnyk area is briefly traced. Considering the long-term (from the beginning of the 19th century) active extraction of oil and gas condensate in the Boryslav area, as well as potash ores in Stebnyk, local seismicity is apparently partly additionally technogenically provoked (induced). Seismic events in the area of Mine No. 2 of Stebnyk MCE “Polymineral” are defined as karst-collapse technogenic earthquakes in the mining area of this mine. Technogenically provoked dangerous geodynamic processes in the area are traced and important energy and kinematic parameters of technogenically provoked seismic events caused by them are estimated. Based on data on the karst-collapse earthquake of September 30 (29), 2017 in Stebnyk and on data on the velocity structure of the crust of west of Ukraine, we clarified the hypocenters of local seismic events in the Boryslav – Stebnyk area and we determined for it local kinematic corrections for seismic stations of the Carpathian Seismological Network of Ukraine and for a number of seismic stations in Poland, Slovakia, Hungary and Romania. Originality. For the first time, using data on the velocity structure of the Earth’s crust in the Carpathian region of Ukraine, methods of refining the seismic events foci in the area of the cities of Boryslav – Stebnyk – Drohobych – Truskavets have been developed. With their use, as well as based on the results of determining the characteristic parameters of the foci of local seismic events, the technogenic karst-collapse nature of seismic events in the area of Mine No. 2 of the Stebnyk potash deposit has been unambiguously established and their important characteristics have been determined. Practical significance. The results of the research make it possible to clarify the nature of the processes and assess natural and technogenic geoecological risks for the Boryslav – Stebnyk – Drohobych – Truskavets area, in particular, in the area of Mine No. 2 of the Stebnyk potash deposit for development an optimized set of necessary engineering and technical measures to minimize these risks. The determined local kinematic corrections for seismic stations of the Carpathian Seismological Network of Ukraine and for seismic stations of Poland, Slovakia, Hungary and Romania provide a significantly more precise determination of the coordinates and depths of the foci of local seismic events in the Boryslav – Stebnyk area, both natural and technogenic in genesis.

Key words: Ukrainian Precarpathians, Boryslav – Stebnyk area, seismicity, tectonics, potash mining areas, technogenic karst, karst-collapse earthquake, hypocentering of earthquakes (determining the coordinates and depths of earthquakes foci on the instrumental data), kinematic corrections.

Introduction

Among the modern seismically active areas of the Ukrainian Precarpathians, the Boryslav – Stebnyk – Drohobych – Truskavets area stands out (Fig. 1), which until very recently was not marked by seismic activity. The modern activation of seismicity in the Boryslav area has been observed since 2014 [Nazarevych et al., 2017, 2018, 2024, 2025; Nazarevych, Nazarevych, 2018a, 2018b, 2019; Nazarevych, 2024]. Before this, no noticeable seismic events (with the possibility of their spatial localization according to the records of at least three nearby seismic stations or according to macroseismic effects) have been registered in this area [Catalog..., 1958–1975; Seismological..., 1980–1988, 1989–1992, 1995–2004; Kendzera et al., 1997, 1998; Carpathian..., 2025]. And this is despite the fact that the group of seismic stations closest to this area (see below, Fig. 2) has been operating for a long time: “Lviv” seismic station (the oldest in the region) – since 1899 (distance to the area 60-75 km), “Morshyn” seismic station – since 1978 (distance to the area 30-40 km), “Shidnytsya” seismic station – since 2006 (distance to the area 7-20 km).

Also, information about such events is absent in the catalog of historical earthquakes of the Carpathian region [Kostyuk et al., 1997] and in other sources ([Evseev, 1961; Kendzera et al., 1997, 1998; Toth et al., 2002; National..., 2007] and others).



a *b*

Fig. 1. The studied area (marked with a pink circle) on the map of Central Europe (a) and on the map of western Ukraine with elements of tectonics (b) (Google Maps map base with relief).

The studied area (the area of the cities of Boryslav – Stebnyk – Drohobych – Truskavets, Fig. 1, *b*) according to the general seismic zoning map GSZ-2004-A [National..., 2007, SBC…, 2014] belongs to the 6-point zone of predicted intensity of seismic shaking. It should also be noted that a significant part of the foci registered in 2014-2020 earthquakes in this area are located in zones where oil and gas condensate have been extracted for a long time (since the first half of the 19th century) ([Atlas..., 1998; Krupskyy, 2001, 2020] and others).

The recent seismicity of the Boryslav – Stebnyk – Drohobych – Truskavets area, according to our data [Nazarevych et al., 2017, 2018, 2024, 2025; Nazarevych, Nazarevych, 2018*a*, 2018*b*, 2019; Nazarevych, 2024], is associated, first of all, with the local component of the regional geodynamic and seismotectonic process, which acts on the tectonic structures of the Carpathian foredeep, i.e., the zone of articulation of the East European platform with the Carpathian folded system. In particular, earthquakes often gravitate here to the zones of intersection of structures of the diagonal north-west (Carpathian) and orthogonal north-east directions [Nazarevych et al., 2017; Nazarevych, Nazarevych, 2018*a*, 2018*b*; 2019, Nazarevych, 2024]. An additional factor contributing to the seismic activation of the Boryslav area may also be a change in the stress-strain state of the rock massifs of the area during oil and gas extraction [Atlas..., 1998; Nazarevych, Nazarevych, 2018*a*, 2018*b*, 2019, Nazarevych, 2024], the relationship between them may have a complex cause-and-effect nature, as some researchers have already noted (see, for example, [Dolenko et al., 1976] and others).

The uniqueness of this area lies in the fact that there has been a long-term (since 1810) active extraction of oil, gas and ozokerite on an industrial scale. Here, in the area of the city of Boryslav at the beginning of the 20th century, several hundred wells were operated on an area of 20 km^2, and today the oil potential of this area has not yet been exhausted. It is known that the extraction of hydrocarbons affects (in particular, through a change in the fluid regime of the earth’s crust structures) changes in the stress-strain state of the geological medium not only in the vicinity of the wells, but also on a much wider scale ([Atlas..., 1998; Nazarevych, Nazarevych, 2011, 2016, 2017, 2018*a*; Ben' et al., 1999; Keranen et al., 2013] and others). Therefore, in the zones of many oil and gas fields in Ukraine and the world, an intensification of technogenically induced geodynamic processes and increased seismicity are noted ([Nazarevych, Nazarevych, 2011, 2016, 2017, 2018*a*, Keranen et al., 2013] and others).

Another factor causing local seismic activity is local technogenic geodynamic processes in the mining areas of the Stebnyk potash salt deposit ([Shamotko et al., 2002; Deshchytsya, Shamotko, 2005; Gaydin, 2017; Dyakiv, 2017, 2018; Rudko, Gaydin, 2019; Nazarevych et al., 2017; Nazarevych, Nazarevych, 2018*a*, 2018*b*; Maksymchuk et al., 2019; Kuzmenko et al., 2019; Hlotov, Biala, 2022; Khevpa et al., 2023] and others).

The Stebnyk potash salt deposit was discovered in 1834, the first mine was built in 1922, and Mine No. 2 was built in 1960.

Dangerous processes in the mines (cracks, water inflows) became more active after the devastating earthquake in the Vrancea area (Romania) on March 4, 1977, with M=7.1 impact on this area.

A major technogenic disaster occurred here on September 14, 1983, after heavy rain, the earthen dam of the tailings pond was broken. A huge mass of highly concentrated saline mud poured into the Solonytsia River basin, then into the Tysmenytsia River, and even further into the Dniester River and the Black Sea. The total mass of this discharge was over 5 million tons, it was a mudflow with a powerful hydraulic head. It polluted the entire surrounding area, caused enormous damage to the flora and fauna of the region, as well as to the hydrobionts of the Solonytsia, Tysmenytsia and Dniester rivers.

All these processes may continue to pose a certain threat to the studied area, including settlements, infrastructure facilities, the oil and gas complex and the Stebnyk mine. Therefore, study and monitoring of local geodynamics, seismicity and seismotectonic processes on these areas (including the area of the cities of Boryslav – Stebnyk – Drohobych – Truskavets) is an urgent task, also taking into account the ecologically hazardous potential of the Stebnyk potash deposit zone located here and the possible threats to the Truskavets – Shidnytsya resort area. Also, a separate task is the study of technogenic geodynamic processes and technogenic earthquakes in the mines of the Stebnyk potash deposit.

Purpose

The purpose of the work is to conduct a comprehensive analysis of the causes, characteristics and consequences of the karst-collapse technogenic earthquake that occurred on September 30, 2017 at 00:46 local time (September 29, 2017 at 21:46 GMT) in the city of Stebnyk in the area of the second mine of the Stebnyk Mining and Chemical Enterprise (MCE) "Polymineral", its analysis in connection with technogenic dangerous geological processes at the Stebnyk potash mine (Ukrainian Precarpathians).

Methodology

The research methodology includes a comprehensive analysis of seismic, geological and other data for the Boryslav – Stebnyk – Drohobych – Truskavets area, in particular, in the Stebnyk potash deposit zone. The localization of the foci of the studied local earthquakes was clarified using the regional seismological hodograph and the method of residuals minimizing [Nazarevych, Nazarevych, 2002, 2003, 2004*a*, 2004*b*; Nazarevych, 2006] taking into account local kinematic corrections [Nazarevych, Nazarevych, 2004*a*, 2004*b*; Nazarevych et al., 2024, 2025] for the peculiarities of the velocity structure of the area crust [Structure..., 1978; Lithosphere..., 1987–1993; Zayats, 2013; Starostenko et al., 2013], determined, in particular, on the results of the hypocentering of the karst-collapse technogenic earthquake in Stebnyk (see below for more details). The parameters of the seismic sources were estimated by the energy and spectral characteristics of seismic oscillations and correlation dependencies [Nazarevych, Nazarevych, 2018*a*, 2018*b*, 2009]. The characteristics of the karst-collapse earthquake at Mine No. 2 in Stebnyk were analyzed taking into account the processes in the mine field [Gaydin, 2017; Dyakiv, 2017; Rudko, Gaydin, 2019; Maksymchuk et al., 2019; Kuzmenko et al., 2019; Nazarevych, Nazarevych, 2018*a*, 2018*б*]. The applied approaches and methods are described in more detail below in connection with the relevant research results.

Results

Seismotectonic activation of the Boryslav – Stebnyk area

Since this article focuses on technogenically provoked dangerous geological processes in the Stebnyk potash deposit zone, the results of study of natural seismicity, seismotectonics and geodynamics of the area are briefly presented here, a separate special publication will be devoted to a detailed analysis of these issues.

Deep structure and modern geodynamics of the Earth's crust in the area. The studied area is located at the junction of the main tectonic structures of the Carpathian region of Ukraine: the Folded Carpathians and the Carpathian Foredeep ([Structure…, 1978; Lithosphere…, 1987-1993; Krupskyy, 2001, 2020; Zayats, 2013] and others, Fig. 1, *b*).

A characteristic feature of the deep structure of the Carpathians in general and this area in particular is a multi-tiered system of thrusts and folds that lie on the structures of the dipping edge of the East European craton ([Structure…, 1978; Lithosphere…, 1987-1993; Krupskyy 2001, 2020; Atlas..., 1998; Zayats, 2013; Nazarevych et al., 2025; Starostenko et al., 2013; Sheremeta et al., 2023] and others).

Characteristic features of the structure of the crust of the Carpathian Foredeep are the stepwise dipping southwestward structures of the East European craton, covered mainly by Neogene sedimentary strata [Atlas..., 1998; Zayats, 2013].

The structures of the Carpathians and the Foredeep are divided into blocks by numerous faults of the Subcarpathian (northwest – southeast direction, az. 130±10º) and orthogonal directions, as well as a number of less pronounced faults of the submeridional and sublatitudinal directions ([Atlas..., 1998; Zayats, 2013] and others). The main Subcarpathian fault here is the Pericarpathian fault (Fig. 1, *b*) with a basement ledge (dip of the southwestern wing up to 1.5 km beneath the Carpathians), which actually separates the Carpathians and the Carpathian Foredeep.

