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THE ORIGIN OF THE LOW DENSITY ZONES IN THE CRYSTALLINE CRUST OF THE TRANSCARPATHIAN DEPRESSION (UKRAINE) FROM PETROPHYSICAL THERMOBARIC MODELLING

Purpose. Based on laboratory *PT*-studies of rocks and their joint analysis with the data from the regional profile RP-17, the aim of this research is to reveal the origin of the low-velocity zones in the Transcarpathian depression as zones of thermobaric rock decompaction and to elucidate the relationship of these zones with earthquakes and hydrocarbon fields. **Methodology.** The essence of such an approach is the comparison of the DSS information with experimental data on the physical parameters of rocks at high pressures and temperatures. For this purpose, we used the results e from high *PT* measurements of physical parameters on rocks analogous to those from the region under study. **Results**. Having analyzed the findings of the laboratory *PT*-experiments, we developed the method of petrophysical thermobaric modelling. This method is based on the characteristics of the "granitoid" type rocks from the Ukrainian Shield and the results of the joint interpretation of these data and information on the regional deep seismic sounding profiles from this tectonic unit. These approaches and techniques were applied to the analysis of the data from Transcarpathia, in particular, to the RP-17 regional profile. Two decompaction zones of the thermobaric origin were revealed along the profile coinciding with low seismic velocity zones. They are supposed to be effective regional traps for the mantle fluids, especially for hydrocarbons which under high pressure, temperature, and decompression penetrate into the near-surface layers of the sedimentary cover and form mineral deposits. In the decompaction zones shallow earthquakes with low magnitudes become activated. They widen the decomposition domains and facilitate the movement of deep hydrocarbons to the location within them. **Originality.** For the first time, it was shown that low velocity zones (the region of thermobaric decompaction of mineral matter) under certain pressure and temperature in the Earth's crust of "thermoactive" region, including Transcarpathia, are its integral part; they are inevitably formed in the process of warming up of the Earth's interior during its "thermoactivation". Horizons of thermobaric decompression of rocks, which under the influence of stresses, multidirectional deformations, and vibrations, acquire the properties of strongly dislocated media forming extensive migration channels of fluids, "degassing pipes". They provide the movement of useful mineral media to the surface and the zones of intense relaxation of tectonic stresses, especially in the form of earthquakes. **Practical significance.** The results of the studies give an opportunity to clarify the geological and structural features of the structure of the Earth's crust of Transcarpathia, to adequately interpret the spatial distribution of geophysical fields and to decipher the features of local geodynamics and seismotectonic process, to clarify the level and nature of geo-ecological hazards, to more effectively predict and study deep regional distribution of mineral resources.

Key words: the Transcarpathian depression (Ukraine), low seismic velocity and density zones, petrophysical thermobaric modelling, thermobaric hydrocarbon traps, shallow earthquakes.

Introduction

One of the goals of the interdisciplinary interpretation of geophysical data is the development of a coherent model for the Earth's lithosphere when calculated wave and gravity fields fit those observed.

The petrophysical thermobaric modelling (PTBM) of the crystalline crust on the Ukrainian Shield (USh) demonstrated that characteristics of low velocity zones (LVZs) depend slightly on mineral composition of rocks at relevant depths. They are mainly related to the geothermal regimes of the crystalline crust in study areas [Burtnyi et al., 2013; Korchin et al., 2013; Korchin, 2017]. Being large-scale systems of transcrustal deep distortions, zones of low elastic properties and densities are the most permeable for ascending hydrothermal solutions and fluids of the mantle origin during the activation of tectono-magmatic processes accompanied with intensive heat flow (HF). Different processes of metasomatosis, formation, and localization of mineral resources (e.g. hydrocarbons) most likely occur in these zones. A satisfactory coincidence was obtained between the position of LVZs (decompaction zones) and mineral deposits in the Kirovograd ore region of the USh, on the NW Black Sea shelf, in certain areas of the Caspian Sea [Burtnyi et al., 2013; Korchin, 2017; Korchin, Rusakov, 2019; Korchin et al., 2013; Rusakov, Korchin, 2015]. It follows that LVZs of the thermobaric nature serve as the diagnostic indicator of deep mineral deposits.

The LVZs are also domains of intensive relaxation of stresses of tectonically-active processes due to weakened elastic properties of their rocks. Here is the action of mechanisms for dilatancy destruction of the mineral environment at certain depths of the crystalline crust. Thermobaric LVZs (area of the lowered elasticity, density and increased porosity of rocks) are the trigger mechanism for the origin of earthquakes and faults of different orientation in the Earth's crust that is confirmed by the greatest number of focuses of crustal earthquakes in the LVZs [Korchin, 2018].

Purpose

The situation described above is characteristic of the Transcarpathian depression (TD) of Ukraine. The investigation is based on the experience of the laboratory *PT*-studies of the velocity, density, and other parameters of the wide range of rocks from the USh and the results of the joint analysis and seismic data from the regional profile RP-17. So, the purpose of this research is to corroborate the occurrence and origin of the LVZs in the crust of the TD (in particular, along the RP-17 regional profile) as the zones of thermobaric decompaction of rocks and elucidate the relationship between these zones and earthquakes and hydrocarbon fields. To achieve this, we applied the approaches and techniques which were realized for the USh.

Methodology

Influence of *PT*-regimes on the elastic characteristics of rocks

We conducted long-term investigations of the experimental changes in velocities and densities with depth for rocks under *PT* conditions relevant to specific regions and at specific depths. The study established the occurrence of the velocity inversion of elastic longitudinal waves (V_P) and density (ρ) at different depths (H). With increasing depth (that is, with increasing pressure (P) and temperature (T) affecting the specimen of the rock), after some initial increase in V_P and ρ, their decrease is observed. Then the velocities and densities increase again (Fig. 1, *a*).

Thus, low velocity zones are manifested on the $V_P=f(PT)=f(H)$ curves whose configuration and location correlate well with elastic anomalies registered by deep seismic sounding (DSS) information from the Earth's crust at depths of 3-25 km. The changes of $V_P=f(H)$ can also be obtained from measuring the isobars of velocities ($V_P=f(T)$ at $P=const$) and their isotherms ($V_P=f(P)$ at $T=const$) (Fig. 1, b).

