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Boundary of recent activation and seismicity on the platform part of Ukraine

V.V. Gordienko[1], I.V. Gordienko[1], Ya.A. Goncharova[2], V.M. Tarasov[1], 2024

[1]S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine, Kyiv, Ukraine
[2]V.K. Gusak Institute of Emergency and Reconstructive Surgery of the National Academy of Medical Sciences of Ukraine, Kyiv, Ukraine
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The purpose of the work is to clarify the boundaries of the recent activation (RA) zone in the platform part of Ukraine. Such limitations are evident for the Alpine Carpathian geosyncline and the Hercynian-Cimmerian Scythian plate. For the East European Platform, the edge of the zone is determined by the magnitude of the mantle gravity anomaly. This option gives a more definite result than the previously used complex of geological and geophysical data. The applied technique, in addition to the usual two-dimensional density modeling along DSS profiles, includes the processing of the obtained data by kriging. This allows you to fill in the area between the profiles and trace the detailed shape of the zone boundary. The magnitude of the anomaly at the edge of the active region was calculated. In the center of the zone, the studied perturbation (the difference between the gravitational effect of the crust and the observed field) is 30—40 mGl, at the edge — 20 mGl. An estimate of the error in determining the anomaly was made, it turned out to be at the level of 10 mGl. The value at the boundary is less than the tripled error. In this situation, a special procedure is needed to detect spatial variations in the position of the boundary. For this, for the first time, two of its calculation options were used: using kriging and using artificial profiles located between the real ones. The crustal sections under the artificial ones were average between the real ones, the observed field on the artificial profile was used. An average difference in the boundary position of 13 km was obtained. The practically important question of the ecological consequences of manifestations of activity in the RA zone on the platform is considered. Seismicity does not pose a significant threat, as does the release of helium with anomalous isotopy and hydrogen. Catastrophes happen precisely during the exploitation of gas and coal deposits, and not as a result of the natural evolution of these objects.

Key words: platform part of Ukraine, boundary of recent activation zone, mantle gravity anomaly.

Introduction. The studies carried out in recent years [Gordienko, Gordienko, 2021, 2023, etc.] made it possible to connect with full certainty the seismicity in the crust and upper mantle of the Alpine and Cimmerian geosynclines of the Tethys and the Pacific Ring with the endogenous regime of recent activation (RA). Such a connection is also obvious for the Carpathians and the Scythian plate on the territory of Ukraine. Earthquake epicenters extend to the outermost borders of these regions. On the platform part of the territory of Ukraine, the situation is more complicated. The unfinished process of recent activation does not manifest so reliably in geological phenomena and anoma-

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lies of physical fields accessible to study.

Nevertheless, within Ukraine, it was possible to outline the contours of the territory covered by the process on the East European Platform (EEP), including the Donbas, and to assess the advantages and disadvantages of the employed geological and geophysical methods. Local and regional criteria were applied. The former are distributed only in separate fragments of Ukraine's territory and are unsuitable for mapping the RA as a whole. The latter are, in principle, suitable for solving the problem, but in practice, they face significant limitations. We are talking about positive anomalies of the heat flow (HF), objects of increased electrical conductivity in the crust and upper mantle, modern surface uplift, and the mantle gravity anomaly.

Despite Ukraine's uniquely detailed geothermal research, significant «blank spots» remain on its territory. In addition, HF anomalies are absent in parts of the RA zones, where superheated crustal objects formed recently, and the thermal effect has not yet reached the surface. Such potential heat sources can be recognized from local outbursts of hot fluids above small magma intrusions into the upper crustal horizons. HF anomalies appear above them, but such sporadic manifestations do not allow area mapping. We can also mention other, less significant, interferences for thermal diagnostics of RA zones, but even those already listed are sufficient for an opinion about its limitations.

The knowledge of Ukraine by methods of deep geoelectrics is also more detailedthan in other countries. Nevertheless, the pattern of distribution of the identified conductors in the crust and upper layers of the mantle looks like a mosaic; it is difficult to distinguish solid heated (and, accordingly, having a reduced electrical resistivity of rocks) massive bodies from it corresponding, among other things, to the regions of the Carpathians and the Scythian plate mentioned above. In the rest of Ukraine, the picture is similar. It can be argued that within the RA zones, the concentration of conductors is greater than outside them. However, this is not enough for reliable mapping. The nature of anomalously high conductivity is not reduced to overheating; it is largely associated with fluids accompanying partial melting, sometimes with electronic conductors, etc. Further research and an improvement of methods for interpreting experimental data may make it possible to obtain a more definite picture. Nevertheless, so far, this result has not yet been achieved.

