

Manifestations of recent activation in the southwest of Ukraine and the adjacent territories of Moldova and Romania. Pt. 1

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The article concerns the endogenous regime of recent activation in SW Ukraine and adjacent territories of Moldova and Romania. Starting from a chronology of research on the topic, it proceeds to outline the current state of knowledge. There are different views of how the activation manifests and why the deep processes are so difficult to grasp. In the region, it is possible to determine the age and nature of geological phenomena identifiable with elements of recent activation. They are different for the platform part and the Carpathians. In the first case, young vertical movements with anomalously high velocities occurred during the Pliocene-Pleistocene. In the second case, a unique concentration of mantle-depth earthquakes (the Vrancea zone) forms a vertical focal structure. Accordingly, the research is divided into two parts. The heat flow on the platform part of the region and the margin of the Scythian plate has a background level of 50—55 mW/m² and two anomalies of up to 80—85 mW/m². The anomalies' intensities and shapes correspond to the calculated parameters of the deep process of recent activation. The differences are due to the crustal intrusions of partially molten mantle rocks, approximately 2—5 million years old, beneath the anomalies. Their thermal models agree with the distribution of seismic wave velocities with sufficient accuracy. It is possible to diagnose even the individual episodes of intrusion of deep superheated material under the crust. Thermal models explain the significant surface uplift during activation, the formation of faults, and the seismicity. The high-conductivity objects also map well onto heat flow anomalies and lie at depths corresponding to intervals of significant superheating and partial melting.

Key words: recent activation, heat flow anomalies, *P*-wave velocities, high-conductivity objects.

Introduction. The concept of recent activation (RA) zones was formulated by G.F. Mirchink. He argued that, in addition to geosynclines and platforms, it is necessary to distinguish «block zones». Their specific feature «... is the tendency toward vertical differential movements of masses with a rupture of the continuity of rocks along cracks, with the outpouring of thick lavas along them, mainly basalts, and the formation of intrusions from

nepheline syenites and alkaline granites. No less characteristic of these block zones are thick, more or less dislocated, often coarse-grained sediments formed due to uplifted blocks adjacent to the depressions».

In the following decades, the idea of RA was considered by many Soviet geologists, including V.V. Belousov, V.E. Khain, E.E. Milanovsky, A.A. Bogdanov, and M.V. Muratov, among others. They identified these zones

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in different regions, made various additions, and clarified the the description of the observed geological processes. The discussions included, in addition to the named authors, A.D. Arkhangel'sky, N.I. Nikolaev, S.V. Obruchev, N.M. Strakhov, and others. The variants of RA belonging to the initial stages of new geosynclinal (post-alpine) processes have been considered. The variants with less significant sets of active (non-platform) events were analyzed. RA zones have been identified within the Alpides that have completed evolving. Activation areas (including significant ones in terms of territory and intensity) have been established in the Mesozoic and, possibly, in the Paleozoic.

Such processes are also mentioned in German geological literature. It is sufficient to recall the «Germanotype tectonics» of H. Stille, which the author presented as a variant of the geosynclinal one, limited to a set of processes and weakened in terms of intensity. On the other hand, in the concept of rifting, H. Cloos described the order of events indicated by G.F. Mirchink, not associated with geosynclines, discovered in many continental regions and at the bottom of the Mediterranean Sea.

According to the geological theory of [Gordienko, 2022, etc.], such phenomena arise from a single-act activation. It takes one event of heat and mass transfer in the upper mantle and the Earth's crust, in contrast to the formations of a geosyncline and a rift, which include three such acts. Such heat and mass transfer occurred quite frequently in the geological history of the Earth, including in the Precambrian. It uses a minimum amount of energy and is followed by a period of tectonomagmatic rest lasting tens of millions of years (if we are talking about a post-Hercynian or older platform).