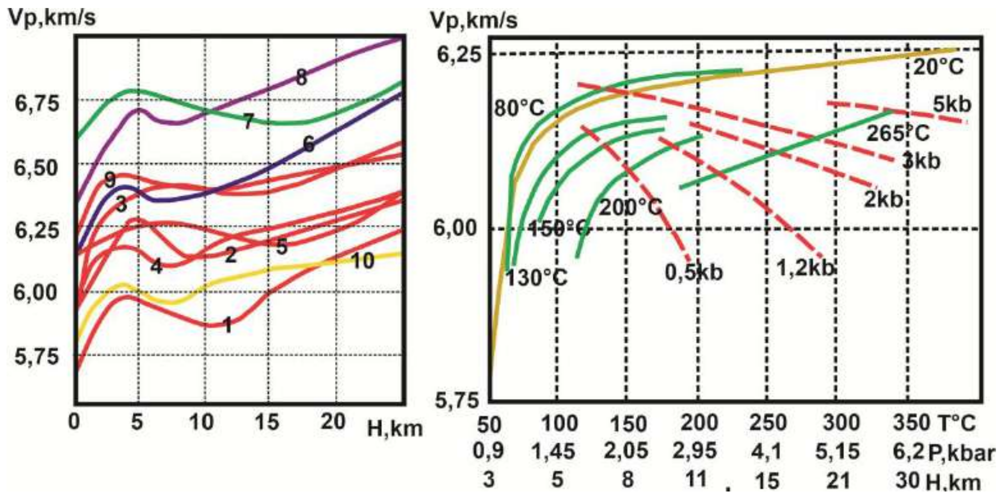
Detailed studies showed that both methods of determining $V_P=f(H)$ plots give identical results [Korchin, 2013a]. Regardless of the methods of determining velocities using several *PT* programs or calculating the isobars and isotherms there is a threshold value of changes of the temperature with depth $(\partial T/\partial H)$ when the anomalous elastic state of mineral matter arises – LVZs.

The changes of velocity of elastic waves with depth (V_P) in the rock of constant mineral composition can be calculated by the ratio of

$$\frac{\partial V}{\partial H}=\left(\frac{\partial V}{\partial P}\right)_T\cdot\frac{\partial P}{\partial H}+\left(\frac{\partial V}{\partial T}\right)_P\cdot\frac{\partial T}{\partial H}.$$

The LVZs in the Earth's crust are determined by the assumption of $(\partial V/\partial H)<0$. As far as $(\partial V/\partial P)_T$ $(\partial P/\partial H)_P$ $(\partial T/\partial H)$ are positive, $(\partial V/\partial T)_P<0$, then to form a zone it is necessary to fulfil the assumption for absolute values:

$$\left|\left(\frac{\partial V}{\partial P}\right)_T\cdot\frac{\partial P}{\partial H}\right|<\left|\left(\frac{\partial V}{\partial T}\right)_P\cdot\frac{\partial T}{\partial H}\right| \quad (1)$$



a b

Fig. 1. Changes of the $V_P=f(PT)$ relationship with depth (a) and isobars and isotherms of change in the velocity of V_P of granite (b):

1 – evenly granular granites; 2 – porphyroid granites; 3 – rapakivi granites; 4 – plagiogranites; 5 – trachytoid granites; 6 – intermediate rocks; 7 – basic rocks; 8 – ultra basic rocks; 9 – charnockites-enderbites; 10 – gneisses.

In most cases, the change of the lithostatic pressure with the depth can be considered as a constant number. Therefore, $(\partial P / \partial H)$ is 0.24–0.32 kbar/km at depths from 3 to 40 km for ancient shields. The temperature gradient at these depths varies within the wide range (from 5 to 25 °C/km) [Korchin et. al., 2013; Kutas, 1978]. The relative increase of velocities with pressure under room temperature is characterized by two intervals: P=(0÷2) kbar is the interval of maximum increase of velocity, P>2 kbar where the minimum velocity gradient is observed. As a rule, the velocity change with temperature under atmospheric pressure has three intervals: T<80÷100ºC (minimal changes), T≈80÷250 ºC (maximal changes).

Further heating within the interval of T=250÷600 ºC results in the small decrease of the velocity. The relative changes of velocity under compensating constant pressure (isobars) and constant external temperature (isotherms) are different in absolute values. Within the interval of 20÷70 ºC under P<0.7 kbar the changes of velocity with temperature are negligible, i.e. up to a depth of 2÷3 km the velocities always increase intensively. It is caused by the growth of V_P with pressure due to induration of rocks. The interval T=100÷250 ºC is the interval of the most intensive changes of V_P=$f(T)$. Here decrease of velocity by two times is possible because of temperature influence under atmospheric pressure and by about 10–20 % under compensating pressure of P≈1÷4 kbar. It is in this interval of pressures and temperatures (P≈1.2÷3.5 kbar; T≈110÷250 ºC) that the greatest negative changes of velocity of the elastic waves are observed and zones of low velocities (LVZs) are revealed. The experiments found $(\partial V / \partial T)_P$=-2.7±0.5 ($P$≈0.5 kbar); -0.7±0.3 ($P$=2 kbar); -0.33±0.1 m/s·ºC (P=5 kbar) and V_P from pressure under different constant temperatures $(\partial V / \partial P)_T$=0.8±0.3 (pressure interval 0÷2 kbar, temperature 20÷80 ºC); 0.01±0.005 (under P≈2÷5 kbar, T≈20÷80 ºC); 0.04±0.01 (under P≈2÷5 kbar, T≈265 ºC). Based on these data and experiments under the low and high-temperature regimes and calculations, it was revealed that under low-temperature ($(\partial T / \partial H)$<9–11 °C/km) the zones of the velocity inversion are not reflected on the curves of V_P=$f(PT)$=$f(H)$. In this case, the condition of (1) is not executed. If the temperature gradient is equal to $(\partial T / \partial H)$<15–20 °C/km in the pressure interval of 1.8÷3.5 kbar, the relationships of V_P=$f(PT)$ clearly revealed LVZs. The decrease in the velocities of different samples varies from 10 to 250 m/s in these zones.

Similar calculations were also performed according to experimental studies of rocks in various thermodynamic conditions of experiments performed by other authors [Christensen, 1989; Christensen et. al., 1995; Kern, 1978]. However, these data can be used for modelling only at depths more than 10–15 km.