The diagnostics of recent activation zones based on the amplitudes of young (in the last millions of years) uplifts is the least reliable. Calculations have shown that this effect is determined with insufficient accuracy. It is possible to imagine a situation in which the process scheme is fundamentally preserved, and the surface displacement has a different sign. In addition, in the southern part of Ukraine, the impact of the subsidence of the Black Sea depression can reduce the uplift in the RA zone to almost zero, which is what happened.

The mantle gravity anomaly in the RA zones of the platform is devoid of a significant part of the considered interferences. The knowledge and accuracy of the observed gravity field are quite sufficient for reliable detection of such a disturbance. This has been established in large areas of Ukraine and other regions in which there is confidence in the calculation of the crustal effect, adequate to the complexity of the geological situation. In practice, it is, first of all, about the use of high-quality velocity sections of the crust along DSS profiles and methods for converting velocity (V_P) into density (σ). The second necessary element in constructing the area effect of the crust is its definition in areas outside the profiles.

An attempt was made to determine the contours of the RA zones using a set of the above methods. Their relative weight in solving the problem could not be determined. Therefore, it was believed that activation was detected with an accuracy of 100 % if all four criteria coincided, 75 % if three, and 50 % if two (Fig. 1).

It is obvious that the tolerances in the location of the estimated boundary of the zone of recent activation on the EEP in the conditions of Ukraine using the considered complex are many tens of kilometers. The practical use of

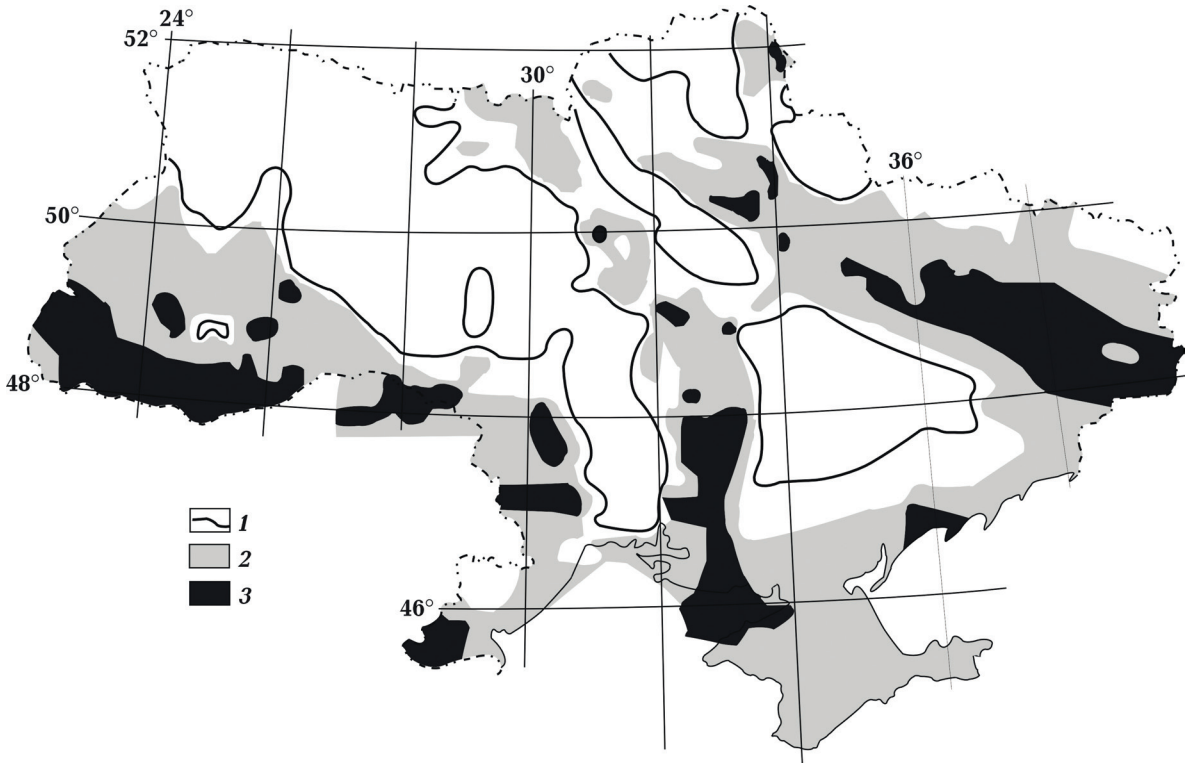

Fig. 1. Contours of the RA zone of Ukraine according to the complex geological and geophysical methods [Gordienko et al., 2020a]. Border of zones with probability RA: *1* — 50 %, *2* — 75 %, *3* — 100 %.

such mapping is minimal; it is a qualitative assessment of the current situation.