The natural seismic activity of the studied area is associated by us (see [Nazarevych et al., 2017, 2024, 2025; Nazarevych, Nazarevych, 2018*a*, 2018*b*; 2019, 2023*a*, 2023*b*, Nazarevych, 2024]) primarily with the Alpine / Carpathian (compression and displacement in the northeast direction) and terrane (tangential sublatitudinal displacements to the east, translation of pressure from the displacement to the east of the northeastern part of the Alkapa terrane, i.e. the crustal structures of the Transcarpathian depression) components of the modern regional geodynamic process. The asthenolithic component of the regional geodynamic process (propagation of the northeastern branch of the convective subhorizontal flow from the as thenolite under Pannonia towards this region) may also have some influence here. Also, a certain contribution to local seismic activity may be made by the influence of the tangential displacement to the east – southeast of the southeastern edge of the West European Platform (Rava-Rus'ka zone) along the structures of the Teisseyre-Tornquist Zone (TTZ) and its tangential-rotational influence on the fault-block structure of the Carpathian foredeep located further south.

Seismicity. Modern seismic activation in the Boryslav – Stebnyk – Drohobych – Truskavets area has been observed since 2014. In 2014–2017, more than 20 small earthquakes with *M*=0.8–2.7 and shallow (H=0.1–6 km) foci depths were recorded in the area (Fig. 2).

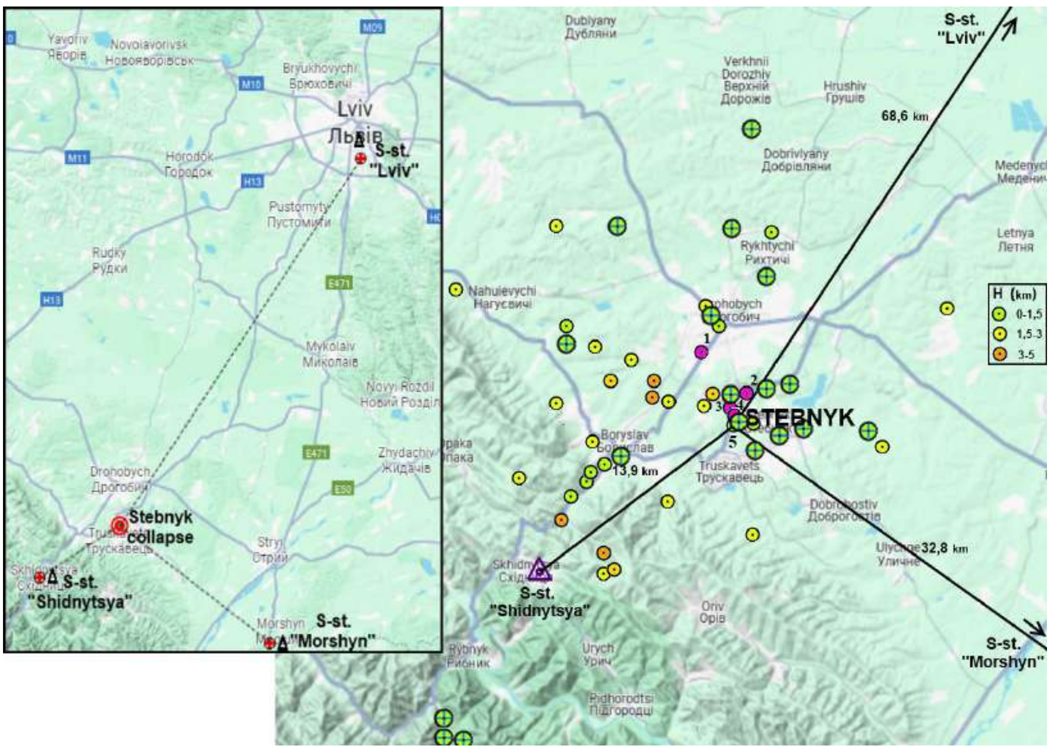


Fig. 2. Major earthquakes in the Boryslav – Stebnyk – Drohobych – Truskavets area for the period of seismic activation 2014–2017 (circles, color is indicator of foci depths) and 2017–2024 (circles with crosses) and clarification of the hypocenter of the karst-collapse earthquake in Stebnyk on September 30(29), 2017; in the frame the location of nearby seismic stations relative to the epicenter of the karst-collapse earthquake in Stebnyk and positive polarities of the first arrivals of P-waves at them are shown (Google Maps map base with relief, explanations are in the text).

The strongest earthquake (magnitude 2.9), determined by our research as a karst-collapse technogenic (see below), occurred here on September 30, 2017 (at 00:46 local time / September 29, 2017 at 21:46 GMT) in the city of Stebnyk on the territory of the Mine No. 2 of the Stebnyk Mining and Chemical Enterprise (MCE) "Polymineral" due to the collapse of the roof of the mine workings, and was accompanied by a collapse on the earth's surface, macroseismic, sound and infrasound effects.

After the karst-collapse technogenic earthquake in Stebnyk in October 2017 (see below for more details), seismic activation of the Boryslav – Stebnyk – Drohobych – Truskavets area continued. In 2017–2020, more than 20 small seismic events were else recorded in the studied area (the main ones are shown in Fig. 2, circles with crosses), some of which are associated with technogenic processes at the mining camp of the Stebnyk MCE "Polymineral", others are associated with natural seismotectonic processes.

After 2020, no seismic events were recorded in the studied area, although since the end of 2017, an additional temporary seismic station has been operating here for several years, located 500 m from the 2017 karst-collapse zone.

For localization of hypocenters of local earthquakes in the Boryslav – Stebnyk – Drohobych – Truskavets area, data from the 4 nearest stationary precarpathian seismic stations: "Lviv", "Morshyn", "Shidnytsya", "Starunya" are primarily used, as well as data from the stations of the Transcarpathian seismic sub-network, from the stations "Novodnistrovsk" and "Kamyanets-Podilskyi" [Carpathian..., 2025], and for the strongest earthquakes also data from seismic stations in Poland, Slovakia, Hungary and Romania are incorporated. Computer processing of earthquake records using the methods of refined hypocenter described below makes it possible to obtain reliable (class A) parameters of hypocenters of local earthquakes. This makes it possible not only to trace seismotectonically active structures in plan, but also to trace active at the current stage of evolution of earth's crust faults in depth. It should be noted that additional (compared to previous determinations) refinement of the hypocenter of earthquakes in this area was achieved based on data on the technogenic earthquake in Stebnyk 2017 (see below) using special methods and computer programs [Nazarevych et al. 2017, 2024, 2025; Nazarevych, Nazarevych, 2018*a*, 2018*b*, 2019, 2024; Nazarevych, 2024].

Spatial localization of local earthquake foci (see Fig. 2), already carried out using new methods (see below), revealed certain peculiarities of the seismotectonics of the area. Comparison of the localization of the foci of these earthquakes with the deep structure of the earth's crust according to regional seismic profiles [Zayats, 2013, Krupskyy, 2001, 2020], passed in this area, shows [Nazarevych, Nazarevych, 2018a, 2019; Nazarevych et al., 2024, 2025], that most of these earthquakes are associated with fault structures and thrust surfaces of the Boryslav-Pokuttya zone of the Carpathian foredeep. Thus, a chain of earthquakes of northeast direction near Boryslav traces the line of the Ratochyn fault. And a lane of seismically active tectonic discontinuities is also traced, which is parallel to the Pericarpathian fault in plan (see Fig. 1, *b*, and Fig. 2). Several earthquakes of different depths were registered in the structures of Bereg, Oriv and others thrusts of the Skyba zone of the Folded Carpathians.

Concerning to the connection of local natural (tectonic) seismicity with the features of the relief and regional geodynamics, we briefly note the following. According to the results of decoding space images and geological and geophysical data (A. Kudryashov, O. Mychak), the Ratochyn lineament of the ortogonal northeastern (anti-Carpathian) direction is traced here, it is coupled with the eponymous fault and is a regional subvertical zone of destruction of the earth's crust (according to R. Bembel) with signs of extension. A certain extension mode of the earth's crust in this area is also indicated by the positive sign of the cripex parameter (Cr) of local earthquakes studied by us [Nazarevych et al., 2004; Nazarevych, Nazarevych, 2018*a*, 2018*b*, 2018*c*, 2019], which well characterizes the actual stress state of the focal zones, obviously caused by local (lowering of the earth's surface, which is characteristic of areas with intensive hydrocarbon extraction) and regional geodynamics namely, a combination of the Alpine / Carpathian, terrane and asthenolitic components of this process. As for the latter, this is associated with the zone of immersion here of the northeastern branch of the asthenolitic flow from under Pannonia and additional cooling and subsidence of the earth's crust due to the attenuation of the asthenolitic process [Nazarevych, Nazarevych, 2018*a*, 2019, 2023*a*; Nazarevych, 2024; Kováčiková et al., 2016]. We conducted in-depth studies of the features of local geodynamics and seismotectonic processes based on the complex of geological-geophysical, geodetic and geomorphological data, and on refinement of the localization of local earthquake foci, taking into account the deep-spatial heterogeneities of the velocity structure of the subregion's crust and the corresponding kinematic corrections established using special methods [Nazarevych et al., 2024, 2025]. These results will be presented in detail in further publications.

Technogenic karst-collapse processes in the Stebnyk mine area

Technogenic seismicity in the area of Stebnyk. Another factor of seismic activation in the Boryslav – Stebnyk area are technogenically provoked geodynamic processes in the mining areas of the Stebnyk potash deposit [Gaydin, 2017; Dyakiv, 2017, Dyakiv et al., 2018; Nazarevych, Nazarevych, 2018*a*, 2018*b*, 2019; Nazarevych et al., 2024, 2025]. The study of these processes is important both from the point of view of clarifying their reflection in seismic data and predicting the corresponding geoecological risks and hazards on this basis, and from the point of view of improving the methods of seismic research and data analysis (see below).

Thus, the earthquakes that occurred in this area on 08/22/2016 and 09/29/2017 deserve special attention. These earthquakes, according to our clarified data (see below), occurred in the area of Mine No. 2 of the Stebnyk MCE "Polymineral". The first earthquake with a magnitude of M=2.3 at 13:36.31.5 GMT was apparently the result of a mine strike or collapse of one of the chambers of the mine field, which was detected at 16:36 local time by the mining service in the currently inactive mine of mining site No. 2.

The second earthquake with a magnitude of M=2.9 occurred on 29/09/2017 at 21:46 GMT (00:46 September 30, local time). This earthquake was recorded by 19 stations of the Carpathian seismic network, its creepex is positive, the spectrum is 2-stage (see below, Fig. 7), which indicates the complex nature of the rupture and different structural-hierarchical levels of destruction in the focus (see below).

This earthquake was the result of a collapse (seismogravitational displacement of rock mass) at potash Mine No. 2 near the town of Stebnyk, that we clearly show below based on the analysis of the data complex. Such seismogravitational displacements occur in an already fractured geological medium, in this case, as a result of karst processes during the flooding of the inactive mine of the 2nd mining site of Stebnyk MCE "Polymineral". As for the collapse area, there was already a gravitational collapse in the lower horizons of the mining workings in the past [Dyakiv, 2017], load-bearing capacity of rocks of the mine field decreased as a result of karst processes. The seismogravitational collapse occurred here in the zone of previous destruction of the pillars of the mine workings and a huge mass of rocks fell onto previously collapsed rocks and a water "mirror" in a giant chamber that was formed when the workings were flooded with groundwater and brines and a number of pillars on the 2nd and 3rd horizons of the mine collapsed (see below, Fig. 3). Therefore, this impact was relatively mild, it did not generate high-frequency seismic shock waves of maximum amplitude, therefore this technogenic seismic event has a specific spectrum (see below, Fig. 7). It has a characteristic stepped shape with a low fundamental cutoff frequency of the P-wave spectrum. At the same time, a noticeable decrease in the steepness of the spectrum growth to low frequencies indicates a limitation of the equivalent discharged stresses (released energy) when moving from lower scale-hierarchical levels of rupture formation to higher ones. All these features of this seismic source are discussed in detail below.

