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CONNECTION OF KRYVBAS TECTONICS WITH NATURAL AND TECHNOGENIC SEISMICITY

Purpose. Studying the tectonic features of the structure of the earth's crust of Kryvyi Rih-Kremenchuk suture zone to clarify the nature of the origin of seismic events in the Kryvbas.

Methodology. To analyze and generalize the data on the Kryvbas seismicity with reference to large-scale geological and tectonic maps of exploration work. To study its tectonic structure based on geological, geophysical studies and drilling of Kryvyi Rih superdeep well.

Findings. In the period 2011–2021, about 1,200 seismic events were recorded on the territory of Kryvbas, the majority of which had a minor magnitude ≥ 2.0. Among them there were identified 13 powerful industrial explosions from $mb = 2.7–3.5$ and 20 earthquakes of tectonic origin with $mb = 2.1–4.5$. Powerful explosions in mines predominantly induce earthquakes. In recent years, local earthquakes began to occur in tectonic fault zones outside the ore mining area, which indicates a change in the elastic-deformation state of the geological environment. The analysis of the attributes of local earthquakes and their locations suggests that Kryvyi Rih tectonic system and the entire eastern flank of the earth's crust of the West Inhulets-Kryvyi Rih-Kremenchuk suture zone are geodynamically active structures, where the processes of thrust and shear tectonics are also observed on a recent geological time scale.

Originality. A detailed analysis of the earthquakes shows that some of them occur at significant depths in the zones of tectonic faults outside of Kryvbas. At the same time, faults in separate directions are activated, where brittle deformations and viscous-plastic formations are manifested in the past geological time. The location of local earthquakes made it possible to single out two sections and five linear zones of seismic activity in the region.

Practical value. Based on the results from this research it is possible to create an applied model of the tectonic section of the earth's crust to solve the problems of evolution and geodynamics of the lithosphere of the Ukrainian shield, mountain geology and to optimize mining. The identified faults of active inherited development are important in determining the development paths for quarries and mines in Kryvbas.

Keywords: *fault tectonics, elastic deformation state, seismic activity, industrial explosion, local earthquake*

Introduction. The deposits of the Kryvyi Rih iron ore basin (Kryvbas) have been actively developed by mining and quarrying since the middle of the *19th* century. The greatest intensity of iron ore extraction occurred in the 80s and 90s of the *20th* century. The main tool in the extraction of iron ore is powerful blasting, which is carried out in quarries and mines. Currently, the following mines are operating in the territory of Kryvbas: "Hihant-Hlyboka", "Ternivska", named after Ordzhonikidze, named after Frunze, "Hvardiiska", "Zhovtneva", "Rodina", "Saksahan" and "Yuvileina" [1]. The depth of individual mines is up to 1.5 km, and the zones of underworking of the crystalline massif above them exceed their area by an order of magnitude. Mines, together with quarries, affect the elastic-deformation state of the massif of rocks in the tectonic zones of Kryvbas and provoke man-made and natural seismic events.

Since the beginning of the *21st* century, seismic events with a magnitude of more than 3.0 have been observed in the area of Kryvyi Rih [2, 3]. The analysis of the number of seismic events in Kryvbas from 2011 to 2021, which were recorded at a considerable distance, shows the reaction of the natural environment to an increase in their number and power since 2018, when the number of observed seismic events increased several times, and the number of natural earthquakes began to increase [4]. Previous studies have established [5, 6] that the main seismic effect is not created by the explosions in the mine themselves, but by their consequences – crushing and displacement of rocks or spontaneous subsidence of the soil in tectonic zones. At the same time, their geolocation went beyond the territory of iron ore mining [7, 8]. The analysis of their distribution shows the presence of activation of discontinuous faults of different directions and depth of layers [4].