When solving both of the above problems of the gravitational field analysis, the anomaly in the RA EEP region will definitely be identified and mapped without using other methods. This is indicated by calculations using the distribution of anomalous densities in the mantle compared to the non-activated platform, which arose due to the considered deep process. The article is devoted to analyzing this approach and the achieved result.

Model Building. The density modeling technique in this case is not considered in detail, this was done in previous works by the authors [Gordienko et al., 2015, 2020a,b; Gordienko, 2022; Gordienko, Gordienko, 2023, etc]. Let us dwell only on the information necessary for solving a local problem — determining the boundaries of the zone of recent activation in the platform part of Ukraine by the magnitude of the mantle gravity anomaly. The anomaly is defined as the difference between the observed field (in our case, the Bouguer anomaly) and the gravitational effect of the density model of the Earth's crust, in which the densities are counted from those typical for the upper mantle horizon — 3.32 g/cm^3. The comparison is carried out taking into account the background; zero Bouguer anomaly on the platform corresponds to the effect of the crust minus 870 mGl. This is an experimental value established as a result of simulations in areas with a clear lack of activation. To estimate the error in determining the anomaly, it is necessary to establish the differences between the calculated and observed fields when the simulation was carried out on the platform. Such work was carried out in [Gordienko, Gordienko, 2023, etc.] on the EEP, Siberian, and North American platforms along profiles thousands of km long (about 2000 km within Ukraine). The results in the territories outside the activation zones are shown in Fig. 2.

It is likely that the error of the observed field is less than the calculation error (although it is difficult to say when comparing

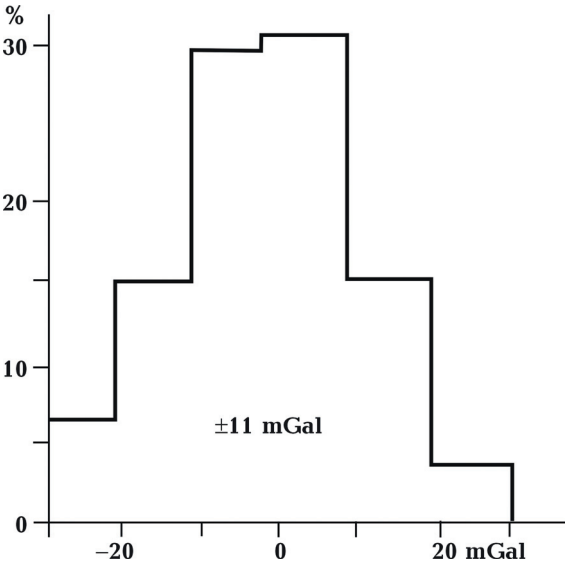

Fig. 2. Histogram of the distribution of deviations of the calculated gravitational field from that observed on platforms outside the zones of recent activation.

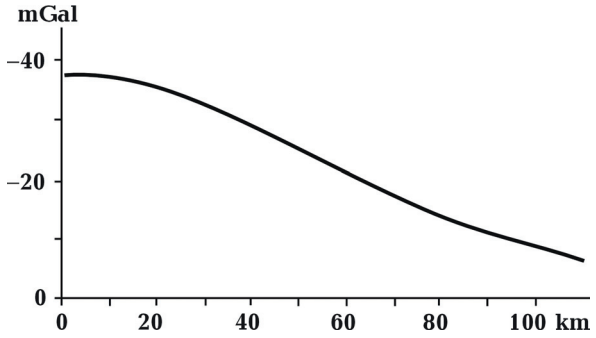

Fig. 3. Mantle gravity anomaly at the edge of the RA zone.

gravity field maps in different atlases [Gursky, 2002; National…, 2007, etc.]), the latter can be estimated at 10 mGl, the former at about 5 mGl. Approximately the same values are obtained when comparing the calculated effects of the crust (for example, in the Donbas — 6±4 mGl [Gordienko et al., 2015]) on intersecting profiles. It can be assumed that on DSS profiles with low detail of velocity sections (oceans, land profiles with a sparse observation network etc.), the error of the calculated field will noticeably increase.