Recent activation started at the final folding of typical Alpides (about 25—35 million years ago). On platforms, it is caused by advective heat and mass exchange between the lower part of the upper mantle (about 300—400 km) and the subcrustal depth interval (about 50—100 km). it makes possible the invasion of partially melted mantle material

(approximately 8 km thick) into the crust (to depths of about 20—40 km), with the immersion of an equivalent amount of eclogitized crustal rocks into the mantle. The center of partial melting can excite intracrustal advection, heating part of the upper crust and forming magmatic chambers to depths of several kilometers.

Mantle advection can occur with the formation of an intermediate chamber at depths of about 200 km. The most realistic version of the process was selected when calculating the gravity field and heat flow (HF) along the system of deep seismic sounding profiles encircling the northern hemisphere. Over thousands of kilometers, the calculated and observed fields were shown to match with an accuracy corresponding to the error values of both methods for models of direct removal of deep matter under the crust, without the formation of an intermediate focus [Gordienko, Gordienko, 2023a,b, etc.].

During the recent activation of the Alpides (possibly also the late Cimmerides), intrusions into the crust occurred from the shallow asthenosphere of such regions.

In both cases, the time intervals between the above-mentioned movements of matter may not coincide for all fragments of the activated territory. Local areas with significantly different temperatures (T) may arise. Accordingly, there emerge various anomalies of the physical properties of crustal and mantle rocks and disturbances of physical fields. Often, there is not enough information to time the deep processes. In particular, for the whole territory of Ukraine, calculations use the same average age of RA (15 million years), and the age of the intrusion of mantle rocks into the crust is taken to be 0.5 million years. Within the southwestern part of Ukraine and neighboring areas of Moldova and Romania, more detailed data are available. They demonstrate the diversity of recent activation manifestations on the platform and within the Carpathian geosyncline. Our research tries to showcase this diversity and explain its nature.

In the first article, we will focus on the platform area (with an insignificant inclusion of

the epi-Cimmerian Scythian plate), and in the second, on the processes in the Carpathian geosyncline.

Stages of recent platform activation. More than 50 years after Mirchink's work, E.E. Milanovsky wrote about the beginning of the period of recent activation: «Some researchers mark its lower boundary ... at the beginning of the Oligocene, others — at the beginning of the Miocene, or Pliocene, or even the Anthropogene, and still others consider it sliding from region to region, and some completely refuse to try to establish such a boundary ...». Such discrepancies remain today. There are at least two reasons. The first is that after the Oligocene, there was more than one phase of activation in the Alpides. The second is that all three (above) heat and mass transfer events occur at different times.

Using experimental data on surface movements and other criteria [Palienko, 1992; Verkhovtsev, 2008; Gordienko et al., 2024, etc.], it is impossible to determine the activation onset moments on the platform. Therefore, the date of 15 million years ago, obtained by averaging a set of data (including those obtained outside Ukraine) for the moment of formation of the anomalous overheated depth interval (50—100 km) in the mantle, was used for calculations. Subsequent events were dated based on specific manifestations of activation in the region or nearby. The bibliography and a more detailed description are given in [Gordienko et al., 2011, etc.]. In the Bacău region (Romania) at the edge of the Pre-Carpathian trough with a platform basement, adesitic magmatism of about 2—5 million years old was encountered. The deeper part of this complex was discovered on the Moesian plate, and a complete set of its crustal and mantle rocks is among the magmatites of the Transcarpathian Trough. Magmatic sources in the crust are at depths of approximately 20—30 km, with shallower ones at 5—10 km.

It is logical to assume that the identified centers are associated with the introduction of mantle material into the crust (about 5 million years ago) and the results of intracrustal advection. Moreover, «In the Middle Pliocene, the Dniester-Prut interfluvium was a lake-

alluvial plain, which began to rise at the beginning of the Late Pliocene. The separation of the Dniester and Prut basins occurred. The maximum amplitude of this uplift from the end of the Middle Pliocene to the Holocene inclusively was 380—390 m, and during the Quaternary period 120—135 m» [Pokatilov, Bakatchuk, 1976, p. 42]. That is, the last event accompanied by magmatism on the platform occurred about 2—3 million years ago. Earlier activation phases are also clearly visible in the Carpathian region, and we will focus on them in the second article.