Literature review. Earthquakes in the city of Kryvyi Rih, during which the intensity of shaking of the earth's surface in

the epicenter was 5–6 points on the MSK-64 scale, occurred on December 25, 2007 (*mb* = 3.9) [6, 8], January 14, 2011 (*mb* = 3.8), June 23, 2013 (*mb* = 4.6) and July 29, 2017 (*mb* = = 4.1) [4.8]. The occurrence of earthquake foci in the zone of the Kryvyi Rih–Kremenchuk fault of the Ukrainian Shield [9, 10] is probably a consequence of the uneven distribution of stresses on the border of the Inhul and Middle Dnipro megablocks of the USH [11], as well as violations of the geodynamic balance caused by powerful explosions during surface and underground mining of minerals and movements of large masses of the geological environment [12]. The influence of blasting operations on the manifestations of earthquakes is confirmed by the coincidence of the time of registration with the time of powerful explosions in mines. The exception is the strongest earthquake on June 23, 2013, which occurred at 22 : 16 GMT. Explosive works are not carried out at night. Studies [2, 4] established that spectrograms of seismic events are of different origin differ, even with the same magnitude level. The spectrograms of earthquakes compared to the spectrograms of explosions are more saturated, with no fading. Clear peaks of the spectral density were recorded in the recording interval of Lg-waves in the frequency range of 1–15 Hz, LR-waves in the band up to 1 Hz. During explosions, an increase in the spectral density on the spectrograms is noted in the recording band of P- and Lg-waves, followed by a sharp fading on the recording. The main part of the energy from explosive sources is manifested in the recording interval of surface waves [2, 12]. Using the model [13] for weak earthquakes and mine seismicity it is possible to obtain the radius of influence of the source on the geological environment. Violation of its geodynamic equilibrium leads to a change in lithostatic pressure and activates near-fault areas of the earth's crust, including fractured ones [14, 15], which become sources of local earthquakes: seismogenic movements along faults, displacement of the block in the roof of the mine, displacement of the shear along the slope line [16, 17].

The depth of the foci of the 2007–2021 earthquakes is more than 10 km, which characterizes the unstable state of the environment in the middle part of the earth's crust. It is possible that earthquakes with a magnitude higher than 4.6 may occur in Kryvbas with the further continuation of large-scale development of mineral deposits with the use of powerful explosive charges.

On the territory of Kryvbas, 1191 seismic events were recorded, including 20 earthquakes for the period from 2011 to 2021 (Fig. 1). This is based on the data of the Main Special Control Center (SCSC) of the National Space Agency (NSA) of Ukraine and the National Seismological Data Center (NCSD) of the Institute of Geophysics named after S. I. Subbotin (IGF) of the National Academy of Sciences of Ukraine. The turning point in explosive works in quarries and mines is the year 2018, when their number and power increased several times [4]. Among the 20 local earthquakes of various nature

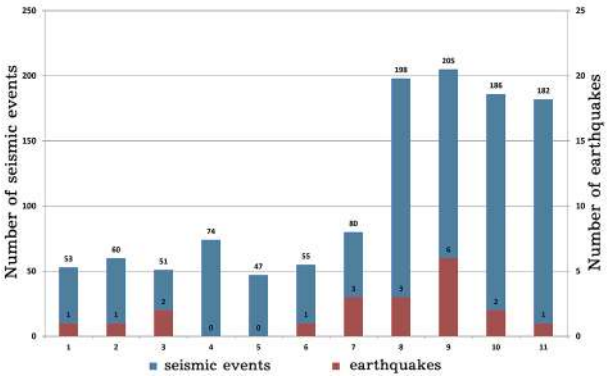

Fig. 1. The histogram of the distribution of natural and technical seismic events for 2011–2021

within Kryvbas, selected on the basis of a comparison of the recording form and spectrograms of earthquakes and explosions in quarries and mines, nine of them occurred late or at night (Fig. 1).

The technique of rejecting seismic events using tectonics. A number of publications [2, 4] show that records and spectrograms of local earthquakes and industrial explosions in quarries and mines within Kryvbas have significant differences. Powerful explosions in mines in which the mb magnitude value exceeded 3.0 were carried out at a depth of 475 to 1300 m, while surface waves prevail; their amplitudes are much higher than the amplitudes of volume waves [2]. The difficulty of identifying the nature of seismic events is due to the fact that the main seismic effect is not created by the explosions in the mine themselves, but by their consequences – crushing and displacement of rocks or sharp subsidence of the soil, including a change in the level of the earth's surface.

In order to clarify their nature, the tectonic basis of rupture faults was constructed, based on tectonic maps of scales 1:50000–1:2500, which were obtained during the geological exploration expedition "Kryvbasgeology" during the search and exploration of iron quartzite deposits.