The error in calculating the gravity anomaly may increase in the case of recent activation due to the uncertainty of the scheme of this incomplete deep process. To select the optimal variant, calculations were carried out along a system of profiles encircling the northern hemisphere [Gordienko, Gordienko, 2023]. Within all intersected RA zones, density anomalies were included in the computational models, corresponding to two schemes of heat and mass transfer — for the activated platform and all other regions. The obtained anomalies made it possible to explain the observed gravitational field without selection with acceptable accuracy. It corresponded to the usual error for other endogenous regimes of the compared calculated and experimental values. The magnitude of the disturbance in the central part of the RA zones was 30—40 mGl, and at the edge, 20 mGl.

The activated blocks of the crust and upper mantle with anomalous densities in the calculations were two-dimensional objects with a width of about 60 km or a multiple of this value [Gordienko, 2022, etc.]. The corresponding distribution of the mantle anomaly at the edge of the RA zone (60 km from the center of the object) is shown in Fig. 3.

Obviously, with the above calculation error, the edge of the active zone can be determined from the magnitude of the anomaly only with an error of a few tens of kilometers.

The calculation of the crustal effect was carried out for all DSS profiles of Ukraine and compared with the observed field. To switch to the areal model, the kriging technique was applied, the conditions for which are rather favorable in this case [Davis, 2002; Demyanov, Savelyeva, 2010; Gordienko, 2022]. The resulting circuit differs markedly from that shown in Fig. 1 towards greater certainty (Fig. 4).

Almost all visual manifestations of recent activation are within the marked contour of the mantle gravity anomaly on the platform. The error in the position of the edge of the contour can be estimated by repeating the calculation using a different calculation option in the territories between the DSS profiles, for example, by replacing kriging with an effect along artificial profiles between real ones. It was assumed that the velocity section of the crust smoothly changes between the