Influence of pressure and temperature on rocks density

The comprehensive experiments on rocks and minerals under different PT-conditions disclosed an increase in relative deformation of grains and their twinning in the LVZs (5–15 km depth). The density of rocks increases inside the blocks of dislocations and decreases on intergrain boundaries. The defects of minerals packing increase. The intergrain boundaries expand due to their mylonitization, the amount of main micro fissures increases. There is depressurizing or opening of the gas-liquid inclusions in minerals in heating because of excess inner pressure. Moreover, the rocks are characterized by the lowered density (Fig. 2) [Korchin, 2013, *a, b*; 2018]. Information on changes density vs. depth was obtained from studies of the volume decrement under PT-experiments and the ultrasonic determinations of the compressibility of the rocks.

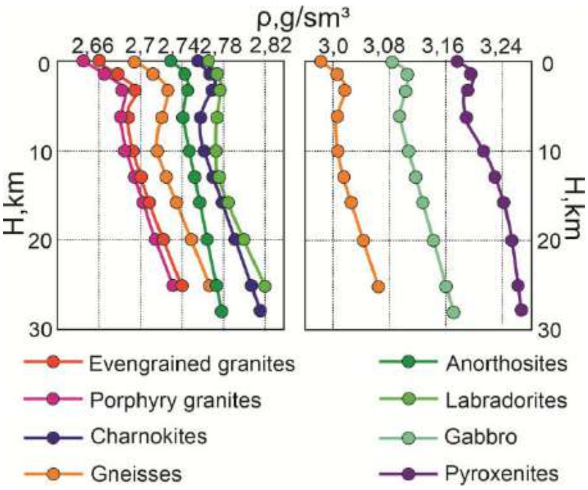


Fig. 2. Plots of ρ=$f(PT)$=$f(H)$ for some rocks.

The density characteristics of the rocks nonlinearly change with depth similarly to the elastic parameters. The ρ=$f(PT)$=$f(H)$ relationships demonstrate maximums and minimums. It implies that deep simultaneous influence of P and T on mineral matter results in the formation of zones of density inversion. This mechanism for the origin of the LVZ is corroborated by studies of rock density under programming influence of P and T. As it was expected, under PT relevant to the LVZs density also decreases. The values of $\partial\rho/\partial H$ sometimes are negative reflecting a considerable density decrease of rocks that creates zones of low density in the crust. Under thermodynamics conditions at 5–15 km depth the gradient of the density increment falls to zero or becomes negative (Fig. 2). The additional experiments show that the LVZs depend weakly on a mineral composition of the crust matter. Obviously, the structural transformations and chemical composition play a key role in the variations of rock density.

The low density is very sensitive to the temperature conditions of the Earth's crust similarly to the LVZs. Increasing deep HF decreases rock density, activates capability to decrease the rock density and increase their permeability and hygroscopicity (activates a process of fluid movement) that, for example, causes metamorphic transformation of rocks. In other words, these LVZs are to be the most active horizons of present-day geological-geophysical transformations of the crystalline crust mineral environment [Korchin, 2013a, b, 2017; Korchin et. al., 2013, 2018a].

A multidisciplinary analysis of DSS data, geothermal and petro- structural modelling showed that the crystal domains of higher temperature gradients are distinguished by more complex character of variations in seismic velocity with depth. Here intensive LVZs occur [Burtnyi et al., 2013; Korchin et al., 2013; Korchin, 2017]. In "colder" crystal domains the thickness of the LVZs is negligible or zones are absent at all.

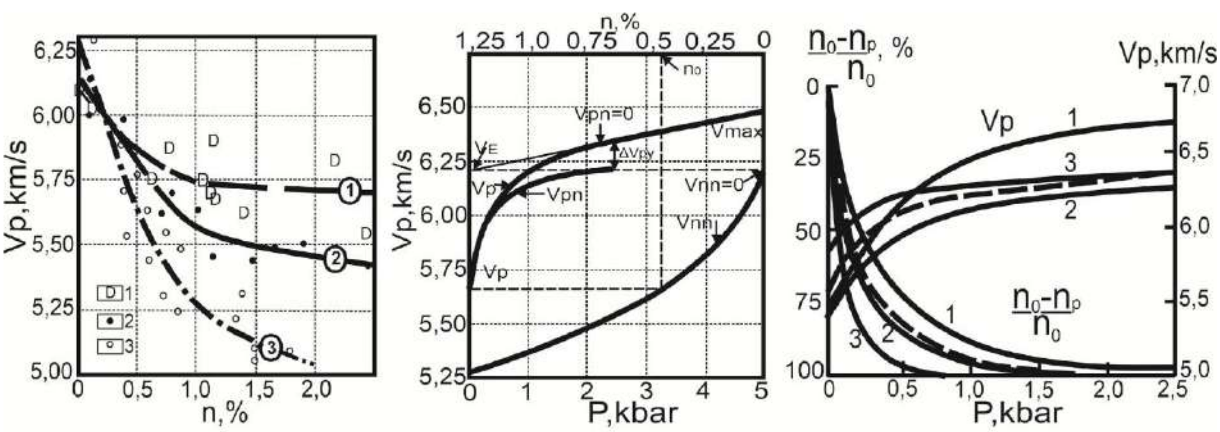
In addition, we confirmed that the variations in the mineral composition of the rocks at depths of 5–20 km influence negligibly on the position of LVZs and their intensity.

The LVZs in the crystalline crust as zones of increased porosity of mineral matter and active transformations of gas-liquid inclusions

The physical parameters of different types of crystalline (igneous and metamorphic) rocks are mainly controlled by the composition and structural-textural peculiarities of mineral material although a jointing and porosity (n) of the rocks, the state of intergrain boundaries also influence these characteristics. The occurrence of different types of pores and fissures is governed by the conditions of their formation and subsequent processes of transformations. Porosity in the crystalline rocks became the subject of the intensive studies due to examining migration of gas-liquid flows, particularly hydrocarbons, at different depths in the lithosphere [Geguzin, Krivoglaz, 1971; Korchin, 2013a,b; 2017; Tripolsky, Sharov, 2004]. Based on the studies of the relationship between porosity and velocity under high PT in the granite samples from the USh, it became possible to characterize more clearly changing porosity and jointing vs. PT environments at different depths. The study also explains some crustal decompaction anomalies of rocks which, in turn, can act as migration pathway for hydrocarbons of the mantle origin. Under atmospheric pressure the clear nonlinear relationship is revealed between the velocity and porosity for 3 groups of the granites which differ in a grain size of rock-forming minerals. The gradients of changing $V_P/f(n)$ increase with increasing the size of grains (Fig. 3).