Karst-collapse technogenic earthquake in Stebnyk, September 30 (29) 2017

Natural-technogenic karst processes in the collapse zone. The nature of natural and technogenic karst processes in the zone of the future collapse at Stebnyk Mine No. 2 (Fig. 3) hawe been studied in detail for years by the mining service of the Stebnyk MCE "Polymineral" and specialists from the Institute of Mining and Chemical Industry "Girhimprom" and are well presented in the works of many authors ([Varlamov et al., 1971; Semchuk, 2001; Bilonizhka, Dyakiv, 2012; Gaydin, 2017; Dyakiv, 2017; Dyakiv et al., 2018; Rudko, Gaydin, 2019; Hlotov, Biala, 2022; Khevpa et al., 2023] and others). These processes are generally similar to processes in other mine fields, salt deposits, and karst zones both in the Western region of Ukraine (Kalush, Solotvyno) and in other regions of Ukraine and the world [Sukhinina, 2022; Chalikakis et al., 2011; Ning et al., 2013; Qingke et al., 2014; Rudko, Gaydin, 2019; Stoeckl et al., 2020; Kuzmenko, Bagriy, 2022; Kuchin et al., 2023; Horishnyi, Pavelchuk, 2024].

According to research data, the activation of technogenic karst in the area of Mine No. 2 (Fig. 3) occurred as a result of the breakthrough of oversalt, weakly mineralized waters (aggressive in terms of dissolving salt-containing rocks in the mine area) into the mine workings due to tectonic disturbances in the area of ore bodies (Fig. 3, *a-e*).

Among the natural causes of this process is the complex geological structure of salt-bearing strata in the mine area (Fig. 3, *a*, *b*). In particular, water inflows were often confined to the so-called "mud pools" – buried zones of tectonic disturbances. The evolution of karst was also facilitated by the complex hydrogeological conditions in this area [Varlamov et al., 1971], which was controlled by numerous hydrogeological wells and confirmed by long-term hydrogeological monitoring [Gaydin, 2017; Dyakiv, 2017, Dyakiv et al., 2018; Khevpa et al., 2023] and special geophysical studies [Shamotko et al., 2002; Deshchytsya, Shamotko, 2005; Maksymchuk et al., 2019; Sapuzhak et al., 2025]. The extraction of ores at the Stebnyk deposit was significantly complicated by its pre-industrial exploitation, which (according to historical data) began in the 12th century; it violated additionally the integrity of the gypsum-clay cap (GCC, Fig. 3, *c*) that protected salt-containing rocks from the impact of aggressive fresh near-surface (salt-soluble) waters [Dyakiv, 2017].

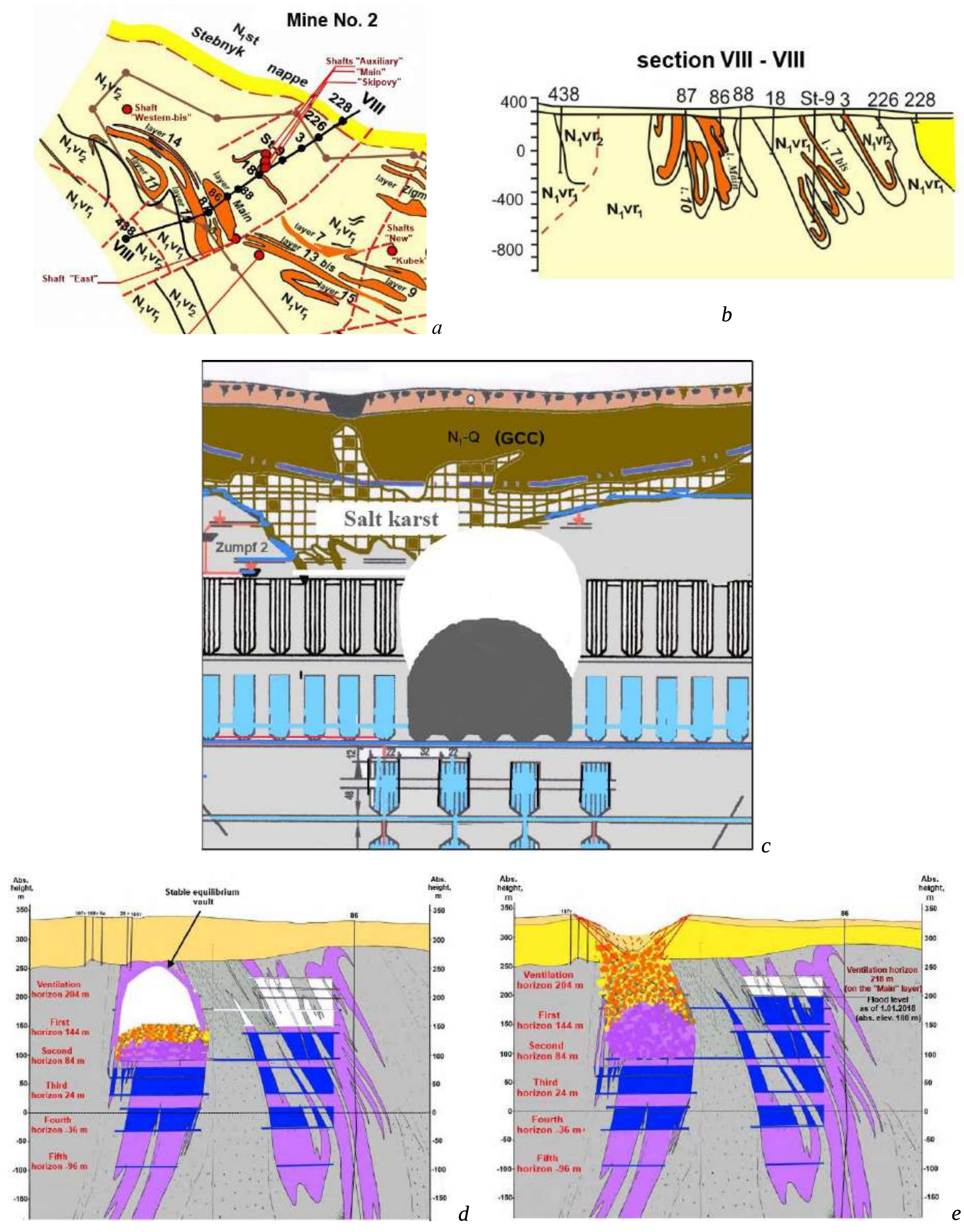


Fig. 3. Schematic geological map (*a*) and section (*b*) in the zone of mining and collapses of Mine No. 2 of Stebnyk MCE "Polymineral" (after [Dyakiv, 2017]) and mine workings scheme of Mine No. 2 and their condition at different stages of evolution of karst collapse processes (explanations are in the text): in November 2014 after flooding of the 2nd mining horizon (*c*) (after [Dyakiv, 2017]); state of the geological medium in the zone of collapse evolution at Mine No. 2 for January 2015 (*d*) and November 2017 (*e*) (after [Dyakiv et al., 2018]) (the main folds and faults, the spatial localization of layers of potassium-magnesium salts, as well as exploration and hydrogeological wells and some elements of mines are shown).

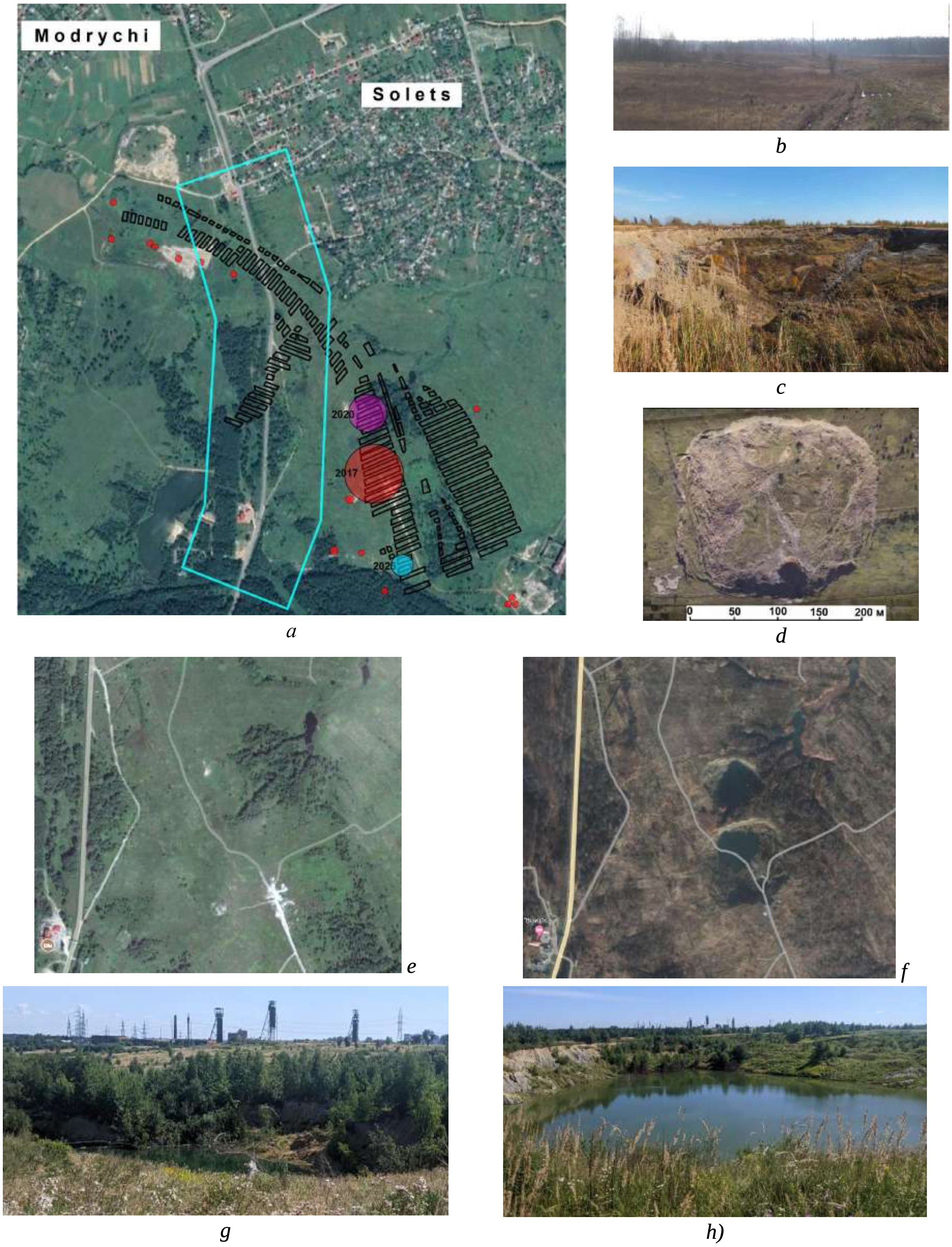


Fig. 4. Contours of mine workings of Mine No. 2 of Stebnyk MCE "Polymineral" (black rectangles (after [Maksymchuk et al., 2019])) and collapses zones: on September 30 (29), 2017 (red circle), March 15, 2020 (pink circle) and February 15, 2025 (blue circle) on Google Maps satellite image before collapses (*a*); view of the territory before collapse (*b*) [Dyakiv, 2017] and after collapse formation (*c*) (October 2017, author's photo); view of collapse in November 2017, drone photo (*d*) [Dyakiv, 2017]; detailed view of the collapses site on Google Maps satellite images (before the collapse (*e*) and in 2023 (*f*), the enlarged collapse of 2017 is visible and the smaller collapse of 2020 next to it); view of the collapses of 2017 (*g*) and 2020 (*h*) (with lakes in the center) in August 2024 (author's photos).

Fig. 5. Surface cracks in the soil in the zone of the 2017–2020 collapses in Stebnyk (*a*-*c*), subsidence and cracks on the Lviv – Truskavets road at the zone of intersection of the mining works (see Fig. 4, *a*) (*d*, *e*) and swampy areas of subsidence in the areas adjacent to the collapses and the road (*f*, *g*) (author's photos, August 2024); view (from a drone) of the collapses of 2020 and 2017 in April 2020 (*h*) (red circle and the arrow indicates the point of collapse in 2025) and the collapse of February 15, 2025 on the same day (*i*) (explanations are in the text).