Naturally, the appearance of overheated objects in the crust cannot occur throughout the entire territory covered by the RA. Most likely, these would be local formations of 1—2 quanta of tectonic action (about 50—100 km), possibly stretched into chains [Gordienko, 2022, etc.], which they should be accompanied by heat flow anomalies. On the rest of the activated territory, the heat flow should be slightly higher than the background platform level. The activation is likely accompanied by seismicity. This statement can be verified using deep temperature calculations. An increase in temperature in the upper horizons of the mantle up to partial rock melting can be accompanied by anomalies in the distribution of seismic velocities and electrical conductivity. Hydrocarbon accumulations may indicate activation [Gordienko et al., 2011, 2012, etc.].

Fig. 1 and 2 present some factual data characterizing the activation of the region.

Precise delineating of the recent activation (and, accordingly, the anomalies in the distribution of the physical properties of the crustal and mantle rocks) is still ongoing. The uncertainties come from insufficient geological knowledge of the territory. In our case, this primarily concerns the areas of the Scythian Plate and the adjacent part of the South Ukrainian monocline (Fig. 2).

Thermal anomalies of the zone of recent platform activation. North of the heat flow anomalies shown in Fig. 2, a series of HF disturbances of approximately the same or slightly lower intensity was encountered on the Volyno-Podolsk Plate. These disturbances

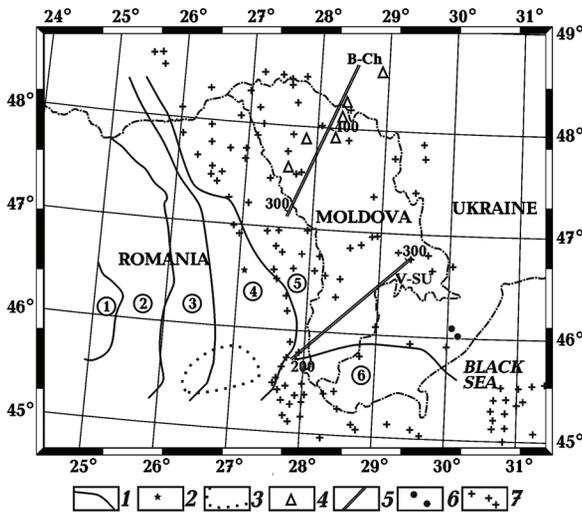


Fig. 1. Tectonic zoning of the southwest of Ukraine and neighboring territories of Moldova and Romania: 1 — boundaries of tectonic zones (1 — Transylvanian Basin, 2 — Transcarpathian Trough and Pannonian Massif, 3 — Folded Carpathians, 4 — Ciscarpathian Trough, 5 — East European Platform, 6 — Scythian Plate (Pridobrudzha Trough)); 2 — manifestation of young magmatism in the Bacău area, 3 — Vrancea mantle earthquakes' epicenters zone, 4 — MTS points [Burakhovich et al., 1997], 5 — profiles along which velocity sections in the upper mantle were constructed [Kharitonov et al., 1993, 1995] (B-Ch — Bucharest—Chornobyl, V-SU — Vrancea—South Ukrainian NPP), 6 — gas fields, 7 — epicenters of crustal earthquakes in the EEP and Scythian Plate.