The porosity and structural-textural peculiarities are principal factors which cause the change in the velocity of elastic waves under 3–5 kbar pressure in the samples of the same mineral composition (Fig. 3, *a*).

The gradients of the change in V_P=$f(P)$ are steeper for granites with larger grains size in the rock-forming minerals. The velocity of the almost "poreless" granites is in good agreement with extrapolated linear segments of the V_P=$f(P)$ plot to the cross with ordinate the (V_E) (Fig. 3, *b*). The curvilinear segments of the V_P=$f(P)$ plots reflect the increase in the velocity mainly due to closing different types of pores and micro fissures (V_{Pn}) as well as to the change in the elastic properties of the rock-forming minerals (V_{nn}=0).



a *b* *c*

Fig. 3. Changes in velocity and pore space with pressure in granites:

a – Change of V_P=$f(n)$ for granites: 1 – fine-grained, 2 – medium- grained, 3 – coarse-grained; b – change of mean values velocity of longitudinal waves for the medium-grained granites vs. pressure (V_P=$f(P)$) and porosity (V_{Pn}=$f(n)$); c –relative change of pore space under the increase of pressure in granites: 1 – fine-grained, 2 – medium-grained, 3 – coarse-grained.

The $\frac{n_0 - n_P}{n_0} = \frac{\Delta n}{n_0} = f(P)$ plots (Fig. 3) characterize the relative change in the pore space (in %) vs. pressure in the granites, where $n = n_0\left(1 - \sqrt{\frac{V_P - DP - V_0}{V_e - V_0}}\right)$, D is the relative change in the velocity vs. pressure plot on the linear segment due to the elastic deformation of the rock-forming minerals (Fig. 3, *c*). Decreasing the velocity of the elastic waves and changing in the density suggests that porosity increases by 10–20 % in the LVZs at a depth of 4–15 km in a comparison with that at the 3–5 km depth (horizons of maximum elastic parameters above the LVZs). Intensive processes of mass and gas-liquid transfer, including deep hydrocarbons, seem to be the most intensive in the zones of decreased porosity (LVZs) [Korchin, 2013a, b; Reider, 1987].

Based on the foregoing, graphical presentations and theoretical calculations demonstrate that the rock porosity decreases by 30–50 % at a 3–5 km depth (Fig. 4).

A comparison of experimental data and geophysical observations

The DSS studies revealed anomalies of elastic behaviour of mineral matter in the form of LVZs (Fig. 1, *a*). They were also registered during the laboratory experiments on the rock samples simulating thermobaric parameters relevant to 3–25 km depths. A comparison of interdisciplinary experimental and field data allows us to put forward several ideas on the physical nature of elastic zoning mineral matter in the upper layers of the crystalline crust [Burtnyi et. al., 2013; Korchin, 2013a; Korchin et. al., 2013].

Model and natural processes or phenomena are considered to be similar if their determining criteria are numerically equal. The theory of dimension and similarity makes it possible to use effective methods of selecting necessary relationships [Korchin, 2013a].

The criteria of similarity (C) are dimensionless quantities which characterize the given phenomenon or process. The similarity analysis was applied to select the dimensionless quantities which mostly control the velocity of the elastic wave in mineral matter. As the velocity mostly reflects the physical state of matter under different thermobaric conditions, it functionally depends on pressure (P), temperature (T), density (ρ), volume (U), specific heat capacity (C_{ou}), and the Poisson coefficient (σ)

$$V = f(P, T, \rho, U, C_{ou}, \sigma) \qquad (2)$$

As objects under study have finite dimensions and are subjected to changing *PT* environments, it is reasonable to consider depending V on changing *PT*-regimes with a depth. Substituting T and P by their gradients (*grad T* and *grad P*), we shall get the following dimensions: $[V]$=m·s^{-1}; [*grad P*]=kg·m^{-2}s^{-2}; [*grad T*]=°C·m^{-1}; [ρ]=kg·m^{-3}; [U]=m^3; [z]=m; [C_{ou}]=m^2·s^{-2} (ºC)$^{-1}$; [σ] – dimensionless.

Solving the matrix of their dimensions we shall obtain the following criteria of similarity:

$$C_1 = \frac{gradP \cdot z}{V^2 \cdot \rho} \qquad (3)$$

$$C_2 = \frac{gradT \cdot z \cdot C_{ou}}{V^2} \qquad (4)$$

The first (C_1) characterizes the influence of pressure on the velocity of the elastic wave of the object of study within a boundary thickness of z, the second (C_2) characterizes the influence of temperature. Consequently, if a model (m) and its natural (n) affinity consist of the same matter and $\rho_m = \rho_n$ and $C_{oum} = C_{oun}$, equality of the velocity in the model and natural settings will occur in satisfying the following condition:

$$gradP \cdot z = inv, \qquad gradT \cdot z = inv, \qquad (5)$$

where inv is invariant.