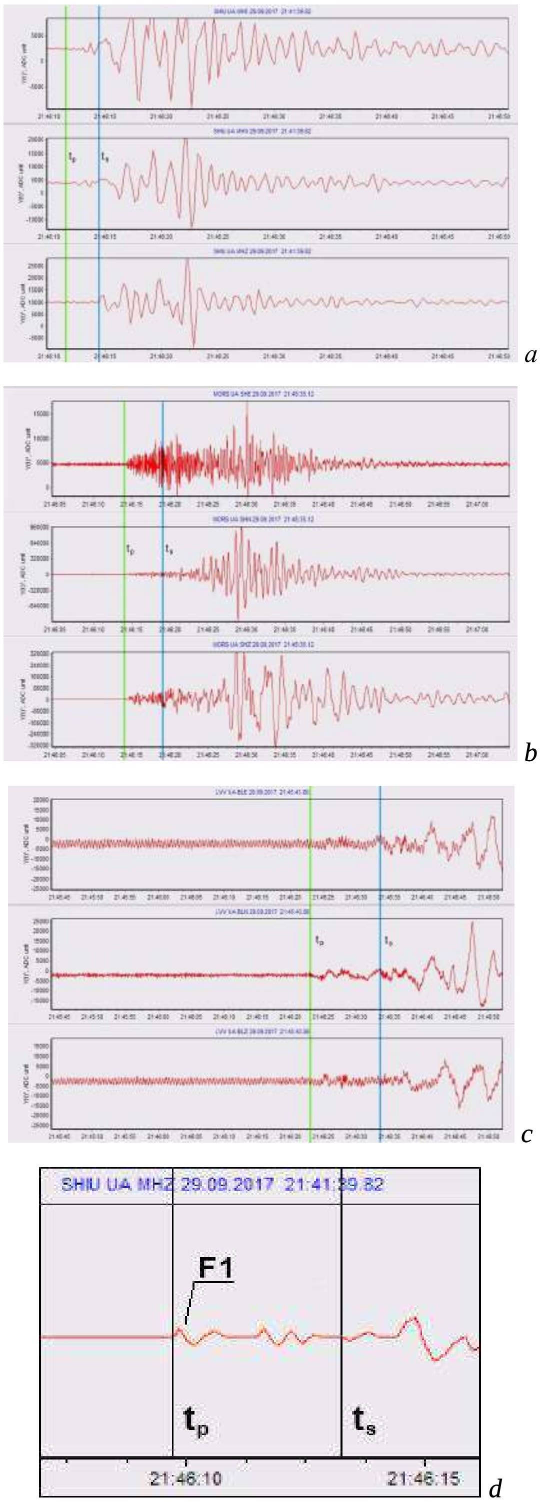


Fig. 6. Seismograms of the technogenic earthquake of September 30 (29), 2017 in Stebnyk (the times of arrival of P- and S-waves are indicated): *a*) – station "Shidnytsya" (Δ=13.95 km); *b*) – station "Morshyn" (Δ=32.61 km); *c*) – station "Lviv" (Δ=68.72 km); *d*) – station "Shidnytsya" (fragment of the Z-component, main phases of P-waves are indicated).

The first significant water inflows into the mine were noticed back in 1978, including places difficult to access for waterproofing. The places of water inflows were connected to the contact zone of potash ores with terrigenous-salt breccia. The activation of water inflows many scientists associate with the impact on this territory of seismic and deformation waves of the destructive earthquake in the Vrancea zone (Romania) on March 4, 1977. To this also associates the activation of the Starunia mud volcano, located relatively close to the same tectonic subzone. Other authors also draw attention to such threats to karst evolution zones (see, for example [Qing-ke et al., 2014]).The constant increase of water inflows was caused by the dissolution of salt-bearing rocks, suffosis, etc. The complex hydrogeological and mining-geological conditions of the deposit led to a constant increase of water inflows, which either managed to be localized, or led to the formation of depression funnels and the activation of karst [Gaydin, 2017; Dyakiv, 2017, Dyakiv et al., 2018; Khevpa et al., 2023].

In 2002, water pumping from the mine stopped, and it was transferred to the wet conservation mode. After that, the water level in the mine rose constantly, from 2006 to 2014 it rose by 40 m, flooding the chambers of the 2nd mining horizon (Fig. 3, *c*). As a result of the dissolution of salts and the destruction of pillars on this horizon in the area of chambers No. 108–113 at the end of 2014, the roof between the 2nd and 1st horizons collapsed and the pillars on the 1st horizon collapsed too with the formation of a stable equilibrium vault (Fig. 3, *c*, *d*) [Dyakiv et al., 2018]. A cavity with a diameter of about 120 m and a height of about 100 m was formed. Subsequently, as a result of salt karst processes in the zone of the formed vault (Fig. 3, *c*), salt-containing rocks were washed out and their delamination and collapse of them and other vault rocks occurred with partial filling of the previously formed cavity with them. The vault grew upwards until it reached less consolidated rocks [Rudko, Gaydin, 2019]. Then, the destruction processes were accompanied by the formation of a liquidity core in weakly consolidated rocks, the "flow" (falling) of these rocks into the cavity with additional filling it with the products of destruction. When this process approached the earth's surface so that the arch contour lost its load-bearing capacity due to the collapse of the zone of persistent pressure in its center [Rudko, Gaydin, 2019], a collapse occurred, which caused an earthquake (see below for more details).

So, on September 30, 2017, at 0 hours 46 minutes (local time), in the Layer No. 10 of the Mine No. 2 of the Stebnyk MCE "Polymineral" in the area of chambers No. 108–113 (Fig. 4, *a*), a single-stage collapse of the soil mass occurred with a diameter of the collapse on the surface of up to 220–230 m and a depth of up to 45–47 m. (Fig. 4, *c*, *d*), which caused a technogenic earthquake (see below).

As of 2024 (Fig. 4, *f*, *h*), the collapse did not undergo noticeable expansion, therefore, its geodynamic potential is currently largely exhausted.

The second collapse in the mining area of the MCE "Polymineral" began to form on March 15, 2020, 200–250 m north of the first (Fig. 4, *a*, *f*). The progress of its formation (unlike the formation of the first collapse in 2017) was very slow, first, fissures were formed in the place of the existing here cracks (Fig. 5, *a–c*), then a ponor (sinkhole), which gradually grew to a collapse with a diameter of about 140–150 m (as of 2023–2024, Fig. 4, *f*, *g*, Fig. 5, *h*), depth up to 55 m. The formation of this collapse lasted from hours (at the first stage, a ponor (sinkhole)) to days and weeks (at the second stage, a collapse (Fig. 5, *h*)) and was not accompanied by noticeable seismic events (due to the extended nature of the process in time and the "amortization" of the rockfalls by water that flooded the mine).

As of August 2024 the deeper parts of both collapses were flooded by rainwater and groundwater, forming two lakes there (see space image in Fig. 4, *f*, photos in Fig. 4, *g*, *h*).

Further processes of destruction of the workings of Mine No. 2 (according to geological services) have slowed down significantly due to the rise of the water table above the roof of the salt-bearing strata, and the approach of the concentration of salts in the water to the saturation state. But these processes have not stopped, therefore the threats of subsidence and collapses remain, as evidenced by the last collapse in the mine area, which occurred in 2025.

This, the third large collapse in the workings zone of the MCE "Polymineral" was formed on February 15, 2025 at approximately 11:00 AM (local time) 250 m south of the first (Fig. 4, *a*, Fig. 5, *i*), in the lowland part of the mine territory. The formation of this collapse was much faster than that of the second one – from minutes at the first stage (formation and growth of the ponor (sinkhole) to tens of minutes and hours at the next (formation of a large collapse, see Fig. 5, *i*). During its formation, no expressed seismic effects were recorded either nearby (macroseismic data) or at the nearest seismic stations located at a distance of 13–35 km (instrumental data), probably due to the "damping" of collapsed rock by water from the flooded horizons of the Mine No. 2, which immediately flooded the collapse (see Fig. 5, *i*). The dimensions of the formed collapse are 70×55 m (as of February 16), the depth (to the water surface) is 20 m.

Technogenically induced dangerous geological processes are observed throughout the area above the mine workings (Fig. 4, *a*). In particular, as a result of flooding of the mine horizons and destruction of pillars in the area of intersection with the Truskavets – Drohobych – Lviv road, subsidence of the earth's surface of up to tens of cm from the level of the 1970s is observed, which is clearly visible both on the road itself and on its sides and adjacent territories [Kuzmenko et al., 2019]. In particular, vertical deformations and tension cracks in the marginal zones of subsidence are clearly visible on the road (Fig. 5, *d*, *e*). This fully correlates with the results of tectonophysical modeling of fault zones formation processes [Nazarevych et al., 2015*a*, 2015*b*], which takes place in the peripheral areas of karst-collapse zones, in particular, at Mine No. 2 of the Stebnyk MCE "Polymineral". In the adjacent to the road territories above the mining zone of Mine No. 2, in the zones of subsidence of the earth's surface (up to 1.5 m and more [Kuzmenko et al., 2019; Hlotov, Biala, 2022]), local marshy areas (sometimes with small lakes) are formed, overgrown with reeds and other moisture-loving plants (Fig. 5, *f*, *g*).

Characteristics of 2017 technogenic earthquake source and its seismic radiation. The seismic source of this karst-collapse earthquake was very peculiar in relation to the sources of ordinary tectonic seismic events. And these peculiarities were clearly reflected in the characteristics of its seismic radiation. We reconstructed the progress of formation process of this seismic source taking into account the general patterns of evolution of karst-collapse processes [Rudko, Gaydin, 2019], the peculiarities of such processes in the zone of this collapse [Gaydin, 2017; Dyakiv, 2017, Dyakiv et al., 2018]. We took into account the sinkhole shape of the formed collapse (Fig. 4, *c*) and the peculiarities of the seismic waves generated by this collapse process.

The processes of seismic wave generation in the source of this earthquake had a multi-stage (multiphase) nature (Fig. 6).

The zero stage of the process is the destruction of the vault above the center of the future collapse (see Fig. 3, *c*, *d*), its loss of stability due to the disappearance of the lateral thrust forces, the beginning of the collapse of the roof-pillar rocks under the action of their own weight with the final separation from the side walls of the formed collapse. Weak compressional P-waves of circular polarization are formed (relaxation of tensile stresses in the upper annular zone of separation of the arch rocks from the side walls of the collapse), they are partially compensated by tensile waves in the lower parts of the side walls of the formed collapse (relaxation of compressive stresses here due to the removal of resistive loads from the arch rocks) and therefore are practically not traced even on the seismogram of the nearest (13.9 km) seismic station "Shidnytsya" (Fig. 6, *d*).

The first, the main stage of the collapse process and generation of seismic waves is the impact of the vault of the mine working on the water and the destroyed rocks of the mine workings lying below (see Fig. 3, *d*, *e*). Here, in the impact zone, a shock P-wave of the first phase with a spherical front (by explosion type) is generated, which had a frequency and amplitude somewhat smaller than if the impact were only on solid rocks (both due to the not instantaneous impact in the central and peripheral parts of the collapse, and due to the absorption of shock by the water layer and the conversion of part of the impact energy of the collapsed rock mass into the energy of a hydroshock wave with the corresponding stretching of this process in time).

This phase corresponds to the first arrivals of P- and S-waves on seismograms, their characteristic periods (0.7–0.8 s) are clearly visible on the records of the nearest seismic station "Shidnytsya" (Fig. 6, *a*, *d*), and on the filtered records of the seismic station "Lviv" (Fig. 8), they are corresponded to the break frequencies of seismic wave spectra of seismic wave f_0=1.02/0.87 Hz (Fig. 7) at the seismic stations "Shidnytsya" and "Morshyn" respectively. The somewhat lower frequency f_0 for the seismic station "Morshyn" is associated with increased attenuation of higher frequencies on a 2.36 times greater epicentral distance for it. The mentioned parameters of seismic waves together with the magnitude reflect the main scale-energy characteristics of this seismic source.