The position of tectonic disturbances was specified using maps of gravity and magnetic fields [18], taking into account the data of seismic exploration and magnetotelluric sounding (by sharp shifts of seismic horizons, changes in geoelectrical resistance, material composition of the crust, and other geological and geophysical features).

General characteristics of the geotectonic elements of the territory of Kryvbas. The Kryvyi Rih structural-facies zone (synclinorium, monocline) is located in the eastern part of the West-Inhulets-Kryvyi Rih-Kremenchuk suture zone (ZIK-KSHZ), in the zone of the Kryvyi Rih-Kremenchuk deep fault [9, 11]. In the east, it contacts the Saksahan dome, composed of ancient Archaean rocks of the granitoid and metabasite-ultrabasite type. In the west – with the Inhuletsky rampart, composed of Neoarchaean rocks mainly of the plagiogranitoid type. Synclinal and anticlinal folds of high order are distinguished in the structure [10]. The hinge of the synclinorium dips in a northerly direction. The maximum depth of the structure, which is calculated according to geophysical data, in the area of mines named after *20th* Party Congress and named after R. Luxemburg is 7.0–7.5 km (together with the underlying rocks of the Sura Formation).

A number of large submeridional faults internally complicates the Kryvyi Rih structure: Western, Tarapakiv, Saksahan, Eastern, and Southeastern, which are interpreted as breaks that define the main structural line of the Kryvyi Rih-Kremenchuk deep fault, which is the western limit of the Kryvyi Rih structure [10, 11].

The eastern wing of the synclinorium is composed of a complete section of the Kryvyi Rih series, the western wing is cut by the Western and Tarapakiv faults. The complexity of the internal arrangement of the structure is obviously explained by the presence of an ancient subduction zone here, which is emphasized by a powerful zone of extended seismic platforms that fall in the lower part of the crust to the east at angles of 45–40° and by the thickening of the lithosphere under this zone.

Rocks of the Kryvyi Rih structure, which have been exposed by many quarries, are crumpled into numerous morphologically diverse folds and broken by a series of transverse and longitudinal faults.

Disruptive tectonic disturbances. The most important fault on the territory of Kryvbas is the transregional Kryvyi Rih-Kremenchuk deep fault of the crustal-mantle deposit, which separates megablocks with different structures and geological histories. We determined the linear extension of the Kryvyi Rih-Kremenchuk structural-facies zone for hundreds of kilometers. The fault is traced through the entire crust according to the displacement of seismic reflective elements [8, 10] and extends for 200 or more kilometers in the north and south di-

rections outside the USH and has a western dip. Its angles of incidence near the surface of the crystalline foundation have an inclination of 75–80° and are more gentle in the lower part of the crust – up to 45–55°. The fault zone [4, 10] within Kryvbas is a multiaxial fault system, where the Western fault is the western axis, the central axis is marked by the Tarapakivsky fault, and the Saksahansky and Eastern faults are in the east (Fig. 2). With the depth of the disturbance, the steep drop is changed to a more gentle one. The change in dip is especially noticeable in the Western Fault. Within its borders, both the western and eastern falls are known. Faults consist of two or three converging parallel faults, and transregional faults (within Kryvbas) consist of three or four faults [10].

Large, almost orthogonal and supporting (shear) tectonic disturbances in the crust of these faults, are traced. These are distinguished by sharp shifts in seismic horizons, changes in the material composition of the crust, and other geological and geophysical features.

The described disturbances are fixed, as a rule, by various types of brittle deformations (brecciation, cataclasis, mylonitization) with thickness up to hundreds of meters. Along with brittle deformations, a wide range of viscoplastic formations is established in fault zones.

The Tarapakiv fault (Fig. 2), which is the central axis of the deep Kryvyi Rih-Kremenchuk fault [10, 11], stretches across the entire Kryvbas and divides it into two parts – western and eastern. The fault has a northeasterly extension with an azimuth of 20–300, a northwesterly dip at an angle of 45–70° and less frequent up to 80°. The horizontal displacement of the rocks along the fault is about 200 m, and the vertical displacement is 40–80 m. At the same time, along its plane, the western part of the structure is pushed against the eastern part and still maintains a tendency to rise. The Tarapakiv fault is a complex zone with a package of strongly compressed folds-scales and plates of Archean granitoids [10]. Fault zones are represented by brecciated and cataclased rocks with slickensides.