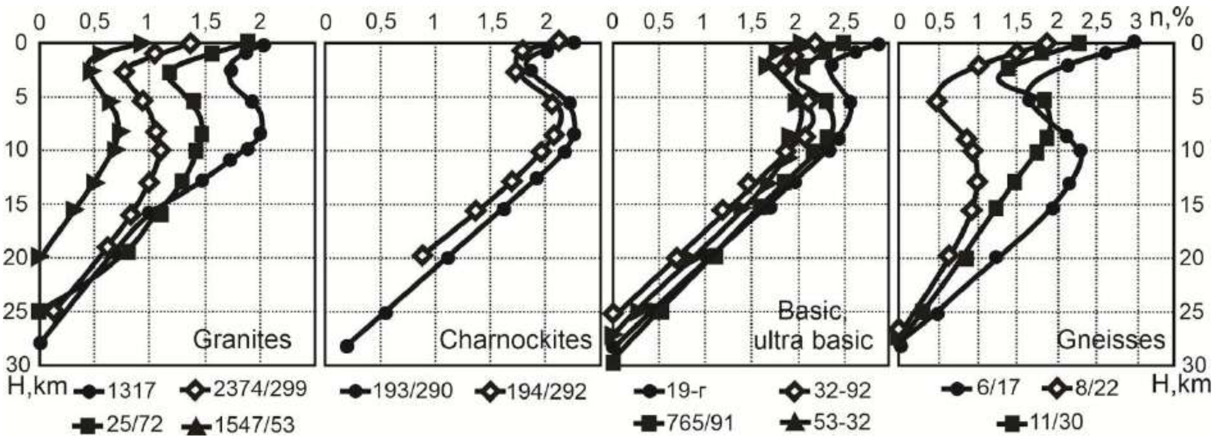


Fig. 4. Change in porosity of the crystalline rocks under thermodynamic conditions at the different depths

Based on these criteria of similarity, equality of mean values of P and T in the model and natural environments is enough to compare the velocity in these both settings. It implies that the V_P/V_S ratio (C_3) must be constant. The mean value of this ratio for the Earth's crust is 1.77 while its laboratory mean value is 1.8±0.1 with 0.95 confidence interval [Korchin et. al., 2006]. It follows that the C_3 criterion is the invariant number, e.g., it is numerically equal in nature and models. Therefore, the velocity of elastic waves in the relevant model must not differ from that in natural conditions. Accordingly, the scale coefficients can be taken to be equal to 1. The equations of the relationships between V_P, X_I, P and T from experiments are invariant and can be applied without changes in simulating natural environments at different depths. Generally, the essence of the petrovelocity thermobaric modelling is the comparability of elastic wave velocity in the lithosphere from DSS method and experimental measurements of this parameter under high PT regimes pressures [Butrny et. al., 2013; Korchin, 2013a; Korchin et. al., 2013]. From this follows that the LVZs at 3–25 km depth are most likely to be of thermobaric origin.

The dynamics of the LVZs in the crystalline crust

We experimentally confirmed the strong relationship between heat conductivity of rocks under different PT-conditions and their elastic properties [Korchin, 2013a,b, 2017; Korchin et. al., 2013].

If one supposes that in a mineral matter the heat transfer is mainly realized by the background thermal conductivity, then its value can be estimated using the simple equations of the Debye theory [Alers, 1968; Korchin, 2013a; Korchin et. al., 2013]. As a result of simple transformations, the equation of background thermal conductivity was obtained:

$$\lambda_f = \frac{1}{3} C_{ou}\rho V_f l_f = \frac{\delta_0 \beta V_{mid} \rho^{-1/3}}{a_0 \gamma^2 \mu^{2/3}} \cdot \frac{\theta}{T} \approx A \cdot V_m \frac{\theta}{T} \qquad (6)$$

Where C_{ou} – specific heat, ρ – density; $V_f = V_m$ – the average velocity of phonons which is equal to the average elastic velocity ($\left(1/V_P^3 + 2/V_S^3\right)^{-1/3}$); l_f – the average length of the free motion of the phonons; δ_0 – the average constant of the lattice; β – compressibility; μ – the average molecular weight; γ – the Gruneizen parameter ($\gamma = \frac{dLn\theta}{dLn\rho}$); T – temperature, θ – the Debye temperature, A –the constant coefficient, including constant parameters independent on the PT-conditions.

This equation implies that the change in thermal conductivity in the Earth's crust in some interval of depths is directly proportional to the change in the elastic-density characteristics of the mineral matter and inversely proportional to temperature. The calculations and experimental studies of $V_P=f(PT)$, $\lambda=f(PT)$ [Korchin, 2013a,b] founded that thermal conductivity of the rocks in the Earth's crust changes similarly to $V_P=f(H)$. The plot of $\lambda=f(H)$ demonstrates minimum values coinciding with the locations of the LVZs. Thus, the LVZs in the Earth's crust are characterized by lowering values of λ and are the reflecting horizon for heat flow whose sources are deep thermally active processes.

According to the classic laws of thermodynamics and thermophysics [Korchin, 2013b; Kutas, 1978; Nashchekin, 1969], a layer of low heat conductivity on the way of distribution of thermal energy results in the increase in temperature on the bottom of a layer and on its roof (Fig. 5, *a*).

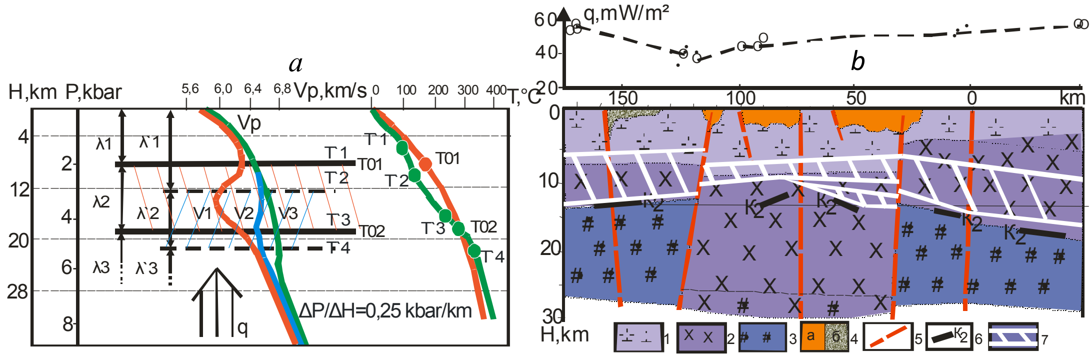


Fig. 5. The change in the parameters of the LVZs vs. deep heat flow (a) and the fragment of the schematic cross-section of the Earth's crust along the IV geotraverse (b):

1 – plagiogranites; 2 – diorites, enderberites; 4 – sedimentary-volcanogenic rocks of greenstone features (a) and Kirovograd-Zhytomyrsky complex (b); 5 – fault zones; 6 – K_2 boundary; 7 – LVZ; q – values of HF.