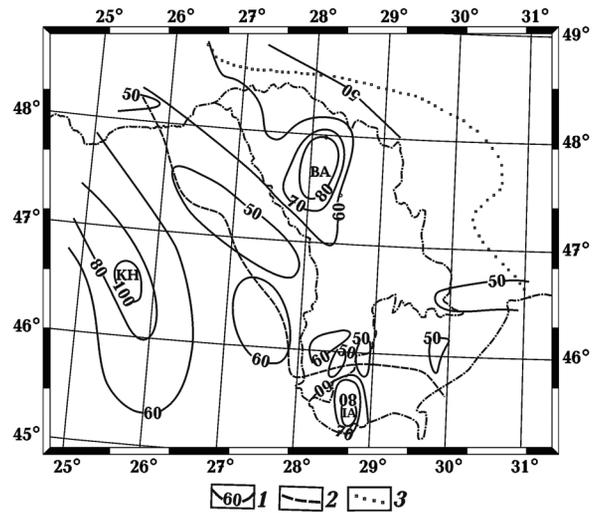


Fig. 2. Distribution of heat flow in the studied region [Gordienko et al., 1996, 2006, etc.]: 1 — heat flow isolines (mW/m^2), 2 — the boundary of the East European platform, 3 — the boundaries of the zones of recent activation of the platform according to the complex of geological and geophysical methods [Gordienko et al., 2024, etc.]. Heat flow anomalies: KH — Kaliman-Khargit, BA — Beltsy, IA — Izmail.

extend all the way to the Ukrainian-Polish border.

HF values collected around the anomalies were used as the basis for interpretation. Their sources were assumed to be isometric objects, the crustal portion of which measured 50 and 25 km (for the Beltsy and Izmail anomalies, respectively). Mantle sources were of the same dimension; their influence on the calculated heat flows is insignificant. Without the effect of crustal sources, the calculated HF differed from the background by an amount not exceeding a threefold error ($45\text{--}55 mW/m^2$ with a platform value of $42\text{--}43 mW/m^2$). In general, the agreement between the calculated and experimental heat flows is satisfactory. The average discrepancy in the areas of anomalies is $\pm(7\text{--}8) mW/m^2$, meaning the error of each value is approximately $5 mW/m^2$, which is not significantly different from the typical experimental error (Fig. 3).

The distribution of calculated temperatures reveals a noticeable zone of partial melting in the mantle beneath the anomalies.

Crustal intrusions of partially molten mantle matter trigger a mechanism that ultimately leads to the formation and migration of hydrogen to the surface. If there is enough carbon in the crust, an ascending (mainly along the permeable fault zones) flow of hydrocarbons

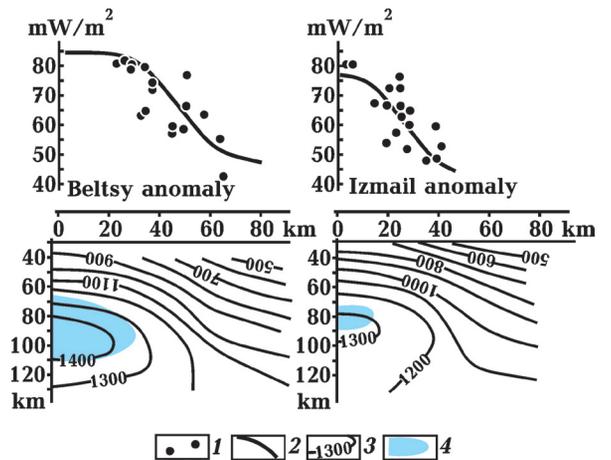


Fig. 3. Results of interpretation of heat flow anomalies. HF values: 1 — experimental, 2 — calculated, 3 — isolines of calculated temperatures in the mantle, 4 — zones of partial melting of mantle rocks.

is formed. In our case, deposits (except for those indicated in Fig. 1) are known in the northern part of the Volyn-Podolsk Plate and on the Black Sea shelf [Gordienko et al., 2012, etc.]. The accumulated geological and geophysical materials in these regions have proven sufficient to argue for the mechanism of their formation and outline the search features of the deposits.

The areas of the examined heat flow anomalies in the southwest of Ukraine and Moldova are of interest as sources of geothermal energy. Temperatures at depths of up to 6 km are not only suitable for hot water supply (exceeding 60 °C); it is also quite possible to obtain steam hotter than 210 °C that meets the requirements for generating electricity without additional heating.