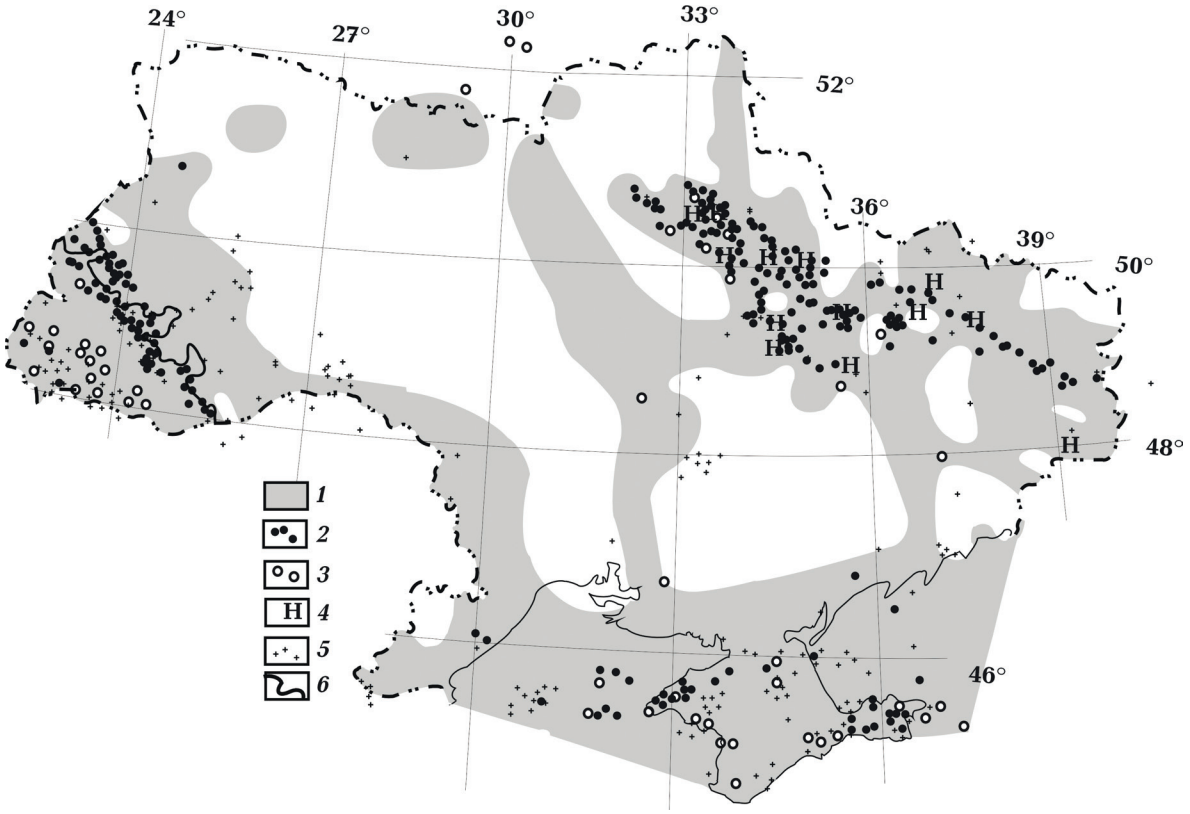

Fig. 4. The zone of recent activation on the territory of Ukraine according to the data on the magnitude of the mantle gravity anomaly [Gordienko, 2022]: *1* — RA zone, *2* — oil and gas fields, *3* — manifestations of anomalous helium isotopy in groundwater and gases, *4* — hydrogen manifestations, *5* — earthquake epicenters, *6* — boundary of the area of young hydrothermal mineralization distribution.

profiles, and the calculated field is compared with that observed on the artificial profile. The changed position of the edge of the RA zone is shown in Fig. 5.

The average difference in the position of the calculated RA boundary is about 13 km, corresponding to the error of each calculation of 9 km.

Manifestations of recent activation. In the literature, the concept of recent activation as an event that poses an extreme danger to the existence of mankind is quite widespread [Makarenko, 1997; Gilat, Vol, 2012, etc.]. According to the authors of these publications, it cannot be considered that something ordinary is happening on the planet now. It is necessary to actively look for the places and phases of a possible catastrophic impulse of activity, which can manifest at any moment. Similar episodes in the Earth's geological history are no exception; local forecasts of modern foci of catastrophic magmatism look realistic. However, all of them are associated with activating alpine geosynclines or rifts. Platforms, in this sense, do not look promising. There are exceptions (for example, Vitim and Aldan on the Siberian platform), but even in these areas of young volcanism, events did not reach catastrophic proportions.

The observed seismicity on the platform part of Ukraine [Gursky, 2002; Nationa…, 2007, etc.], confined mainly to depths of 5—10 km, refers mainly to energy classes 9—9.5. A significant part of the least intense earthquakes may not be recorded. It can be assumed that, within the RA zone, weak earthquakes at shallow depths are very widespread, as indirectly indicated by the very high permeability of the channels for transporting fluids during the formation of deposits of oil, gas, and hydrothermal ores. The permeability is three orders of magnitude higher than the