This process violates PT-equilibration in the LVZ. The decreasing temperature in the upper domain violates the thermobaric condition (1). The state of the rocks in the upper layer equilibrates with that of the overlying rocks and the upper boundary of the zone descends (Fig. 5, *a*). The T_{01} border descends on the T'_2 boundary. At the same time, there occurs overheating the zone bottom in the lower part of underlying rocks. This effect is proportional to the difference of the thermal conductivity of the mineral environment in the zone. In turn, this process results in violation of the condition (1) and the lower boundary of the zone descends on the T'_4 boundary. Higher pressure ceases the growth of the zone due to the compensating effect of structural distortions under pressure. Thus, the zone modifies the configuration: its thickness can be increased due to the increase of intensity of deep HF or the zone can disappear in case of lowering it. Such an instability of the thermodynamics of the LVZs causes their episodic occurrence in the Earth's crust as well as their vertical and horizontal migration depending on the temperature variations in the deep horizons of the Earth [Korchin, 2013a,b, 2017; Korchin et. al., 2013; Tripolsky and Sharov, 2004].

In the crystalline crust, rocks are subject to compression, heating up, various structural and sometimes material transformations resulting from the action of pressures and temperatures. Heating causes an increase in rocks volume. The coefficient of volumetric thermal expansion of rocks: $2\cdot10^{-6}$–$4\cdot10^{-4}K^{-1}$; the average $3\cdot10^{-5}$ K^{-1}. When the rocks are heated to 300 °C, we observe an increase in the volume of mineral matter by 1–1.5 % and a corresponding decrease in density [Burtny et. al., 2013; Korchin, 2013a, 2018; Korchin et. al., 2018a,b]. The action of high pressure, as a rule, leads to compression of the substance, the value of which is determined by compressibility or the coefficient of comprehensive contraction. At a depth of 5–10 km, the pressure of P=2.5–3.0 kbar can increase the crystalline rock densities by no more than ~0.5 %. Thus, thermodynamic forces that facilitate the development of local high microstresses will predominate at depths from 3 to 10 km, causing volumetric destruction of structural integrity of the rocks, that results in the formation of deconsolidation of the Earth's crust mineral matter at these depths [Korchin, 2013a, 2018; Korchin et. al., 2018a,b]. In this PT interval in the crystalline rocks, a substance decomposes due to the internal multi-oriented stresses, which in local mineral contacts reach values exceeding the strength of individual minerals. This results in a fragile microdestruction of the environment. The number of main microcracks increases (loosening). At the same time, the migration of free liquid and gas through microdisruption of minerals and inter-grain contacts activates in the intergranular space, destroying the rock and forming secondary pores and cavities in it. This is a key process for the movement of deep fluids through rocks in the LVZs under natural conditions. In the LVZs, an increase in porosity is observed by 10–25 % compared with values at depths of overlying layers (Fig. 4) [Korchin, 2013a; 2017].

Several distinct LVZs were revealed in the crust of the USh from the DSS data. The PTBM for the parameters of these zones [Burtnyi et. al., 2013; Korchin, 2013a, b, 2017] (Fig. 5, b), as it was mentioned above, demonstrated that their characteristics depend slightly on mineral composition of rocks at relevant depths and are mainly related to the geothermal conditions at relevant depths. Depending on the total HF value, the temperatures vary in the lithosphere and, consequently, the physical properties of its rocks change.

Correspondingly, at a depth of 25 km the followings dependences are calculated for T vs. HF: T=250 ºC, q=30 mW/m^2; T≈300 ºC, q=40; T≈500 ºC, q=60 mW/m^2. As HF in the study area of USh varies from 30 to 55 mW/m^2 (Fig. 6), different blocks have different depth temperature gradients, and they are characterized by different configurations of the LVZs. Indeed, the model (Fig. 5, *b*) demonstrates that the LVZ is registered more clearly and confidently in the western and eastern areas, where q≈50÷60 mW/m^2, and T_{25}=350÷425 ºC ($\partial T/\partial H$≈14÷17 ºC/km). In the central block (110–70 km) where q≈35÷45 mW/m^2, and T=270÷305 ºC, ($\partial T/\partial H$<12 ºC/km) the LVZs are less expressed, have a small thickness, form separate lenses rather than homogeneous horizon.

Due to lower q and heterogeneity of the thermal field, the two areas of low velocities can be distinguished in the central block (75–30 km): the first – at a depth of 6–9 km in granites (ΔV≈0.15 km/s) and the second – at 10–12 km depth in diorites (ΔV=0.03 km/s).

The seismic K_2 boundary seems to be thermobaric in origin which results from the intensive increase in V_P above the LVZ. However, it is not excluded that the intensive increase in the velocity above the LVZ can also be associated with occurrence of the high velocity rocks instead of the low velocity ones. In this case, deep thermobaric conditions facilitate a higher velocity jump.

Results

Geological interpretation of the PTBM results

A comprehensive analysis of seismicity, geodynamics, volcanic activity, and mineral deposits in the Ukrainian Transcarpathian depression (TD) is mainly based on new information on geological, geophysical, geodesic, structural, and geomorphological studies [Chekunov et al., 1969; Gordienko et al., 2011; Kutas, 2014, 2016; Tretyak et al., 2015; Nazarevich and Nazarevich, 2002, 2004; Nazarevich et al, 2002, 2011].

The TD (Fig. 6) is the part of the Carpathian orogeny where the significant restructuring of the tectonic pattern took place at the turn of the Paleogene and Neogene periods that resulted in a significant difference in the Earth's crust structure of the region. Active post-Alpine tectonic processes caused the formation of both the depression itself and young volcanic features. The depression extends from the NW to the SE and consists of two major units (Fig. 6). They are the NW Chop-Mukachivsky basin on the Central massifs of the Internal Carpathians and SE Solotvinsky basin superimposed on the flysch zone of the Outer Carpathians. These units are separated from each other by the Vygorlat-Guta volcanic ridge. The Chop-Mukachivsky basin descends, while elevation, horizontal movement, and high seismicity are characteristic of the Solotvinsky basin [Tretyak et al., 2015].