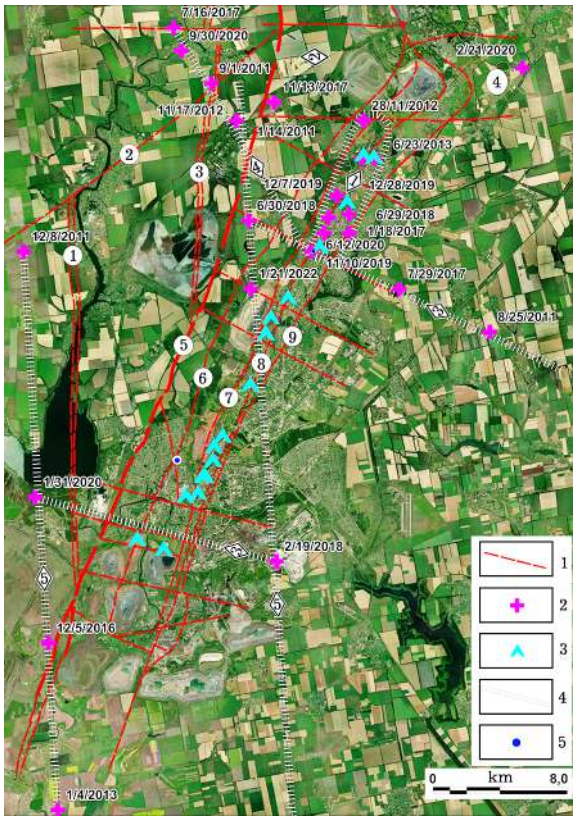

Fig. 2. Tectonic scheme of the territory of Kryvbas and the location of local earthquakes from 2011 to 2021 and estimated seismically active tectonic disturbances (with direction of extension, in degrees). Conventional designations:

1 – discontinuous violations; 2 – geolocation of the seismic event and its date (month/day/year); 3 – location of mine management; 4 – position of predicted seismically active zones; 5 – the location of the hydrogeodeformation monitoring well. Numbers in circles. Discontinuous violations and their name: Karachunivsko-Lozuvatskyi – 1; Diagonal – 2; Iskrovskyi; Devladivskyi – 4; Kryvyi Rih-Kremenchuk (Western) – 5; Tarapakivskyi – 6; Saksahansky – 7; Eastern – 8; East sided. Numbers in diamonds. Forecast linear zones with azimuths: 20 ± 5° – *1*; 270° – *2*; 290 ± 5° – *3*; 330 ± 5° – *4*; 350–355° – *5*

The Saksahan fault zone (Fig. 2) is the most powerful thrust-type zone within the structure with a vertical movement amplitude of 500–1000 m in the southern part of the basin and up to 1500–2000 m in the northern part. It extends in the submeridional direction for no less than 30 km. Starting in the south of the basin, the thrust-type fault has a westerly dip at angles of 38–45°. In the middle part of the structure, the thrust plunges steeply (at angles of 75–80°) to a considerable depth. Further to the north, its surface shifts sharply, while a diagonal thrust structure is formed. Even further north, the slope of the Saksahan thrust plane changes to the east, and already in the area of the northern deposits, it has a steep east dip at an angle of 75–80°.

Along the complex plane of the Saksahan thrust, a powerful movement, of the allochthonous part of the monocline of the complex of rocks of the Skelevat and Saksahan formations took place, which created a kind of cover, which was previously interpreted as the Saksahan anticline.

As a result of these movements, a very complex fold of movements developed in the thick layered strata of rocks of the Saksahan Formation, and when the strength limits of ferruginous quartzites and quartzite-schists were exceeded, zones of closely spaced spalls formed, a system of fine fissures and fine-plastic cleavage along the thrust plane was formed.

During the movement of the thrust part of the monocline (alochthon) along the shifter, powerful zones of tectonic breccias, mélanges, and friction surfaces were formed.

A similar structure with changes in rocks on a smaller scale is also observed by other major disturbances of the submeridional extension, including the Eastern Thrust (Fig. 2), which also captures the rocks of the monocline. It passes east of Saksahansky through the rocks of the Skelevat Formation and is fixed on the so-called “talc horizon”.