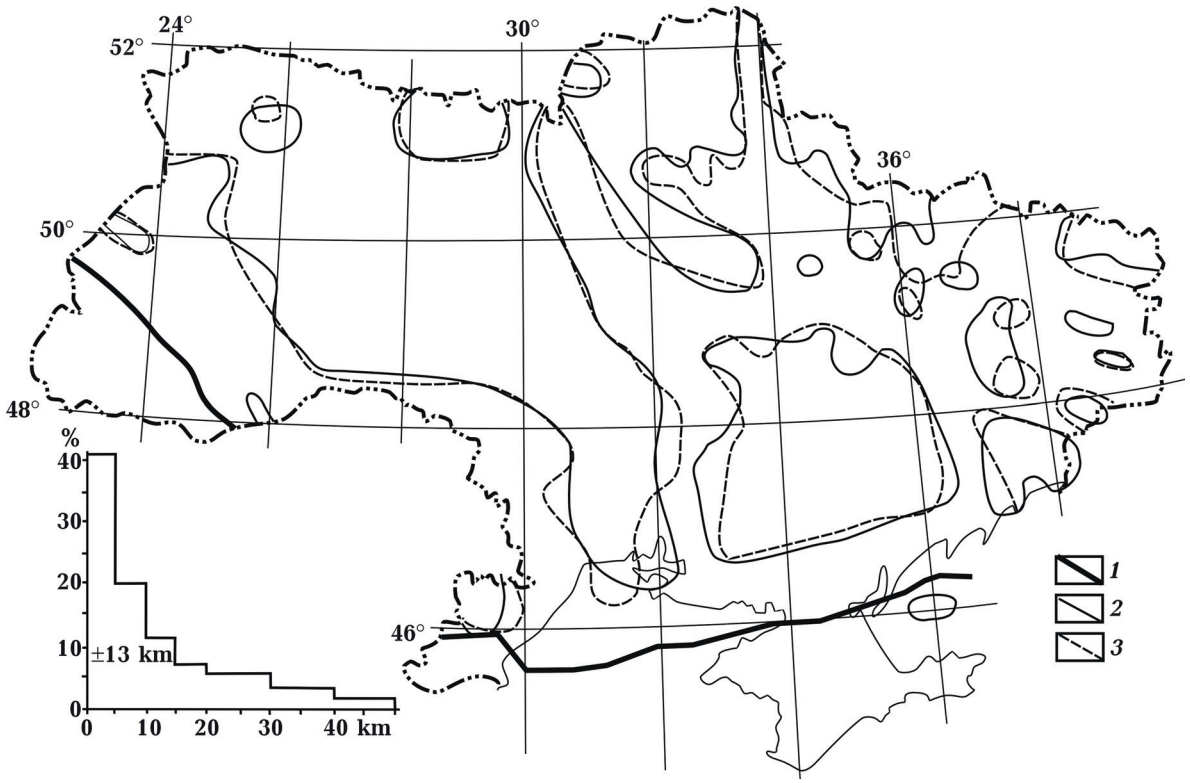

Fig. 5. Variants of the location of the edge of the RA zone in the platform part of Ukraine: *1* — platform boundary, *2, 3* — RA zone boundary constructed with (*2*) kriging and without (*3*) kriging. The inset shows a histogram of the distribution of differences in the position of the two variants of the boundaries.

corresponding real porosity [Gordienko et al., 2020b]. In the area of widespread hydrocarbon deposits (for example, in the Dnieper-Donetsk depression), the network of deposits looks much denser than the network of known earthquakes (see Fig. 4).

The stresses relieved by such events reach a maximum of several MPa, which is two orders of magnitude less than the strength of the crustal rocks. A formal calculation of temperatures in the RA zone due to mantle and crustal heat sources shows that such stresses can be thermoelastic and form not only within it, but also tens of kilometers beyond its boundaries. However, such a conclusion does not take into account stress relaxation. Estimates of the relaxation time can already be made quite reliably now. In our case, it turns out to be very small — no more than 100 thousand years. During this period, there are still no noticeable thermal anomalies outside the RA zone associated specifically with the youngest (crustal) heat sources. I.e., earthquakes of a thermal nature should not go beyond the boundaries of the zones. Exceptions are formed near permeable faults up to a kilometer thick, through which deep-seated hot fluids circulate. They are associated with hydrocarbon deposits (including on the platform) and hydrothermal ore deposits (arising within the Carpathian geosyncline). The last objects on the platform (including Donbas) in the RA zone are barren. When old faults are «revitalized» by recent activation, the movements along them (and the accompanying earthquakes) can locally go beyond the boundaries of the zones.

By itself, the network of modern faults on the platform appears as a result of the movement of upper crustal material over objects with a density that has changed during the RA. These disturbances limit blocks with sizes of 60 and 120 km [Verkhovtsev, 2006]. They exactly match the sizes of tectonic action quanta [Gordienko et al., 2020a, etc.]. Fluidization lenses are formed in their interior