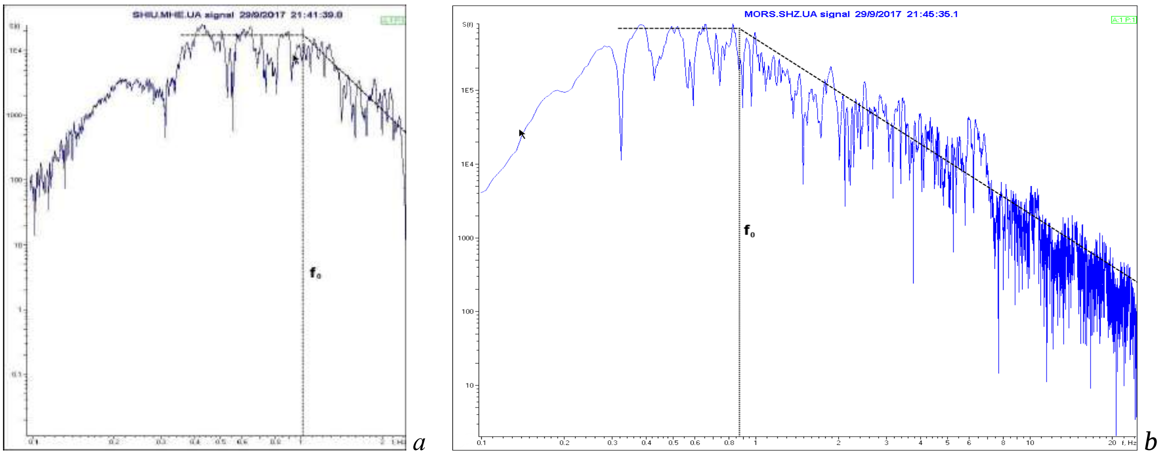


Fig. 7. Spectra of seismic waves from the technogenic earthquake on September 30 (29), 2017 in Stebnyk: a) – at the station "Shidnytsya" (Δ=13.95 km); b) – at the station "Morshyn" (Δ=32.61 km).

The second stage is sliding of newly collapsed rocks over previously collapsed underlying rock and the impact of the hydroshock wave on the side walls of the mine workings and on nearby intact pillars (Fig. 3, *c*) during its propagation through the mine workings of the Mine No. 2. In the process of further propagation through the mine workings, the hydroshock wave was partially attenuated, and part of the hydroshock energy was transmitted to the walls of the mine workings.

During these processes, relatively low-frequency seismic waves are generated. At the same time, sub-sources were also present, associated with the sliding and gravitational compaction of the collapsed rock mass over previously collapsed rocks of the 1st and 2nd levels of the mine (Fig. 3, *c*, *e*). This corresponds, in particular, to the increased spectral components in the 2–7 Hz range (relative to the uniform decline at frequencies above f_0, see Fig. 7, *a*, *b*). These components reflect the scale-energy characteristics of these additional seismic sources.

The third stage is the impact of a hydraulic shock wave on the outside (dead-end) walls of the mine workings of the Mine No. 2. In this process, the remaining energy of the hydraulic shock is transferred to the walls of the mine workings generating the lowest frequency seismic waves.

All these processes correspond to the main visible periods / frequencies (T=1.3–1.4 s, f=0.7–0.8 Hz) on the primary records of the "Lviv" seismic station (Fig. 8). They reflect the scale-energy characteristics of the low-frequency seismic source. It should be noted that the shape of the seismic oscillation spectra is influenced not only by the features of the generation of seismic waves by the source, but also by the features of the attenuation of these waves during propagation in the earth's crust. In particular, this is an increased attenuation of higher frequencies with distance, which is well illustrated by a comparison of the spectra of the records from the "Shidnytsya" (epicentral distance Δ=13.95 km) and "Morshyn" (Δ=32.61 km) seismic stations (see Fig. 7, *a*, *b*).

Stages 2 and 3 correspond to more pronounced P-waves on the E-W and N-S horizontal components of the "Shidnytsya" seismic station and on the E-W components of the "Morshyn" seismic station and the

N-S components of the "Lviv" seismic station (located just in close azimuths, see Fig. 2), associated with the propagation of shock waves through more superficial, lower-velocity layers.

According to the data of the nearest seismic station "Shidnytsya" (see Fig. 6, *d*), the active bash process of seismic shock generation lasted about 0.15–0.2 s (according to the model constructions of the processes of generation of seismic waves by the earthquake source given in [Nazarevych, Nazarevych, 2009]), the total duration of the main processes in the source of this earthquake (1st and 2nd stages) can be estimated at 1.2–1.5 s.

Thus, the result of the collapse on September 30, 2017 was a technogenic earthquake and a hydraulic shock. According to seismological data, the specified time of the earthquake was determined (for more details, see below), as 0 hours 46 minutes, 4.8 seconds (local time) on September 30, 2017 (21.46.04.8 September 29, Greenwich Mean Time).

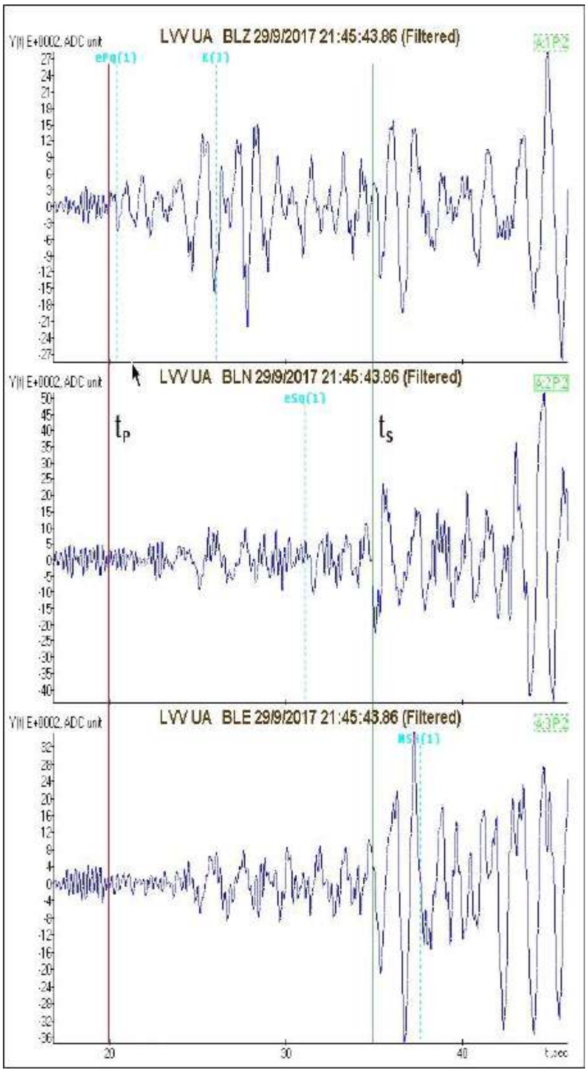


Fig. 8. Filtered recordings of the technogenic earthquake of September 30 (29), 2017 in Stebnyk at the "Lviv" seismic station (fragment).

The technogenic nature of this earthquake is confirmed (in addition to the macro-seismic effects described below) by the positive polarity (compression phase) of the first arrivals of P-waves[1] (in the projection on the direction of their arrival at the station) at all seismic stations involved in its refined hypocentering (in particular, the closest ones, see Fig. 6 and 8), which surround the earthquake focus from all sides (see Fig. 2, frame), this directly indicates the shock ("explosive") nature of the generated P-wave.

Before this, we note that this is why attempts to determine the mechanism of the source of this seismic event as a tectonic earthquake (which is characterized by a 4-quadrant distribution of the polarities of the first arrivals of P- and S-waves) using known seismological methods did not yield adequate results.

The technogenic nature of the earthquake is also indicated by the time of the power outage on the 35 kV power line (0 hours 46,5 minutes local time), registered by the dispatchers of PrJSC "Lvivoblenergo", when two poles of this power line fall through into the collapse (see photo in Fig. 4, *c*).

At the end of this part of the data analysis, we note once again that the seismogenic potential of the source of the studied karst-collapse earthquake was exhausted in the process of a single-act seismogenic collapse, neither a noticeable expansion of this collapse (except the minor stabilization processes of subsidence on the slopes), nor additional collapses in the lower horizons of the mining workings (which could be registered by sharp changes in the water level in the flooded workings), nor even weak seismic events (aftershocks) associated with such processes were registered here in the next few months, even at the nearest seismic station "Shidnytsya" (Δ=13.95 km).

Macroseismic effects of the earthquake. The earthquake was accompanied by characteristic macroseismic effects. Residents of the outskirts of the village of Solec and the city of Stebnyk, adjacent to the collapse (see Fig. 4, *a*), felt the ground shaking caused by the impact of a huge mass of rock that collapsed almost simultaneously on the water and the underlying rock of the mining working. This was accompanied by a corresponding sound effect of a shock character with a subsequent hum caused by the further movement of masses of rocks as they slid to the bottom of the collapse and gravitational compaction.

This sound effect was also accompanied by a characteristic infrasonic effect, like a breath of wind

[1] The times and polarities of the first arrivals of the P- and S-waves of this earthquake at seismic stations were significantly refined, compared to previous express determinations, using various options for frequency filtering of seismograms, polarization analysis of oscillations, and correlation approaches.

(a powerful "shock" infrasonic wave), caused by the piston effect of the impact on the air of the movement of a large (over 200×200 m) mass of rocks as it collapsed into the sinkhole.

Energy characteristics of the earthquake. We will present some energy and scale-energy estimates of the source of this technogenic earthquake, including comparison with statistical data (according to [Nazarevych, Nazarevych, 2009] and others) on natural tectonic earthquakes with similar parameters.

Seismological estimates of the source energy. The magnitude of the event, determined according to seismological data and methods [Instruction..., 1981; Riznichenko, 1985], is 2.9. To convert to energy (E_S), we use the well-known formula of T. Rautian [Rautian, 1960; Riznichenko, 1985] to convert to energy class K (K=M×1.8+4), where K is the power exponent when determining earthquake energy ($E_S=10^K$). Therefore, K=2.9×1.8+4=9.2, and

$$E_S=109.2\approx1.585\times10^9 \text{ J.} \qquad (1)$$

Physical-energy estimates. They were carried out through the potential energy of collapsed rocks released during the collapse process ($E_P=M\times g\times h'$, where M is the mass of collapsed rocks, g is the acceleration of free fall, h' is the height of the fall).

The mass of the rockfall was calculated using the formula $M=V\times\rho$ (V is the volume of the rock, ρ is its density), and the volume V (taken in the form of a cylinder) was calculated using the formula $V=S\times h$, where S is the base area ($S=\pi\times r^2$), h is the height (thickness of the rock layer). The average radius of the collapse r was taken to be 100 m [Dyakiv, 2017, Dyakiv et al., 2018; Rudko, Gaydin, 2019] (taking into account the noticeable conicity of the karst sinkhole), the thickness of the falling rock layer h is 70 m (see Fig. 3, *d*), the density ρ of the rocks is 2.5 t/m^3. According to these data, the mass of collapsed rocks was estimated at 5.5±0.5 million tons, the average height of the fall (according to [Dyakiv, 2017, Dyakiv et al., 2018; Rudko, Gaydin, 2019] was taken as 30 m. Based on this, the potential energy of the falled rock mass and its impact energy during the collapse were estimated:

$$E_P=1.62(\pm0.15)\times10^9 \text{ J.} \qquad (2)$$

As we can see, both energy estimates agree very well with each other, it is one more confirmation of the karst-collapse nature of this seismic source.

The energy released during the collapse corresponds to an explosion energy of about 400 tons or 0.4 kt in TNT equivalent (considering that 1 kg of TNT gives 4.184 MJ during an explosion).

Scale-energy estimates. Other features of the source of this technogenic earthquake are specific correlations between its various parameters, different from those for natural tectonic events.

Thus, the lower, creepex frequency of the P-wave spectrum for different stations is 0.3–0.5 Hz (Fig. 7), on average 0.4 Hz. This frequency corresponds to the length of the rupture in the source (according to the correlation dependencies established by us for the region [Nazarevych, Nazarevych, 2009]) of the order of 3.5 km (at the estimated velocity V_P=2.0 km/s for the upper layers of rocks), which in order of magnitude corresponds to the total length of the underground workings of Mine No. 2 (see Fig. 4, *a*).