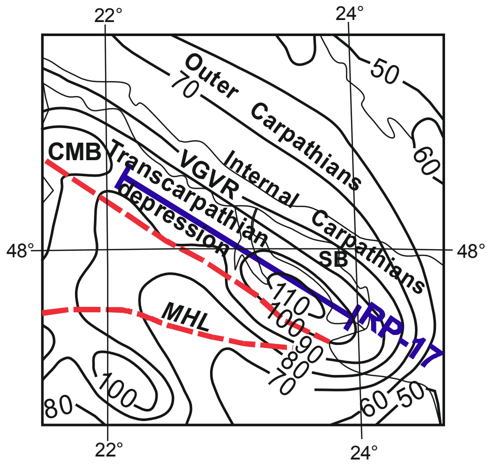


Fig. 6. The schematic map of the regional tectonic units, location of the RP-17 seismic profile and isolines of heat flow [Chekunov et al., 1969; Nazarevich and Nazarevich, 2002, 2004; Nazarevich et al, 2002, 2011; Kutas, 2014, 2016]:

CMB – Chop-Mukachivsky basin, VGVR – Vygorlat-Guta volcanic ridge, SB – Solotvinsky basin, MHL – Mid Hungarian line.

Drilling data show that the basement of the Transcarpathian depression consists of the Paleozoic metamorphic schists, the Triassic dolomites and dolomitized limestones, the Upper Cretaceous marls and mudstones with sandstones, and the Palaeogene sandy-clay formations [Nazarevich, Nazarevich, 2002, 2004].

The Paleozoic sediments are exposed in the NW depression. The Cretaceous and Paleogene sediments crop out mostly in the south-east, in the Solotvinsky basin. Thus, from the north-west to the south-east the younger sediments gradually replace the basement of the Transcarpathian depression where numerous faults, clearly registered by both geophysical and geological methods give rise to a complicated block nature of its structure [Nazarevich, Nazarevich, 2002, 2004; Kutas, 2014].

The block tectonics is a specific characteristic of the Chop-Mukachivsky basin while it is much less expressed in the Solotvinsky depression. Active vertical and horizontal movements and high seismicity can occur here [Chekunov et al., 1969; Gordienko et al., 2011; Kutas, 2014, 2016; Tretyak et al., 2015; Nazarevich, Nazarevich, 2002, 2004; Nazarevich et al, 2002, 2011]. Along the TD the RP-17 profile [Chekunov et al, 1969] revealed the following horizons (1) the sedimentary cover (V_P=1.7 to 4.8 km/s), (2) the Mesozoic basement of the depression (V_P=5.3 to 6.0 km/s) and (3) the Paleozoic basement (V_P=6.0 to 6.4 km/s). In the Solotvinsky basin Precambrian rocks (V_P=of 6.2–6.5 km/s) and the Conrad boundary (V_P=6.6 to 6.8 km/s) are also delineated (Fig. 7). The velocities of V_P=7.5–8.5 km/s are registered on the Moho discontinuity. The minimal thickness of the folded basement of the depression is 3 km in the SE Chop-Mukachivsky basin.

It increases to 4.0–4.5 km in the Solotvinsky basin. The layer of "granitoids" is determined by the velocity of 6.1-6.4 km/s for the Horizon II at depths from 4.5 to 8 km. The LVZs (Horizon III-LVZ) with the velocity of 6.0–6.1 km/s are situated below.

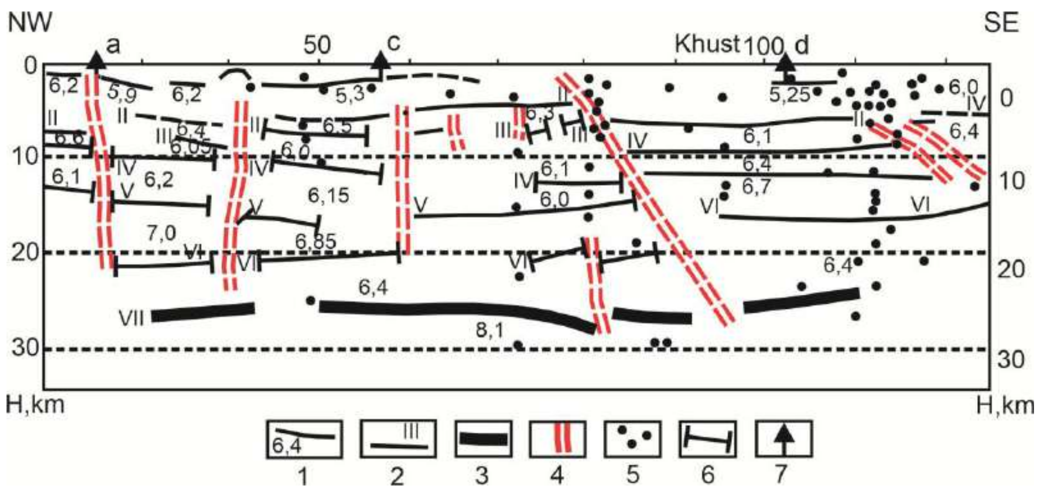


Fig. 7. Seismic section of the Earth's crust and local earthquake hypocentres along the TD [Chekunov et al., 1969; Tretyak et al., 2015; Nazarevich, Nazarevich, 2004; Nazarevich et al, 2002, 2011].

1 – refraction layers and velocities along them; 2 – reflection horizons and their numbers; 3 – Moho discontinuity; 4 – faults; 5 – earthquake focuses; 6 – seismic boundaries; 7 – hydrocarbon exploitation wells