The possible connection between temperature anomalies in the crust of recent activation zones and seismicity is considered in detail in [Gordienko et al., 2024]. Here, we will only briefly dwell on this issue. Calculations show that the specific elastic energy capacity of crustal rocks at real temperatures is several J/cm³. This is a significant value, capable of providing the energy of an earthquake common in the region (about 9). However, its preservation is limited by a geologically short stress relaxation time (no more than 0.1 million years). Therefore, it is necessary to focus on the stresses generated by recently appeared sources. Thermoelastic stresses occur with a value of approximately 1 MPa when T changes by 1 °C. Near the described heat sources, the temperature increases by hundreds of degrees. Stresses can reach tenths of a GPa, which brings them closer to conventional estimates of the shear strength of crustal rocks. But such heating sharply (by an order of magnitude or more) reduces the stress relaxation time due to a decrease in the rock viscosity. However, there is a reasonable opinion that increased intergranular sliding, which reduces viscosity, decreases strength to the same extent. A synthesis of all circumstances has not yet been achieved. Therefore, it is rational to change the approach to assessing overheated objects as a source of faults and seismicity.

Calculating the thermal expansion effect of an overheated block, considering compensating cooling in the lower part of the upper mantle (with a twofold lower coefficient of thermal expansion), leads to a surface rise of approximately 0.5—1.0 km. To «support» such a block, a stress less than an order of magnitude different from the strength of rocks at a depth of several kilometers is required. Anomalous heating reduces the strength, so it seems very likely that a rupture in the rock's continuity and an earthquake will occur. Perhaps this is why the earthquakes shown in Fig. 1 are concentrated in the upper half of the crust.

Calculated amplitudes of surface displacements are comparable with experimental ones.

Heating of the upper mantle and longitudinal seismic wave velocity anomalies. The use of a unique source of seismic waves — the Vrancea focal zone — made it possible to construct unusually detailed velocity sections of the upper mantle horizons of the region (to depths of about 150 km) along the Vrancea—South Ukrainian Nuclear Power Plant and Bucharest—Chornobyl profiles [Kharitonov et al., 1993, 1995]. Therefore, it was possible to detect velocity anomalies caused by thermal

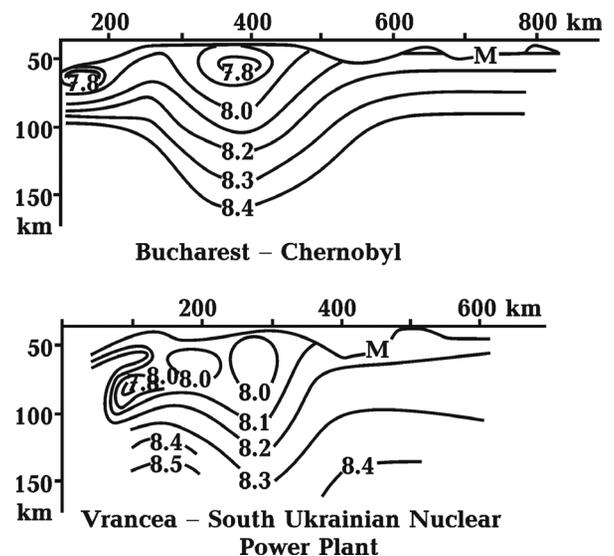


Fig. 4. Distribution of longitudinal seismic wave velocity (km/s) along the Bucharest—Chornobyl and Vrancea—South Ukrainian NPP profiles.

effects of individual quanta of tectonic action (Fig. 4). Their sizes are pretty close to those predicted by geological theory [Gordienko, 2022, etc.].

The Bucharest—Chornobyl profile clearly shows a gap between two intrusions of deep superheated matter into the subcrustal mantle. On the second profile, the same velocity anomaly is less expressive, but also present. The authors encountered this aspect of velocity model analysis for the first time. It makes sense to consider the correspondence of the observed disturbances to the thermal models constructed interpreting heat flow anomalies. Naturally, quantitative estimates of the correspondence between experimental and calculated data are not quite standard in this case: the profiles do not pass directly through the heat flow anomalies. However, the linear size of the velocity anomalies already indicates that they record the same disturbances as the thermal ones. For mantle rocks, the authors have repeatedly tested the conversion of thermal anomalies into velocity ones. Significant errors were recorded only in cases where most rocks were not of peridotite, but of eclogite paragenesis. In our case, it is not to be expected. Therefore, the calculation was

performed according to the standard scheme. The velocity distribution by depth beneath the platform varied in accordance with the anomalous temperature (Fig. 5) and partial melting (0.07 km/s for each percent of melt) (Table).