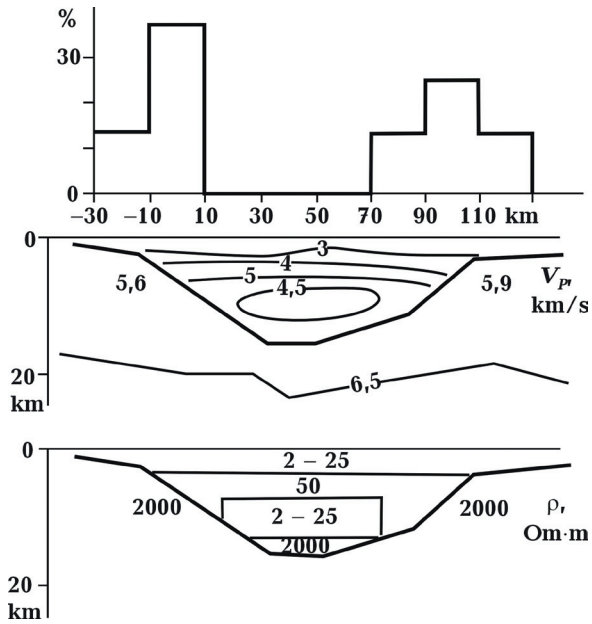

Fig. 6. The top part of Information shows a histogram of the distribution of the number of earthquake epicenters along the profile that intersects the DDB. Zero picket is located in the area of the southwest marginal fault. In the middle part of the figure is an averaged velocity section of the studied part of the depression [Pavlenkova, 1980; Pavlenkova, Baranova, 1980]. In the lower part of the figure is an averaged model of the electrical resistivity distribution of the rocks of the sedimentary layer and the DDB basement [Gordienko et al., 2015, etc.].

over zones of partial melting in the lower and middle crust [Gordienko et al., 2020b, etc.]. It is natural to assume that under suitable conditions (the presence of carbon on the hydrogen uplift path), such blocks include hydrocarbon deposits [Gordienko et al., 2020b, etc.]. In the most complete form, the process can be observed in the distribution of the physical properties of rocksand the seismicity of the Dnieper-Donetsk Basin (DDB). For a more complete characterization of the location of earthquake epicenters, in addition to Ukrainian data [Safronov, 2005, etc.], information obtained from seismic stations in neighboring Russian regions was used [Nadezhka et al., 2008; Savko et al., 2008; Efremov, Rogozhin, 2010, etc.].

Fig. 6 presents the relevant information. It refers to the section of the DDB between meridians 33—37°E longitude.

The presence of an object with reduced seismic wave velocity and electrical resistivity in the lower part of the sedimentary layer is evident. The reduced resistance body is fragmented and includes elements with parameter values up to 50—150 Ohm·m. The object as a whole should also have a noticeable anomalous density, which is about minus 0.15 g/cm^3. The magnitude of the lifting force is 15 MPa, which is more than an order of magnitude less than the strength of the rocks. Naturally, the displacements (and earthquakes) are concentrated at the object's edges in the zones of long-lived faults framing the depression.

In the second region, where the considered phenomena could manifest themselves — the Precarpathian trough (about 50 km wide) — the situation is less favorable for their confident diagnosis. The distribution of deep temperatures is affected by contact with the Carpathian geosyncline (a part of the trough can be attributed to it), the thickness of the sedimentary layer is not large enough, and the locations of faults associated with RA and the previous history differ markedly. It is possible to conditionally identify a trough-related discontinuous electrically conductive object at a depth of 10 km with a total longitudinal conductivity of 500—5000 S. Velocity anomaly is not diagnosed. The distribution of earthquake epicenters along the transverse profile through the trough is shown in Fig. 7.

The supply of helium with a mantle isotope label and hydrogen (most likely from the lower crustal floor of thermal serpentinization of ultrabasites) to the near-surface depths contributes to understanding the content of the deep process but does not pose an en-

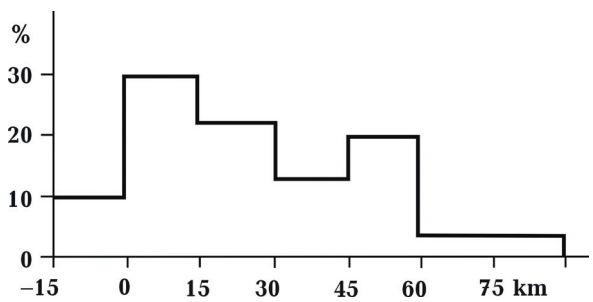

Fig. 7. Distribution histogram of earthquake epicenters number along the profile that crosses the Carpathian Foredeep [Safronov, 2005, etc.].

vironmental hazard [Gordienko et al., 2015, 2020a; Bagriy, 2020, etc.].

The physicochemical instability of hydrocarbon deposits formed during the RA process [Lukin, 1997] during the rise of mainly lower crustal hydrogen and its reaction with middle crustal carbon [Gordienko et al., 2020b] can create a certain threat during exploitation. Large fires occurred in the western (located mainly on the platform) and eastern basins. In one case, it was necessary to use a nuclear charge during extinguishing. The same impact was also used to stop the emission of coal mine methane, the intensity of which increases with the heating of the bowels of the activated areas. However, these rather serious incidents should still be attributed to man-made rather than natural disasters. Significant harmful geochemical anomalies do not occur naturally either (for example, under the influence of reduced fluids on the soil above the deposits) [Environmental Health Criteria].