On the other hand, since the actual length of the source is 230 m, its radius R_{eqv}=115 m, according to our correlation dependencies from [Nazarevych, Nazarevych, 2009] the visible oscillation frequencies and the frequency f_0 should be approximately 5.1 and 6.1 Hz, respectively (oscillation periods are 0.196 and 0.165 s). In particular, the presence of seismic sub-sources of such a scale is evidenced by a distinct peak on the slope of the spectrum of the recording of the seismic station "Morshyn" in the frequency range 5÷7 Hz (Fig. 7, *b*).

At the same time, according to other dependencies described in the same study [Nazarevych, Nazarevych, 2009], the average rupture length for earthquakes of this class / magnitude is of the order of L=0.8 km (rupture area S=0.5 km^2, focal zone volume $V\approx5.4$ km^3). And using the frequency f_0 of the spectra in Fig. 7 (f_0=0.95÷1.02 Hz), such estimates give quite close results, L=0.69÷0.74 km, S=0.37÷0.43 km^2, $V\approx3.48\div4.3$ km^3. Note that the obtained values of the geometric parameters of the conditional seismic foci are close to each other, which is not surprising, since the energy characteristics of seismic events are instrumentally determined by the parameters of seismic oscillations, excited by these events and recorded at seismic stations.

Comparing the obtained values with the actual geometric characteristics of the collapse (L=0.23 km, S=0.042 km^2, $V\approx0.011$ km^3), we can conclude that the specific energy stored and released during such technogenic earthquake (per unit volume of the focal zone) is almost three orders of magnitude greater than the elastic energy stored in rocks and released during a tectonic earthquake.

Refinement of hypocenters of earthquakes in the Boryslav – Stebnyk area

Data on the karst-collapse technogenic earthquake of September 30, 2017 in Stebnyk, on the one hand, became an impetus, and on the other, the basis for the development of methods for significantly clarification the hypocentering of local earthquakes. Initially a regional seismological hodograph was used for the hypocentering of earthquakes in the Ukrainian Precarpathians, including the Boryslav – Stebnyk area. However the velocity structure of the lithosphere of the region (see [Structure…, 1978; Lithosphere…, 1987–1993; Zayats, 2013; Nazarevych et al., 2025; Starostenko et al., 2013; Sheremeta et al., 2023] and others) is far from both the standard model of the platform lithosphere, well reflected by the Jeffreys hodograph [Jeffreys & Bullen, 1940], and from the simply horizontally layered model reflected by the regional hodograph (see, for example, [Nazarevych, 2019; Nazarevych et al., 2024, 2025]). The use of one or another hodograph without corrections, despite the significant increase in the number of seismic stations in the region in recent years [Carpathian..., 2025], a priori does not give sufficiently reliable results of hypocentering (radii of ellipsoids of residuals can reach 3–5 km, and sometimes more). Similar problems are also evident in other areas with karst collapses threats (see, for example [Xiangteng et al., 2023]). Various approaches are used to address these challenges ([Nazarevych, Nazarevych, 2002, 2003, 2004*a*, 2004*b*; Nazarevych, 2006; Nazarevych et al., 2024, 2025; Osadchii et al., 2023; Xiangteng et al., 2023] and others).

It was not possible (and not relevant) to develop earlier methods for refinement the of local earthquakes hypocenters in the Boryslav – Stebnyk – Drohobych – Truskavets area using seismological data and appropriate methods [Nazarevych, Nazarevych, 2002, 2003, 2004*a*, 2004*b*; Nazarevych, 2006] due to the absence of recorded instrumental seismic activity and appropriate seismological data in the area. The occurrence of seismic events in this area in the last 11 years [Nazarevych et al., 2017, 2018*a*; Nazarevych, Nazarevych, 2018*a*, 2018*b*, 2019; Nazarevych, 2024, Nazarevych et al., 2024, 2025] actualized this issue and made it possible to apply both the received seismological data (in particular, data on the karst- collapse earthquake in Stebnyk) and data from other geological and geophysical studies and methods of their processing ([Zayats, 2013; Starostenko et al., 2013; Osadchii et al., 2023; Xiangteng et al., 2023] and others) to solve it.

One of the unique and extremely valuable features of this karst-collapse earthquake for the development of methods for refinement the hypocenters of local earthquakes is that the coordinates and depth of the focus (karst collapse on the surface) are precisely known (φ=49.2990±0.0009º, λ=23.5160±0.0015º, H=0,10±0.015 km (≈245 m abs., Figs. 2, 3). This made it possible to accurately (with an accuracy no worse to half the horizontal size of the collapse, i.e. at the level of ±100 m) determine the epicentral distances Δ for each of the recording seismic stations (Fig. 2, Table 1).

Using these data and approaches, we developed a simple and effective method for refinement the hypocenter of seismic events in the area of the cities of Boryslav – Stebnyk – Drohobych – Truskavets. The course of construction and application of the method was as follows (see Figs. 2, 6, 8):

- based on the data on the localization of the focus of the karst-collapse earthquake (collapse), the precise epicentral distances to the seismic stations were determined (Fig. 2);
- based on instrumental seismological data (including using Vadati graphs (see below, Fig. 10) and methods for refining station times and polarities of the first arrivals of P- and S-waves, Fig. 8), the time at the source (time of collapse) was refined;
- based on the refined epicentral distances and station times, the equivalent velocities of propagation of seismic waves to the seismic stations were refined (see below, Table 2);
- based on the comparison of all refined data and data of previous hypocentering (according to the regional seismological hodograph), local (for the Boryslav – Drohobych – Stebnyk – Truskavets area) station corrections for epicentral distances Δ for the seismic stations of the Carpathian network (involved to the hypocentering) were determined (see below, Table 2, last column);
- using these corrections and special techniques (in particular, linear interpolation / “weighted” approach), we clarified the hypocenters of local earthquakes in the Boryslav – Drohobych – Stebnyk – Truskavets area.

The localization of the foci of local earthquakes in the studied area, refined by this method, is shown in Fig. 2.

As already mentioned, in the process of refining the hypocenter of earthquakes in the Boryslav – Stebnyk area using primary seismic records, the arrival times of P- and (especially) S-waves were also refined, in particular, the identification of the corresponding phases was carried out. The need for such clarification is related, in particular, to the specific karst-collapse mechanism of this technogenic earthquake described in detail above (see Fig. 3) and to the specific conditions in its source (the presence of a water surface in the karst cavity in the area of destroyed pillars of the flooded 2nd horizon of the Mine No. 2), as a result of which the arrivals, especially of S-waves, on some components of the records are inexpressive (Fig. 6), multi-phase and are recorded indistinctly and ambiguously against the background of the P-wave train. The arrivals of P-waves at farther seismic stations (see Fig. 6, *a* in comparison with Fig. 8) are also often indistinct (due to the attenuation of high-frequency wave components and the noisy of the records by local noise disturbances). Therefore, for their reliable selection, frequency filtering in different spectral windows (see Fig. 6, *c* and Fig. 8), polarization analysis, correlation approaches were used, etc. To control the correctness of the determinations of the arrivals and phases of waves and to clarify the time in the source, data on the ratio of the velocities of P- and S-waves and Wadati graphs (see below, Fig. 10) were used.

The refined parameters of the arrivals of P- and S-waves for the closest stations involved in the hypocentering of this karst-collapse earthquake, as well as a number of other data used or determined during these studies, are given in Table 2.

To refine the earthquakes hypocenters in the studied area, a second approach was also used. It also served as a check for the first and all other techniques described here. This approach consisted in specifying the earthquakes hypocenters in the Boryslav zone by taking into account the peculiarities of the velocity structure of the earth's crust in this part of the territory (just like in the method for constructing calculated hodographs, see [Nazarevych, 2006, 2019; Nazarevych, Nazarevych, 2004, 2024, 2025]) based on data about the velocity structure of the upper crustal horizons along the Chop – Boryslav – Rudky profile [Zayats, 2013] (Fig. 9), geotraverse PANCAKE [Starostenko et al., 2013] and data on P-wave velocities in wells of oil and gas fields located in this area [Atlas..., 1998; Skakalska, Nazarevych, 2015; Skakalska et al., 2021].

In particular, based on the velocity structure of the earth's crust in this area (Fig. 9) and the extension of seismic tracks from the focus of the karst-collapse earthquake in Stebnyk to nearby seismic stations (Figs. 2, 9), the average velocity of seismic P-waves propagation on the fastest ray path focus to "Shidnytsya" seismic station was accepted to be 3.2 km/s (2.5–3 km deepening of the ray path), on the focus to "Morshyn" seismic station ray path was accepted 3.4 km/s (6–8 km deepening of the ray path), on the focus to "Lviv" seismic station ray path was accepted 3.8 km/s (8–10 km deepening of the ray path). When determining the above estimates of velocity, it was taken into account that the station "Shidnytsya" is located near the Boryslav seismogenic zone (see Fig. 2 and Fig. 9), 10–15 km south (i.e., the velocities for it are the same as for the Boryslav area at shallow depths on the profile fragment in Fig. 9), the "Morshyn" station is located to the southeast (Fig. 2 and Fig. 9), the seismic ray path runs along the Carpathian foredeep at a greater (about 35 km) distance (i.e., the velocities will be somewhat higher due to the slightly greater "dip" of the ray path), and the "Lviv" station is located even further (about 70 km, Fig. 2) and to the northwest (here the velocities will be noticeably higher both due to the greater "dipping" of the longest seismic ray path deep into the crust and due to the rise in this direction of higher-velocity crustal horizons closer to the surface, see Fig. 9).

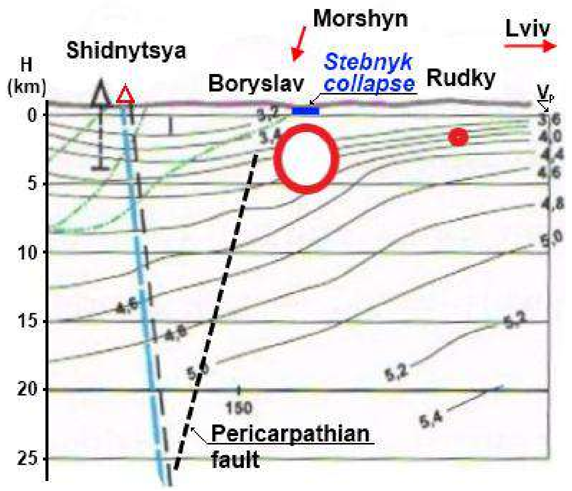


Fig. 9. Profile Chop – Boryslav – Rudky (fragment in the area of Boryslav) [Zayats, 2013] with velocity characteristics of the section.

When assessing the deepening of seismic traces, the results of calculations of seismic ray propagation for the velocity models of the crust of Transcarpathians, Pobuzhzhia and west of Ukraine were also taken into account (see [Nazarevych, 2006, 2019; Nazarevych, Nazarevych, 2004; Nazarevych et al., 2024, 2025]) and the fact that the crust of the Precarpathians in the Boryslav seismogenic zone in the upper horizons is much less gradient with depth, therefore, the "dipping" of seismic traces will be relatively smaller.

The results of the refining of the hypocenter of the karst-collapse earthquake of September 30(29), 2017 in Stebnyk using the second approach (taking into account the heterogeneous, different from the horizontally layered model, velocity structure of the earth's crust of the subregion) are given in Table 1 (localization of the focus) and 2 (kinematic parameters of different hypocentering variants) and illustrated in Fig. 10.

Note that here the center of the seismogenic collapse of 2017 (Fig. 10, *a*, hypocentering variant B) is marked with a small orange circle with two arrows pointing towards it. In contrast, hypocentering variants A, C, D are marked with larger circles with dots in the center. We see that taking into account the velocity heterogeneity of the earth's crust in the subregion made it possible to radically (by a factor of 10 and more) improve the hypocentering results, the deviation of the hypocenter determined in this way from the factual one using instrumental data decreased from 4.94 km to 0.45 km.