The calculation results compared with experimental data are in Fig. 6.

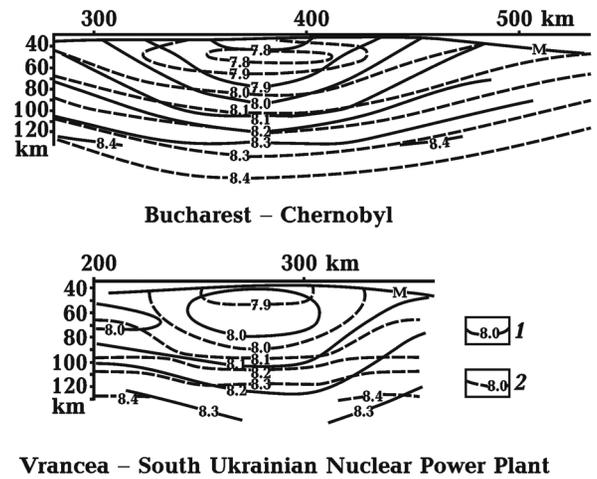


Fig. 6. Comparison of experimental (1) and calculated (2) distributions of longitudinal seismic wave velocity in the mantle beneath heat flow anomalies in the areas of Bucharest—Chornobyl and Vrancea—South Ukrainian NPP profiles.

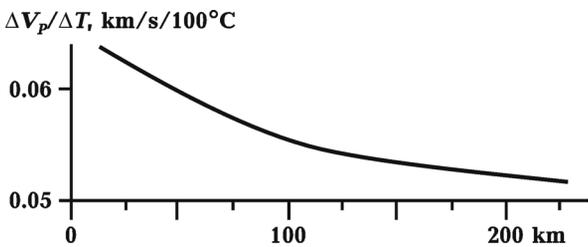


Fig. 5. Dependence of seismic wave velocity in mantle rocks on temperature at different depths.

The average difference between the experimental and calculated velocities is 0.06—0.07 km/s. This is three times less than that obtained, for example, when comparing the velocity values on two intersecting Deep Seismic Sounding, profiles in Ukraine. Thus, the agreement between the adopted thermal model of the upper tectonosphere and the independently obtained velocity model is almost complete.

Parameters of the upper mantle material

Depth, km	Platform temperature, °C	Solidus temperature, °C	Thermal reduction V_{P1} , km/s/100 °C	Platform V_{P1} , km/s
25	300	600	0.067	6.5
50	520	1200	0.062	8.15
75	730	1290	0.058	8.22
100	940	1370	0.055	8.30
150	1220	1510	0.053	8.37

Electrical conductivity anomalies in the crust and upper mantle. In Moldova, geoelectric MTS studies did not record significant objects of high electrical conductivity deeper than the sedimentary layer [Burakhovich et al., 1997]. Within Moldova, such work was limited and done by employees of the Institute of Geophysics of the National Academy of Sciences of Ukraine. However, in Ukraine close to the border, the observation network was fairly dense and the research was done by employees of the Institute and industrial organizations [Burakhovich et al., 1997; Gordienko et al., 2012, etc.]. Thus, the layout of the identified conductive objects in the northern part also includes the results of such «border» models (Fig. 7).

The duration of field change records at observation points allowed us to record variations with periods of up to 1600 and 3600 seconds, as observed by the industrial organizations and the Institute o, respectively. Such data are sufficient to construct models of resistivity distribution to depths of approximately 50–60 km.