The recovered fluid should contain traces of a complex procedure of its formation. They can be estimated from the available data on rocks and processes in hydrothermal fields of mid-ocean ridgesand continental mafic-ultramafic rock masses. They have also been found in Ukraine's oil and gas deposits [Lukin, 2009] as microparticles of native metals, carbonates, and sulfides. The authors do not consider them to be traces of the participation of anomalously large mantle depths in the process [Gordienko et al., 2020b]. The serpentinites through which the fluid passes contain residual avaruite, disseminated pentlandite, heathlewoodite, and spinel occur. Fine grains form chromite (with impurities of Al and Mg, less often Mn, Ti, V), Pt (and platinoids), Au, SnO_2, and TiO. Cassiterite includes dissemination of Ti, Nb, Ta, Fe, Cr, V, and W with a size of 1—100 μm. During pyroxene metamorphism (bastitization), chromium and aluminum are removed from the rock. Accumulations of these impurities, which are foreign to the host rocks, pose a risk of chemical contamination. However, it is not implemented under the conditions of exploitation of deposits [Environmental Health Criteria].

In general, it can be stated that the recent activation of the platform part of Ukraine is relatively confidently outlined (with the indicated tolerances) and does not create, according to the available data, a significant environmental hazard.

Conclusions. The study of recent activation zones on the territory of Ukraine has been conducted for more than 30 years. It contains comprehensive geological and geophysical information that characterizes this phenomenon, unavailable in other countries. Fundamentally important results have been obtained that have created a stable framework for the general scheme of the deep process. However, it refers only to the past part of it and, in many ways, has an inaccurate time frame. At the same time, it is becoming increasingly clear that without considering the manifestations of RA, it is impossible to correctly interpret geological phenomena and geophysical anomalies of a different nature. Research into recent activation must be continued despite all the difficulties accompanying it. Some (albeit small) contribution is made to them by the results presented in this article.

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Межа сучасної активізації та сейсмічності на платформній частині України

В.В. Гордієнко*[1], *І.В. Гордієнко*[1], *Я.А. Гончарова*[2], *В.М.Тарасов*[1], *2024

[1]Інститут геофізики ім. С.І. Субботіна НАН України, Київ, Україна
[2]Інститут невідкладної і відновної хірургії ім. В.К. Гусака НАМН України, Київ, Україна

Мета роботи — уточнення межі зони сучасної активізації (RA) у платформній частині України. Такі обмеження є очевидними для альпійської Карпатської геосинкліналі та герцинсько-кімерійської Скіфської плити. Для Східноєвропейської платформи край зони встановлюється за величиною мантійної гравітаційної аномалії. Цей варіант дає більш певний результат, ніж комплекс геолого-геофізичних даних, що використовувався раніше. Застосовувана методика крім звичайного двовимірного моделювання щільності вздовж профілів DSS включає обробку отриманих даних кригінгом. Це дає можливість заповнити територію між профілями та простежити детальну форму межі зони. Розраховано величину аномалії краю активного району. У центрі зони досліджуване збурення (різниця між гравітаційним ефектом кори і спостережуваним полем) становить 30—40 мГал, на краю — 20 мГал. Оцінено похибку визначення аномалії, вона виявилася на рівні 10 мГал. Значення на межі виявляється меншим за потрійну помилку. У цій ситуації необхідна спеціальна процедура виявлення просторових варіацій стану межі. Для цього вперше використано два її розрахункові варіанти: з використанням кригінгу та застосуванням штучних профілів, розташованих між реальними. Розрізи земної кори під штучним профілем були середніми між реальними, використовувалося спостережене поле на штучному профілі. Отримано середню різницю у положенні межі 13 км. Розглянуто важливе питання щодо екологічних наслідків проявів активності в зоні RA на платформі. Сейсмічність не становить значної загрози, як і виділення гелію з аномальною ізотопією та водню. Катастрофи трапляються саме під час експлуатації родовищ газу та кам'яного вугілля, а не як результат природного розвитку цих природних об'єктів.

Ключові слова: платформна частина території України; межа зони сучасної активізації; мантійна гравітаційна аномалія.