In the southern part of the Kryvyi Rih structure, the Yekaterininskyi and Skelevatskyi faults are traced. From them there depart a number of abutting discontinuities, which determine the block structure of the Skelevatskyi deposit. The dip of the fault surfaces is western, the dip angles are in the range of 50–70°. The zones of discontinuity are accompanied by brecciation and mylonitization of rocks [10]. Their thickness is from 0.5 to 6–8 m. The total horizontal displacement in the zones reaches 1000 m, vertical – 100–240 m.

In the Kryvbas region, the sublatitudinal system of faults is represented by faults with a direction of 285–295°, which has an almost vertical dip (75–90°) [4, 8].

Fig. 2, which is represented by a multispectral satellite image, clearly shows the presence of sublatitude and west-northwest discontinuities. Its visual analysis makes it possible to distinguish a diagonal west-northwest system of faults with an extension of approximately 290–295° based on the geomorphological features of the relief, the ridge-beam system and the river valleys of the Inhulets and Saksahan rivers.

In addition to the main systems of large faults in relation to the folds, the following small systems are distinguished: cleavage cracks, usually closed, which have a considerable length; separation cracks – divided into regional and local; delamination cracks, which coincide with the layering of rocks, repeating all folds of layers.

In the Inhuletskyi Wall, located to the west of the Kryvyi Rih structure (Fig. 3), all tectonic disturbances are recorded

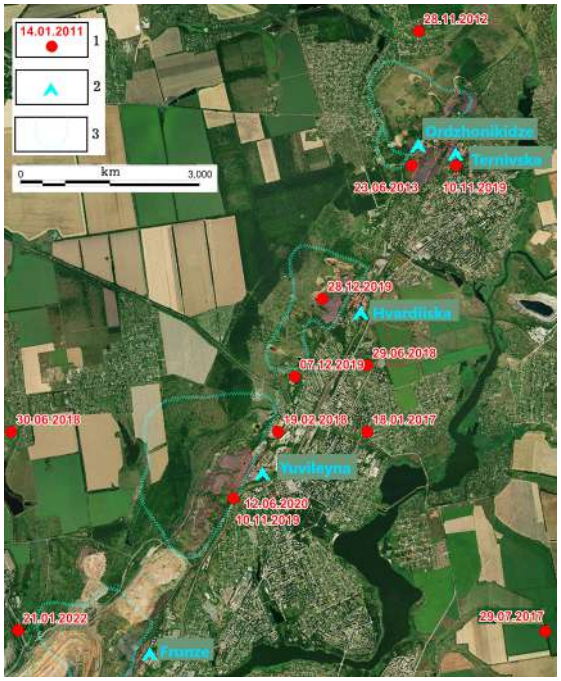

Fig. 3. Seismic events in the northern part of Kryvbas.

Conventional designations:
1 – geolocation of the seismic event and its date (*day. month. year*); *2 – mine management and their name*; *3 – the artificial space above the mine*

by brecciation, cataclasis, flaking and mylonitization of rocks with a thickness of several tens of meters (Zakhidno-Inhuletskyi, Karachunivsko-Lozuvatskyi, Inhuletskyi, Central (Heikovskyi), Iskrovskyi) to a few hundred meters (Inhuletskyi fault). On both sides of the Kryvyi Rih-Kremenchuk fault, the thickness of these tectonites can reach 1.5–2 km. At the same time, mylonites usually form tectonic seams in the inner fault zone, which are ten times less than the total thickness of tectonites. The Western Inhulets fault zone dips in the western direction. The combination of irregularities with different angles of inclination forms a rather complex system of wedge-shaped structures.

Tectonic movements along the Western-Inhuletskyi fault [11], more intense within the Inhuletskyi, and particularly powerful deformations in the Kryvyi Rih-Kremenchuk fault zone led to the reconstruction of Proterozoic folded structures (mainly synclines) into folded-flaky structures and monoclinal flakes.

Results of geological and tectonic analysis of the nature of earthquakes. Visual analysis of the location of local earthquakes shown in Figs. 2 and 3, allows one to identify and localize two areas and five linear fault zones of seismic activity in the plain.