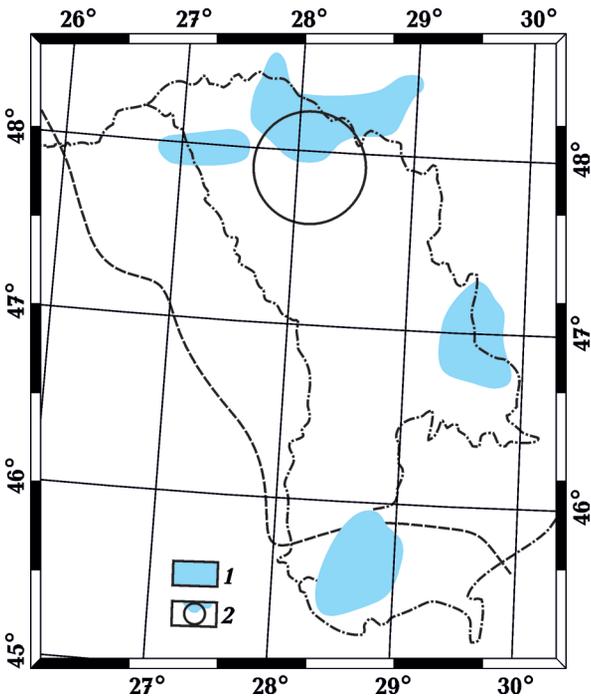


Fig. 7. Conductive objects: 1 — based on two-dimensional and quasi-three-dimensional modeling, 2 — based on observations along the Bucharest—Chornobyl profile.

In the studied region, a distribution scheme of the summary longitudinal conductivity of the sedimentary layer was constructed based on its thickness and rock properties. Typically, in the northern part of the region, values range from several tens to the first hundreds of Siemens. In the southern part, they are noticeably larger, reaching 500–700 Sm on the Scythian Plate. This information was used for modelling.

A two-dimensional model along the latitudinal profile and a quasi-three-dimensional model were drawn up for the southern part. A zone of increased electrical conductivity was found in the depth range from the middle crust to the depth of reliable interpretation (60 km). Resistance ranges from several to the first tens of Ohm·m. The object's location is in good agreement with the sources of the Izmail HF anomaly (see Figs. 2 and 3).

In the northern part of the region, quasi-3D modeling [Kovachikova et al., 2016] found conductive zones at depths of 10–20 km. Their existence in the area of the Beltsy anomaly (most likely at a depth of 20 km) seems highly probable. Partial melting of amphibolite facies metamorphic rocks at a temperature of approximately 600 °C is entirely possible here (see Fig. 3). More definitive results were obtained using MTS data along the Bucharest—Chornobyl profile [Burakhovich et al., 1997] (Fig. 8).

Modelling the object as approximately isometric, we project it onto the surface shown in Fig. 7. It is evident that it is in good agreement with the Beltsy HF anomaly.

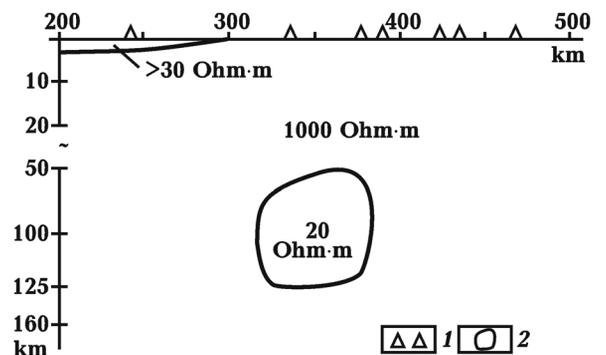


Fig. 8. High-conductivity object in the mantle beneath the Moldavian plate: 1 — MTS points, 2 — low-resistivity object.

Calculations show that heating rocks by hundreds of °C in an environment with a background specific electrical resistance of 1000 Ohm·m will lead to a reduction to the first hundreds of Ohm·m. The determining factor in the appearance of high-conductivity zones (with specific electrical resistance of units to tens of Ohm·m) is often precisely the partial melting of rocks. In this case, it seems highly probable: directly at the Beltsy and Izmail anomalies, thermal models include layers of melt in the crust and mantle, and high HF values are widespread. Parts of the conductive crustal objects near the Beltsy anomaly occur outside the 60 mW/m² HF field. However, the level of detail in studying the heat flow here is limited, and it is possible to miss the anomaly. In addition, there are known situations (for example, in the Dnieper-Donets Basin [Gordienko et al., 2006, 2024, etc.]) where the signs of RA are obvious, conductors are present in the crust, and the heat flow does not differ from the background. This is due to the youth of the crustal heat sources, the heating from which has not yet reached the depths of temperature measurements in wells.