Table 1

Previous (according to the seismological hodograph), refined by the velocity structure of the crust and factual parameters of the hypocenter of the karst-collapse earthquake of September 30(29), 2017 in Stebnyk

	Date, day/month/year (local time / GMT)	Time at source t_0, hr/min/s (local time / GMT)	Source coordinates		Depth H, km ±ΔH	Epicentral distance / seismic station **Δ,** km (code, see Table 2)	Notes*
			φ (degr.) ±Δφ	λ (degr.) ±Δλ			
A	30.09.2017 29.09.2017	00.46.08,4 21.46.08,4 ±0.8 s	49.34ºN	23.49ºE	1.9±0.5	15,96±0.1 (SHIU) 36,88 ±0.1 (MORU) 65,98±0.1 (LVV)	Prelim. determ. (by seismol. hod.) σ**Δ**=4.94 km
B	**30.09.2017 29.09.2017**	**00.46. 04,80 21.46.04,80 ±0.2 s**	**49,2990 ±0.0009ºN**	**23,5160 ±0.0014ºE**	**0.10±0.015**	**13.95±0.05** (SHIU) **32.61±0.05** (MORU) **68.72±0.05** (LVV)	**Factual data (by location of collapse)**
C	30.09.2017 29.09.2017	00.46.05,31 21.46. 05,31 ±0.5 s	49,3031 ±0.0030ºN	23,5150 ±0.0055ºE	0.15±0.07	14,17±0.1 (SHIU) 32,93 ±0.1 (MORU) 68,39±0.1 (LVV)	Refined definition (by velocities) σ**Δ**=0.45±0.1 km
D	30.09.2017 29.09.2017	00.46. 04.80 21.46.04.80 ±0.2 s	49,3008 ±0.0022ºN	23,5141 ±0.0035ºE	0.10±0.04	13,97±0.1 (SHIU) 32,83 ±0.1 (MORU) 68,60 ±0.1 (LVV)	Refined definition (+ refined entry times) σ**Δ**=0.25±0.05 km

**(σΔ – distance of the focus, determined by the corresponding variant of the method, from the factual collapse (see Fig. 10, a))*

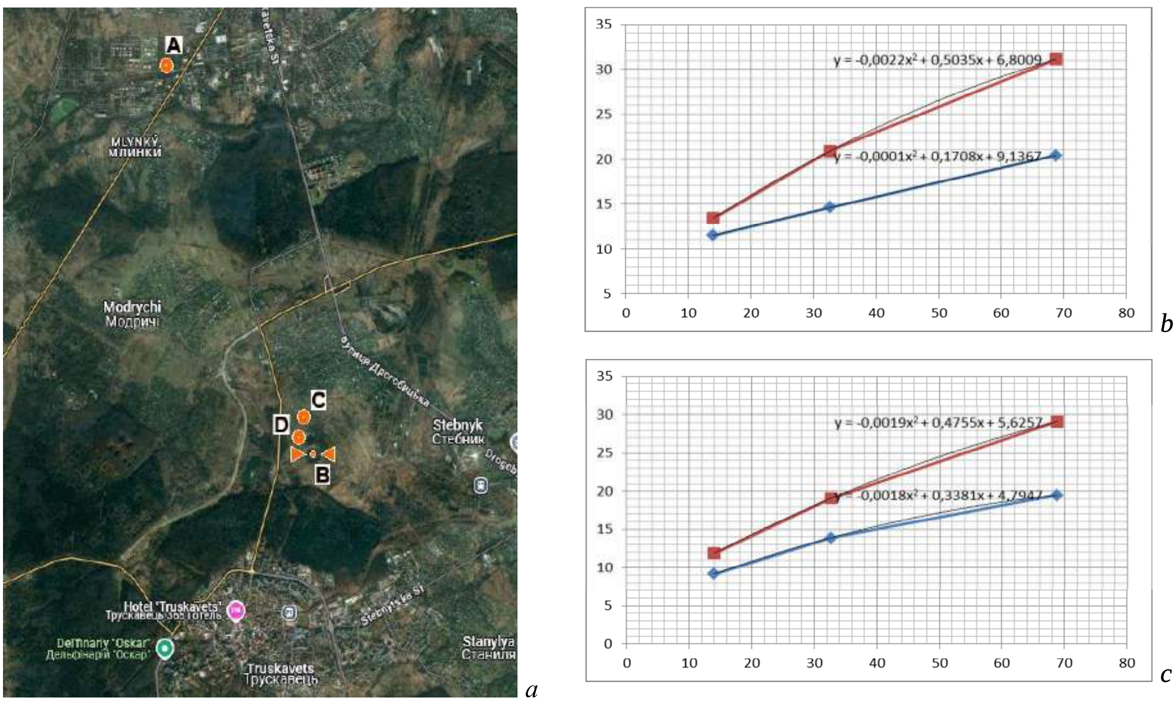


Fig. 10. Hypocentering of the karst-collapse earthquake of September 30 (29), 2017 in Stebnyk (on Google Maps satellite image), variants A – D (a) and Vadati graphs for hypocentering variants A (b) and D (c) (explanations are in the text)

Table 2

Initial data and station kinematic parameters for different variants of hypocentering of the karst-collapse earthquake of September 30(29), 2017 in Stebnyk

	No. s/n	Seismic station Code	Name	$`t_0$ (s)	$`t_p$ (s)	Δt_p (s)	$`t_s$ (s)	Δt_s (s)	$\Delta t_{s\text{-}p}$ (s)	$*V_p$ (km/s)	$*V_s$ (km/s)	V_p/V_s $\Delta t_p/\Delta t_s$	**Δ** (km)	**Δ(P)** (km)	**Δ(S)** (km)	**σΔ** (km)	**σΔ(P)** (km)	**σΔ(S)** (km)	**KΔ** **($\Delta_i=\Delta\times K\Delta$)**
A	1	SHIU	"Shidnytsya"	08,4	**11,5**	3,1	**13,4**	5	1,9	5,148	3,192		15,96			2,01			**0,874**
	2	MORU	"Morshyn"		**14,6**	6,2	**20,9**	12,5	6,3	5,948	2,950		36,88			4,27			**0,884**
	3	LVV	"Lviv"		**20,4**	12	**31,1**	22,7	10,7	5,498	2,907		65,98			-2,74			**1,041**
B	1	SHIU	"Shidnytsya"	*08,4*	**11,5**	3,1	**13,4**	5	1,9	4,510	1,613		**13,95**			0			
	2	MORU	"Morshyn"		**14,6**	6,2	**20,9**	12,5	6,3	5,260	2,016		**32,61**			0			
	3	LVV	"Lviv"		**20,4**	12	**31,1**	22,7	10,7	5,726	1,892		**68,72**			0			
C	1	SHIU	"Shidnytsya"	5,31	**9,69**	4,38	**13,00**	7,69	3,31	**3,2**	1,82	1,76		14,016	13,996		-0,066	-0,046	
	2	MORU	"Morshyn"		**14,1**	8,79	**19,06**	13,75	4,96	**3,75**	2,40	1,56		32,9625	33,000		-0,353	-0,39	
	3	LVV	"Lviv"		**19,5**	14,19	**30,00**	24,69	10,50	**4,8**	2,76	1,74		68,112	68,144		0,608	0,576	
D	1	SHIU	"Shidnytsya"	**<u>04,80</u>**	**9,16**	4,36	**11,88**	7,08	2,72	**3,20**	1,96	1,62		13,952	13,88		-0,002	0,07	
	2	MORU	"Morshyn"		**13,90**	9,10	**19,06**	14,26	5,16	**3,60**	2,29	1,57		32,76	32,66		-0,150	-0,05	
	3	LVV	"Lviv"		**19,50**	14,70	**29,10**	24,30	9,60	**4,67**	2,83	1,65		68,649	68,77		0,071	-0,05	

A – previous hypocentering (on the seismological hodograph (according to 17 stations), data from the working bulletin);

B – determination on the factual localization of the source (data from 3 nearby stations, wave arrival times from the bulletin) and time in the source on variant A;

C – hypocentering on the velocity structure of the crust, wave arrival times were refined in manual mode;

D – hypocentering on the velocity structure of the crust, (wave arrival times are specified using computer technologies for seismograms processing, the specified time in the source is indicated in bold with an underline)

$`t_0$ – time at the source (in seconds) relative to 21.46.00 GMT on September 29, 2017 (00:46:00 local time on September 30), $`t_P$, $`t_S$ – corresponding arrival times of P- and S-waves at the corresponding seismic stations (initial data for calculations are marked in bold).

Table 3

Station kinematic parameters for European seismic stations for the karst-collapse earthquake of September 30(29), 2017 in Stebnyk (explanations are in the text)

№ з/п	Stations code	Network	φ °N	λ °E	t_p (s)	$*\Delta t_p$ (s)	Δt_p (s)	**$K(t_p)$**	*Δ (km)	Δ (km)	**K(Δ)**	σΔ(s) (km)	$*V_p$ (km/s)	V_p (km/s)	**$K(V_p)$**	Source parameters 2017/09/29	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	KWP	PL	49.6314	22.7075	46:20.7	6.2	15.9	**2.56**	42.8	69.3	**1.62**	26.5	6.90	4.36	**0.63**	$*t_0$=21.46.14.5	**t_0=21.46.04.8**
2	TRPA	HU	48.1048	22.5374	46:35.5	21.0	30.7	**1.46**	147.6	150.2	**1.02**	2.6	7.03	4.89	**0.70**	*φ=49.37ºN	**φ=49.2990ºN**
3	ABAH	HU	48.3039	21.2006	46:42.7	28.2	37.9	**1.34**	185.2	201.9	**1.09**	16.7	6.57	5.33	**0.81**	*λ=23.14ºE	**λ=23.5160ºE**
4	BMR	RO	47.672	23.496	46:43.4	28.9	38.6	**1.34**	190.8	180.3	**0.94**	-10.5	6.60	4.67	**0.71**	H=10 km	**H=0.1 km**
5	NIE	PL	49.4182	20.2996	46:49.6	35.1	44.8	**1.28**	205.9	232.9	**1.13**	27.0	5.87	5.20	**0.89**		
6	OJC	PL	51.319°	19.152	47:01.6	47.1	56.8	**1.21**	356.5	382.8	**1.07**	26.3	7.57	6.74	**0.89**		
7	VYHS	SK	48.4939	18.8360	47:02.2	47.7	57.4	**1.20**	329.5	353.1	**1.07**	23.6	6.91	6.15	**0.89**		
8	LANS	SK	49.1505	19.4678	47:08.0	53.5	63.2	**1.18**	267.9	294.0	**1.10**	26.1	5.01	4.65	**0.93**		

** – data from [EMSC, 2017] (as of 10/10/2017) and related to them.*

Additional refinement was achieved by refining the arrival times of seismic waves at seismic stations, the resulting deviation of the hypocenter determined by instrumental data from the factual one decreased to 0.25 km. The results obtained clearly indicate that the registered seismic event was exactly a karst-collapse earthquake in Stebnyk, rather than a tectonic event.

The results of the above studies on the refinement of the hypocenter of the described karst-collapse earthquake of 2017 in Stebnyk have actualized the problem of refining the hypocenter of earthquakes both specifically in the Boryslav seismogenic zone and in the entire western Ukraine, in particular, the Carpathians, the Precarpathians and Volyn-Podillia. To solve it, we subsequently applied the approaches we previously implemented to refine the hypocenter of earthquakes in Ukrainian Transcarpathians and central Ukraine (the Pobuzhzhia subregion) [Nazarevych, 2006, 2019; Nazarevych, Nazarevych, 2004].

These approaches are based on the construction of averaged velocity models of the earth's crust of specific regions using data from regional seismic profiles, in particular, profiles of the DSZ-CMRW, with the subsequent construction of corresponding calculated hodographs for these models (regions), which are used for the refinement of hypocenter of local crustal earthquakes. Such an averaged velocity model of the earth's crust of western Ukraine was constructed using data from regional profiles RP-1 – RP-5, RP-10 and RP-11, from international geotravers II, VIII and PANCAKE [Structure…, 1978; Lithosphere…, 1987–1993; Zayats, 2013; Starostenko et al., 2013; Sheremeta et al., 2023]. The calculated hodograph "Precarpathian" was built on its basis and was used to refine the hypocenter of earthquakes in the Precarpathians [Nazarevych et al., 2024, 2025]. Subsequently, taking into account the significantly inhomogeneous velocity structure of the crust of the region, kinematic corrections to this calculated hodograph for specific seismic stations and focal zones were determined and used for further refinement of hypocenters. The effectiveness of different variants of the methods for refining the hypocenter of earthquakes in the Boryslav – Drohobych – Stebnyk – Truskavets area was tested using data from the 2017 karst-collapse earthquake in Stebnyk. The results of such tests are shown in Fig. 2 (localization of the earthquake focus according to different variants of the refined hypocentering method is shown by pink circles with numbers 1–4, and the collapse itself is shown by a circle with number 5. These methods and results have already been partially published in the materials of the international conferences [Nazarevych et al., 2024, 2025], they will be described in more detail in a separate special article together with the results given in Tables 1, 2 and Fig. 10.