According to the depth of their location, they include: up to 5 km – in the cultivated space around the mines, which provoke failures above them (Fig. 3); from 7 to 10 km – at the boundary of the closure of the Kryvyi Rih structure and its underlying granitoids of the Dnipropetrovsk complex; more than 10 km – directly in the crust of the Ukrainian shield.

By lateral location. *The northern section* is connected with the area of intersection of diagonal faults of the north-west, northeast trend with the zones of the Kryvyi Rih-Kremenchuk and Devladiv faults (Fig. 2). The northern part of Kryvyi Rih Region is a complex folded structure on the northern extension of the eastern wing of the Saksagan syncline of the Kryvyi Rih structure. It is located in the May Day flexure, broken by diagonal and transverse breaks in relation to the stretching of the rocks. The structure is crossed by the zone of the Devladiv fault, which is a deep fault of the coro-mantle deposit. Most of the longitudinal faults of the Kryvyi Rih syncline disappear in the zone of the Devladiv fault. Here there is a change in the extent of rocks of the Kryvyi Rih series from northeast to northwest.

Statistical analysis of the structural elements of discontinuous faults allowed us to systematize them along four strike directions: 20, 60, 330 and 355°; and in each extension there are two symmetrical oppositely falling directions of fall, the average angle of fall is 60–70°. This genetic localization of gaps in space creates complex fault-block tectonics, characteristic only for the Terniv (Pershotravnevo) district of northern Kryvbas (Fig. 3).

According to the results of the analysis of gravimetric maps of various scales [18], a system of large diagonal faults, which are located in a stage-like manner in relation to the extension of the rocks, can be clearly traced. This system is presented as the result of the manifestation of vertical and horizontal movements along a single zone of the Kryvyi Rih-Kremenchuk deep fault.

The Kryvyi Rih ultra-deep well NG-8 [19] is located within the selected northern section, the geological section of which shows the complex structure of the intersection zone of diagonal faults of the northwest trend with the zones of the Kryvyi Rih-Kremenchuk and Devladiv deep faults. In the main shaft of the well, 26 tectonic zones with a width of 5 to 15 cm were established. Their largest number was located at depths of 3600–3850 m, where open cracks make up to 40 % of the well section. In the bottom of the well (up to 5430 m), zones of intense cataclysm were discovered – the crushing and stressed state of the geological environment, which geologists associate with the intersection of the Tarapakiv thrust and the Devladiv sublatitude zone. Intensive formation of voids (up to 8–12 cm) was noted at these depths.

The second (Ternivska) site (Figs. 2, 3) is located in the area of active mining of iron ore by quarry methods and mine in the past.

It can be seen from the space photo that there are dips in the created space above the mines, which indicates that this area is in the zone of recent unloading and stretching of the upper part of the earth's crust. Therefore, the effect of explosive works on the manifestation of individual earthquakes is observed in the form of the coincidence of the moment of their registration with the time of powerful explosions in mines.

Active mining of ore with the execution of powerful explosions in the mines in this area leads to consequences with a sharp subsidence of the soil (failures) and the formation of induced local earthquakes.

Generalization of geological, geophysical and space images (Fig. 2) shows that, in general, Kryvbas can be divided into two areas according to the manifestations of seismic events: the northern one, where the largest number of them is registered, and the southern one. At the same time, it can be seen that the system of diagonal faults in these parts has a different angle of extension. This fact allows us to make an assumption that the northern part of Kryvbas experiences tension, while the central and southern parts experience weak compression.

The stretching of the earth's crust in the northern part of Kryvbas can be clearly traced by the presence of large dips above the minefields. At the same time, the depth of epicenters of seismic events, as a rule, does not exceed 5–7 km. That is, the process takes place at the bottom of the Kryvyi Rih structure, which is composed of high-density rocks overlying non-dense granitoids of the Dnipropetrovsk complex. It is possible that the thrust nature of the iron ore structure on the granitoids causes stress fields in the places of their adhesion with subsequent fragile deformations under the influence of powerful explosions in quarries and mines. This provokes induced earthquakes.