In local anomalies near permeable faults, heating is evident at relatively shallow depths. The nature of the conductive object installed at latitude 47° is unclear. There is too little information here for a detailed analysis. Most likely, its nature is not thermal.

Conclusions. The analysis of geological and geophysical data of the eastern part of the region (outside the Alpine geosyncline of the Carpathians in Romania) allowed us to consider in comparative detail the course of three stages of heat and mass transfer during the modern activation on the Precambrian Platform and the margin of the Scythian Plate. Changes in the physical properties of crust and upper mantle rocks, as well as associated

anomalies in physical fields, were established. It was possible to demonstrate that the models of physical properties' distribution constructed in accordance with the geological theory are quantitatively consistent with independently established environmental parameters and anomalies of physical fields.

1. The background experimental values of the Earth's heat flow are consistent with the calculated (amounting to about 50—55 mW/m²). Most of the HF values over 60 mW/m² occur within the Beltsy and Izmail anomalies. The intensity and shape of these field disturbances are explained with satisfactory accuracy by the calculation results. The differences from the experimental data do not exceed 7—8 mW/m².

2. The distribution of deep temperatures in the upper mantle horizons beneath the heat flow anomalies, constructed using the model of heat and mass transfer in the tectonosphere of the zone of recent activation, recalculated into the distribution of longitudinal seismic wave velocity, agrees with the experimental seismological data with high accuracy (the average discrepancies are 0.06—0.07 km/s).

3. The territorial coincidence of high conductivity objects with partial melting zones beneath the heat flow anomalies definitely supports the adopted scheme of the deep process. The result is currently at a qualitative level; several issues related to the interpretation of experimental data and the dependence of the specific electrical resistance on the state of the rocks still need to be resolved to move to matching characteristics quantitatively.

In general, we can assume that the first part of the work has significantly developed the ideas about the recent activation of the platform.

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Прояви сучасної активізації на південно-західній Україні та сусідніх територіях Молдови та Румунії. Ч. 1

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Наведено відомості про історію досліджень ендегенного режиму сучасної активізації та стан вивченості проблеми на сьогодні. Констатовано широкий діапазон наявних думок про форми її проявів і труднощі виявлення схем відповідних глибинних процесів. На території південно-західної частини України та сусідніх районів Молдови та Румунії є можливість визначити вік і характер геологічних явищ, які можна ототожнювати з елементами сучасної активізації. Вони різні для платформної частини регіону та Карпат. У першому випадку відомі молоді вертикальні рухи аномальної швидкості у пліоцені—плейстоцені. У другому — унікальна концентрація землетрусів

на мантийних глибинах (зона Вранча), що утворюють вертикальну фокальну структуру. Розгляду результатів дослідження цих двох районів і присвячено дві статті. Тепловий потік на платформній частині регіону та області Скіфської плити представлений фоном у $50\text{--}55\text{ мВт/м}^2$ і двома аномаліями інтенсивністю до $80\text{--}85\text{ мВт/м}^2$. Обидва значення і форми аномалій відповідають розрахунковим параметрам глибинного процесу сучасної активізації. Різні прояви пов'язані з наявними під аномаліями корових вторгнень частково розплавлених мантийних порід віком $2\text{--}5$ млн років. Побудовані під аномаліями теплові моделі дають змогу з достатньою точністю пояснити розподіл швидкості поширення сейсмічних хвиль. Вдається діагностувати навіть окремі частини глибинного перегрітого матеріалу, винесеного під кору. Теплові моделі дають змогу пояснити значний підйом поверхні в період активізації, утворення розломів і сейсмічність. Дані по об'єктах високої електропровідності також територіально узгоджуються з аномаліями теплового потоку і знаходяться на глибинах, що відповідають інтервалам значного перегріву і часткового плавлення.

Ключові слова: сучасна активізація, аномалії теплового потоку, швидкості P -хвиль, об'єкти високої електропровідності.