Kinematic corrections for the Boryslav – Stebnyk area for European seismic stations. Using data on the factual localization of the focus of the studied karst-collapse earthquake of 2017 in Stebnyk, we determined kinematic corrections for the Boryslav – Stebnyk area for a number of European seismic stations (Table 3). Because this seismic event was recorded by seismic stations in Poland, Slovakia, Hungary and Romania close to the Carpathian region of Ukraine at epicentral distances of up to 380 km (Table 3, column 11). But the results of operational processing of data from European seismic stations [EMSC, 2017] gave a localization of the focus of this earthquake (Fig. 11, Table 3, column 18) that was far from the factual (Fig. 11, Table 3, column 17), the deviation was more than 28 km to the west (Fig. 11).

Fig. 11. Comparison of the results of the operational hypocentering of the karst-collapse earthquake of September 30 (29), 2017, in Stebnyk according to data from European seismic stations (blue circle, see data in Table 3) with the factual (red circle) localization of the seismogenic karst collapse (Google Maps map base with relief).

Therefore, based on the comparison of data on the factual and operationally determined hypocenters and the corresponding station kinematic parameters (Table 3), we calculated the relevant correction coefficients for time $K(t_P)$, epicentral distance $K(\Delta)$, and P-wave velocity $K(V_P)$ for the method of determining the localization of the focus involved in the operational processing and for the seismic stations involved in it (Table 3, columns 9, 12, 16). These corrections can be used for the hypocentering of tangible earthquakes in the Boryslav – Stebnyk area according to the data of the corresponding European seismic stations; they provide a significant (up to 3–5 times or more) refinement of the localization of the foci of local seismic events. A special article will be devoted to a more detailed presentation of this material.

Originality

For the first time, using data on the velocity structure of the earth's crust in the Carpathian region of Ukraine, methods of refining the seismic events foci in the area of the cities of Boryslav – Stebnyk – Drohobych – Truskavets have been developed. With their use, as well as based on the results of determining the characteristic parameters of the foci of local seismic events, the technogenic karst-collapse nature of seismic events in the area of Mine No. 2 of the Stebnyk potash deposit has been unambiguously established and their important characteristics have been determined.

Practical significance

The results of the presented research make it possible to clarify the nature of the processes and assess natural and technogenic geoecological risks for the Boryslav – Stebnyk – Drohobych – Truskavets area, in particular, in the area of Mine No. 2 of the Stebnyk potash deposit for the development of an optimized set of necessary engineering and technical measures to minimize these risks. The determined local kinematic corrections for seismic stations of the Carpathian Seismological Network of Ukraine and for seismic stations of Poland, Slovakia, Hungary and Romania provide a significantly more precise determination of the coordinates and depths of the foci of local seismic events in the Boryslav – Stebnyk area, both natural and technogenic in genesis.

Conclusions

Summing up the above, we note that:

- a comprehensive analysis of seismic, geological-geophysical and other data was carried out in the area of the cities of Boryslav – Stebnyk – Drohobych – Truskavets, in particular, in the area of the Stebnyk potash deposit;
- the localization of local earthquake foci was clarified using the regional seismological hodograph and the method of minimizing residuals, taking into account local kinematic corrections, determined, in particular, based on the results of the hypocentering of the karst-collapse technogenic earthquake 2017 in Stebnyk;
- to verify the localization of focus of earthquake of September 30 (29), 2017, in Stebnyk, a refined hypocentering was also carried out using the specially designed method taking into account the actual velocity structure of the earth's crust in the subregion according to data from regional profiles;
- the parameters of the studied seismic foci were estimated based on the energy and spectral characteristics of seismic oscillations and correlation dependencies;
- the characteristics of the karst-collapse earthquake at Mine No. 2 in Stebnyk were analyzed taking into account the processes in the mine field, the energy characteristics of the source consist very well with physical estimates of the energy of collapsing rock masses.

One of the main results is this, that through a joint analysis of a complex of geological, geophysical and seismological data using modern approaches, interpretation methods and computer technologies, it was possible to unambiguously establish the karst-collapse nature of the seismic event recorded by seismic stations of the Carpathian Seismological Network on September 30 (29), 2017, to link it specifically to the collapse on the earth's surface in the area of Mine No. 2 of the Stebnyk MCE "Polymineral", to specify the time of this event – 0 hours 46 minutes, 4.8 seconds (local time) on September 30, 2017 (21.46.04.8 September 29, Greenwich Mean Time).

The arguments in support of this are as follows:

1. In the studied time interval (the time of collapse in Stebnyk ±15 min), seismic waves from only one local seismic event were instrumentally recorded (see Fig. 6 and 8), no other seismic events in this area were recorded at this time.

2. The magnitude of the studied seismic event M=2.9, determined by instrumental data, indicates that this event must have been accompanied by pronounced macroseismic effects. Such effects are accompanied by all shallow (with a source depth of up to 3–5 km) local earthquakes with magnitudes of 2.4–2.5 or higher. In confirmation of this, data on recent perceptible earthquakes on June 1, 2020 in the area of the city of Dolyna [Nazarevych, Nazarevych, 2021] can be provided, the first of which with a magnitude of M=3.2 and a focal depth of 2.2 km was felt in the epicenter (village of Yakubiv) and in neighboring villages (within a radius of 5–6 km), the second, weaker (M=2.7, depth of 2 km) was felt only in the epicenter (village of Trostyanets, within a radius of 3 km).

3. Macroseismically (shaking of the earth's surface, sound waves, infrasonic "shock" wave, all this was felt on the outskirts of the village of Solec and the city of Stebnyk adjacent to the collapse, see Fig. 4, *a*) only one seismic event was also registered, specifically a collapse in the mine field of Mine No. 2 of the Stebnyk MCE "Polymineral", no other events with macroseismic effects within a radius of 10–15 km from the collapse site were registered at this time.

4. The localization of the focus of the instrumentally recorded seismic event, refined on the factual velocity structure of the earth's crust in the subregion, coincides with the coordinates of the collapse in Stebnyk with an error margin of no more than 250–450 m (see Tables 1 and 2, Fig. 2 and 10).

5. Positive (P+) P-wave arrivals recorded at seismic stations located around the epicenter of the event (see Fig. 2) directly indicate the specific shock ("explosive") karst-collapse nature of the seismic source, but not its tectonic nature with a characteristic 4-quadrant distribution of different-polar (P+ and P–) P-wave arrivals.

6. The time of the registered instrumentally seismic event coincides with the time of the outage of the 35 kV power line, two poles of which collapsed into a karst sinkhole.

7. The energy estimates of the seismic event based on instrumental seismological data and the karst collapse based on physical data correspond very well.

The methods developed in the these studies for specifying the hypocenter of seismic events in the area of Boryslav – Stebnyk – Drohobych – Truskavets have shown their effectiveness, their use makes it possible to significantly increase the reliability of determining the coordinates and depths of the foci of local earthquakes in the area. This provides reliable time-space monitoring of the course of local seismotectonic processes and the solution of various scientific and practical problems associated with this. Further development of the described approaches, determination and application of refined kinematic corrections for the entire territory of the region, for operating and equipped new seismic stations will provide even more reliable tracking by the regional seismic network of the time-space course of local natural seismotectonic and technogenically provoked dangerous geological processes.

Also the practical value for the work of the operational seismic services of EMSC, Poland, Slovakia, Hungary and Romania are the kinematic corrections for this area for European seismic stations, determined based on the results of data analysis of the hypocentering of the karst-collapse earthquake in Stebnyk.

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КАРСТОВО-ПРОВАЛЬНИЙ ТЕХНОГЕННИЙ ЗЕМЛЕТРУС 30 (29) ВЕРЕСНЯ 2017 р. У СТЕБНИКУ (ЗАХІДНА УКРАЇНА) І ТЕХНОГЕННО СПРОВОКОВАНІ ПРОЦЕСИ НА СТЕБНИЦЬКОМУ КАЛІЙНОМУ РУДНИКУ

Метою роботи є комплексний аналіз причин, характеристик та наслідків карстово-провального тежногенного землетрусу, який стався 30 вересня 2017 р. в 00 год 46 жв за місцевим часом (29 вересня 2017 р. о 21 год. 46 жв за Гринвічем) у м. Стебнику в зоні другого рудника Стебницького ГХП "Полімінерал", його аналіз у зв'язку з тежногенно спровокованими небезпечними геологічними процесами (зокрема, з утворенням карстовиж провалів) на Стебницькому калійному руднику (Українське Передкарпаття). Методика. Методика досліджень об'єднує комплексний аналіз сейсмічних, геологічних та інших даних щодо зони Стебницького калійного родовища, включно з уточненням локалізації вогнищ місцевих землетрусів, оцінками параметрів сейсмічних джерел, з використанням для цього напрацьованих підходів і методик, адаптованих відомих і спеціально створених комп'ютерних та ГІС-технологій та їх варіантів, розроблених відповідних програмних засобів. Результати. Коротко простежено сучасну сейсмічну активізацію району Борислава – Стебника (2014–2024 рр.). Враховуючи довготривале (з початку XIX ст.) активне видобування у районі м. Борислава нафти і газоконденсату, а також калійних руд у Стебнику, місцева сейсмічність, очевидно, частково є додатково техногенно спровокованою (наведеною). Сейсмічні події в районі рудника № 2 Стебницького ГХП "Полімінерал" визначено як карстово-провальні техногенні землетруси у зоні гірничих виробок цього рудника.

Простежено техногенно спровоковані небезпечні геодинамічні процеси в зоні цього рудника й оцінено важливі енергетичні та кінематичні параметри спричинених ними техногенно спровокованих сейсмічних подій. За даними про карстово-провальний землетрус 30 (29) вересня 2017 р. у Стебнику і за даними про швидкісну будову кори заходу України уточнено гіпоцентрію місцевих сейсмічних подій району Борислава – Стебника, для нього визначено локальні кінематичні поправки для сейсмостанцій Карпатської сейсмологічної мережі України і для деяких сейсмостанцій Польщі, Словаччини, Угорщини та Румунії. Наукова новизна. Вперше з використанням даних про швидкісну будову земної кори Карпатського регіону України розроблено методики уточнення гіпоцентрії сейсмічних подій у районі міст Борислава – Стебника – Дрогобича – Трускавця. З їх використанням, а також за результатами визначення характеристичних параметрів вогнищ місцевих сейсмічних подій однозначно встановлено техногенну карстово-провальну природу сейсмічних подій в районі рудника № 2 Стебницького калійного родовища та визначено важливі їх характеристики. Практична значущість. Результати досліджень дають можливість уточнити перебіг процесів та оцінки природних і техногенних геоекологічних ризиків для району Борислава – Стебника – Дрогобича – Трускавця, зокрема, в районі рудника № 2 Стебницького калійного родовища з метою напрацювання оптимізованого комплексу необхідних інженерно-технічних заходів для мінімізації цих ризиків. Визначені локальні кінематичні поправки для сейсмостанцій Карпатської сейсмологічної мережі України і для сейсмостанцій Польщі, Словаччини, Угорщини та Румунії забезпечують суттєво уточнене визначення координат і глибин вогнищ місцевих сейсмічних подій району Борислава – Стебника як природного, так і техногенного походження.

Ключові слова: Українське Передкарпаття, район міст Борислава – Стебника, сейсмічність, тектоніка, зони калійних шахт, техногенний карст, карстово-провальний землетрус, гіпоцентрія землетрусів, кінематичні поправки.

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