The following sources of local, natural earthquakes are linear zones (Fig. 2), which are associated with modern seismic activity:

The first predicted linear zone (Fig. 2) coincides in plan with the Kryvyi Rih-Kremenchuk system of faults with a predominant strike azimuth of 20 ± 50°. Spatially, in the north of Kryvbas, it coincides with the second section (Fig. 3), which is located in the area of active mining of iron ore by the mine method and is confined to the Tarapakiv and Saksahan faults.

The second predicted linear zone of latitudinal extension with an azimuth of 270° is associated with the Devladiv zone of deep faults (Fig. 2), which is the most seismically active in the northern part of Kryvbas. The fault zone in the latitudinal direction is traced for 200 km through the entire Middle Dnieper megablock.

The third predictive linear zone of sub-latitudinal extension 290 ± 50° (Fig. 2) can be traced in the geomorphological features of the relief, the dyke system and the river valleys of the Inhulets and Saksahan rivers. The fault system has a later formation [8, 10] and is mainly represented by closed cleavage and separation cracks with a dip of 75–90°.

The fourth forecast linear zone with azimuths of extension 330 ± 5° (Fig. 2). Its activation started quite recently from the end of 2011 and it does not gravitate towards the territory of mineral extraction. The closest seismic event to the area of active iron quartzite mining occurred on December 5, 2016 at 1 : 51 : 29 (UMC), i. e. at nighttime, indicating its natural origin.

The fifth forecast linear zone of northwestern extension with an azimuth of 350–355°. It is located to the west of the Karachuniv-Lozuvatskyi fault and has a parallel extension. Within its limits, brecciation, cataclasis, flaking and mylonitization of rocks with a thickness of several tens of meters are recorded. From the Proterozoic to the present, it is a geodynamically active structure, where the processes of thrust and shear tectonics can be traced even at the modern geological stage.

The nature of the spatial position of the faults allows us to conclude that the entire Kryvyi Rih tectonic system is shifting to the right.

The most deep-focus earthquakes gravitate to the diagonal fault located west of Kryvbas. The depth of their cell reaches 33 km, which indicates their lower crustal origin. As shown by the results of the analysis of seismological observation data, they are weak with a magnitude of slightly more than 2.0 [4].

The analysis of the attributes of local earthquakes and their locations allows us to assume that the Kryvyi Rih tectonic system and the entire eastern flank of the Earth' crust of the Western-Inhulets-Kryvyi Rih-Kremenchuk suture zone with the Proterozoic and to the present time is a geodynamically active structure. Here the processes of thrust and shear tectonics can be traced as a recent geological process, but probably with a smaller amplitude in time. Our conclusions are confirmed by the results of hydrogeo-deformation monitoring, which has been conducted since December 2007 by the Dnipropetrovsk geophysical expedition "Dniprogeofizika" in an exploratory drilling well 815 m deep (Fig. 1) with a relative static water level in it -106 m from the day surface [20]. As can be seen from the graph (Fig. 4), for 2021, there is a general trend in the decrease in the water level, but at the same time, intervals of its rapid and abrupt change can be traced, which is associated with small neotectonic movements in the Kryvyi Rih-Kremenchuk seam zone.

The attenuation and activation of geodynamic processes in the Earth's crust is probably related to the rotational process of the Earth during its rotation and the varying degrees of inertia of large geological structures and tectonic blocks of different masses. The overlap of natural processes in the earth's crust and powerful explosions in mines and quarries is a trigger for the manifestation of local earthquakes, collapses and landslides.

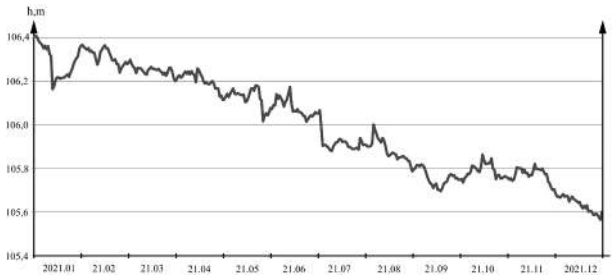

Fig. 4. Graph of fluctuations in the level of underground water in a deep well for 2021

Conclusions. The occurrence of foci of local earthquakes in the area of the Kryvyi Rih-Kremenchuk fault zone is associated with a violation of the geodynamic balance caused by powerful explosions during the development of rich ore deposits at great depths. The movement of huge masses (quarry, mine – dump, tailings repository) in space and time and a complex of other natural and man-made conditions also disturb the balance of the geological environment. At the same time, the Kryvyi Rih structure is currently geodynamically active, where the processes of thrust and shear tectonics continue, but with a smaller amplitude in time. Changes in the rhythms of these processes are possibly related to the Earth's rotation process, and powerful explosions in mines and quarries are a trigger for the manifestation of local earthquakes.

The analysis of the location of local earthquakes made it possible to identify and localize two areas and five linear zones (faults) of seismic activity in the plain.

They are divided into groups according to the depth of their location, up to 5 km – in the cultivated space around the mines, which provoke failures above them; from 7 to 10 km – at the boundary of the closure of the Kryvyi Rih structure and its underlying granitoids of the Dnipropetrovsk complex; more than 10 km – directly in discontinuous disturbances of the earth's crust of the Ukrainian shield.

The length of rupture faults is relatively small and the depth of their propagation is mainly limited to the earth's crust (40–50 km), so it is probably not necessary to expect powerful local earthquakes of tectonic origin with a magnitude of more than 3.5–4.0.

Separate seismic events of a destructive nature can occur only in the case of superimposition of man-made and tectonic events. With the further continuation of large-scale mineral development with the use of powerful charges during blasting and their coincidence in time can generate earthquakes with a magnitude higher than 4.0 and create a danger to the lives of the population.

The epicenters of the earthquakes mainly gravitate to the northern part of the Kryvyi Rih structure, and their proximity to the zone of the Tarapakiv and Saksahan faults, which control the position of rich iron ore deposits. This suggests that it is in a critical stress-deformed state that can generate local seismic events.

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Зв'язок тектоніки Кривбасу із природньою й техногенною сейсмічністю

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Мета. Вивчення тектонічних особливостей структури земної кори Криворізько-Кременчуцької шовної зони для уточнення природи походження сейсмічних подій на території Кривбасу.

Методика. Аналіз та узагальнення даних по сейсмічності Кривбасу з їх прив'язкою до крупномасштабних геолого-тектонічних карт пошуково-розвідувальних робіт. Вивчення його тектонічної структури за результатами геологічних, геофізичних досліджень і буріння Криворізької надглибокої свердловини.

Результати. За період 2011–2021 рр. на території Кривбасу зафіксовано близько тисячі двісті сейсмічних подій, що мають, здебільшого, незначну магнітуду ≥ 2,0. Серед них виділено 13 потужних промислових вибухів з *mb* = 2,7–3,5 та 20 локальних землетрусів тектонічного походження з *mb* = 2,1–4,5. Землетруси переважно мають індукований характер за рахунок потужних вибухів у шахтах. В останні роки локальні землетруси почали відбуватися і в зонах тектонічних розломів за межами території видобутку руди, що свідчить про зміну пружно-деформаційного стану геологічного середовища. Аналіз атрибутів локальних землетрусів і місць їх розташування дозволив припустити, що Криворізька тектонічна система та увесь східний фланг земної кори Західно-Інгулецько-Криворізько-Кременчуцької шовної зони із протерозою й по теперішній час є геодинамічно активною структурою, де процеси насувної та зсувної тектоніки простежуються й на сучасному геологічному етапі.

Наукова новизна. Детальний аналіз землетрусів показує, що окремі з них відбуваються на значних глибинах у зонах тектонічних розломів за межами Кривбасу. При цьому активізуються розломи окремих напрямів, в яких виявлені крихкі деформації та в'язко-пластичні утворення в минулому геологічному часі. Розташування локальних землетрусів дозволило виділити у плані дві ділянки та п'ять лінійних зон сейсмічної активності.

Практична значимість. Результати досліджень дозволяють створити на їхній основі прикладну модель тектонічного розрізу земної кори для вирішення проблем еволюції й геодинаміки літосфери Українського щита, гірничої геології та оптимізувати видобуток корисних копалин. Виділені розломи активного успадкованого розвитку мають важливе значення при визначені шляхів розвитку кар'єрів і шахт у Кривбасі.

Ключові слова: *розривна тектоніка, пружно-деформаційний стан, сейсмічна активність, промисловий вибух, локальний землетрус*

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