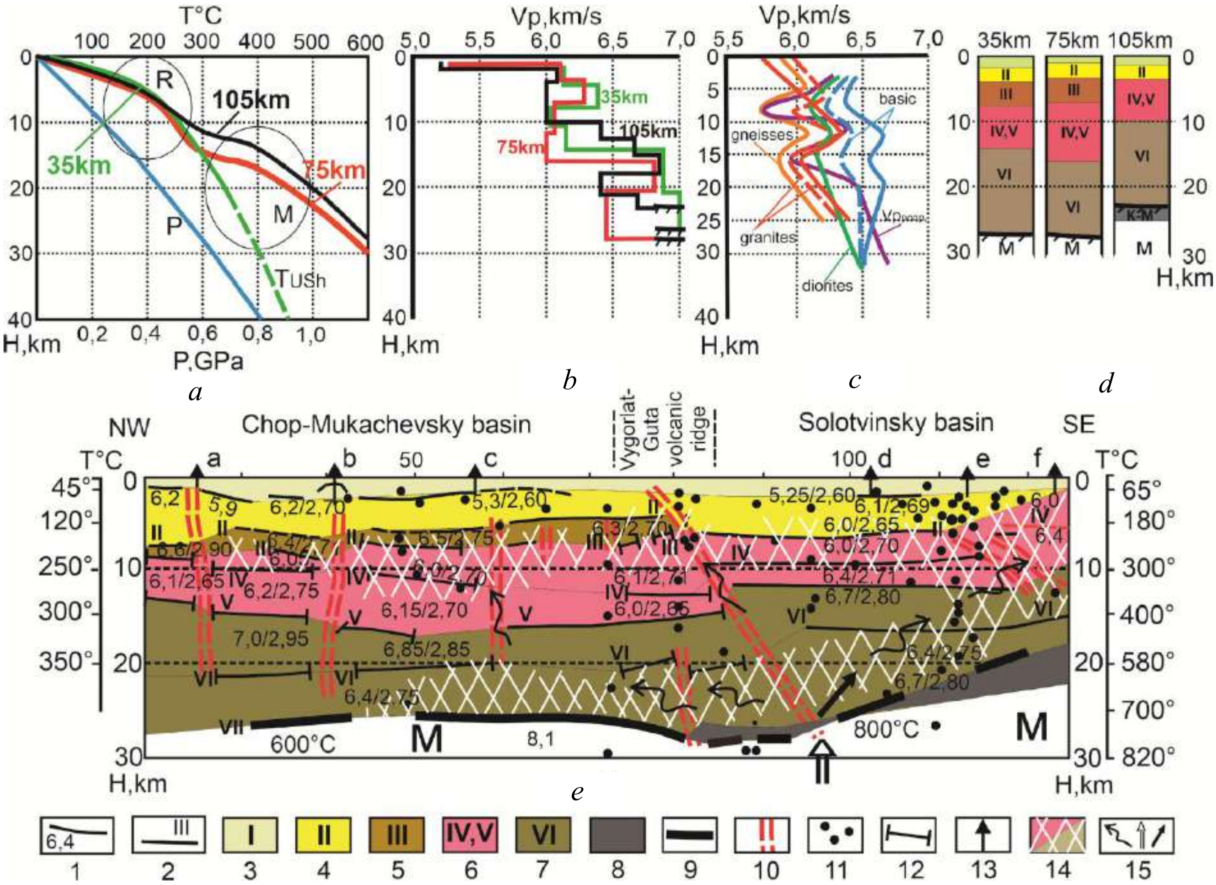


Fig. 8. Elements of PTBM for areas of 35, 75, 105 km of the RP-17 DSS profile (a–d) and the model of rocks distribution with a depth along TD (e) (this study and data from Chekunov et al., 1969; Tretyak et al., 2015; Nazarevich, Nazarevich, 2004; Nazarevich et al, 2002, 2011):

a – temperature regimes; b – seismic velocity; c – calculated $V_P=f(PT)=f(H)$ for thermal regime of 105 km; d – distribution models for mineral materials vs. depth according to these velocities. 1 – refraction layers and velocities along them; 2 – reflection horizons and their numbers; 3 – Neogene layer; 4 – folded basement; 5 – Paleozoic amphibolite facies (gneisses); 6 – Proterozoic (Precambrian) gneisses with LVZs; 7 – basic rocks; 8 – crust-mantle mixture; 9 – Moho discontinuity; 10 – faults; 11 – earthquake focuses; 12 – seismic boundaries; 13 – hydrocarbon exploitation wells; 14 – LVZs; 15- fluid flows

The seismic horizon IV (6.2–6.5 km/s) at depths of 6–14 km was earlier believed to be the Conrad boundary (V, K_2). However, it is now interpreted to be LVZ of the thermobaric origin located at depths of 6–17.5 km [Korchin, 2017]. The Horizon VI is the second LVZ with a velocity of about 6.4 km/s in the crystalline crust of the TD. This layer is located above the Moho discontinuity (Fig. 7, 8). Its velocity values are small for basic rocks. The explanation of the nature of the upper and lower LVZs is possible in analyzing HF in the TD. There are its stationary component and non-stationary anomalies due to geodynamic processes and the distribution of radiogenic heat sources and thermal parameters of the environment [Gordienko et al., 2011; Kutas, 2014, 2016]. In the depressions of the TD HF varies from 90 to 120 mVt/m^2. The intensive anomalies (110 mVt/m^2) occur along the Central TD. Temperatures are very heterogeneous laterally and vertically: 5 km – 85–150 °C, 10 – 180–300, 20 – 300–470, 30 – 450–650, at the M – 600–800°C (Fig. 6, 8).

The PTBM allows us to explain the origin of the LVZ along the profile [Burtnyi et.al., 2013; Korchin, 2013a, 2017, 2018; Korchin et.al., 2018b, 2019a,b]. For this purpose, the samples are selected of slates, quartzites, metaconglomerates, mylonites, granite-gneisses, diorites, gabbroides, and basalts from the USh and Transcarpathia because they seem to form the deep horizons of the TD. Their elastic characteristics were studied in detail at relevant PT conditions [Burtnyi et.al., 2013; Korchin, 2013a, 2017, 2018; Korchin et.al., 2018b, 2019a,b] at low-temperature regime of the Chop-Mukachivsky portion of the profile. In constructing models of other parts of the profile with high-temperature regime (abnormally high for the territory of Ukraine), temperature corrections were made for the values of velocities of the relevant rocks. For depths of 10–35 km relationships of $V_P=f(PT)=f(H)$

were obtained applying isobars and isotherms of velocities obtained by the authors of this study, as well as data on rocks forming the deep horizons of the Earth's crust [Christensen N., 1989, 1995; Kern H., 1978]. As an example of such a modelling, for the area around 105 km of the RP-17 DSS profile, Figs. 8 *a*, *b*, c, and d demonstrate the data on temperature regimes, seismic velocities, calculated $V_P=f(PT)=f(H)$. A model is also presented for the distribution of mineral environments with depth corresponding to these velocities. Having analyzed these materials, we made an assumption about the nature of the LVZs zones in the TD.

In the TD (Fig. 8, *d*), the upper LVZ-I resulted from high T in compared with its average values due to radiogenic heat generation of clays, siltstones, sandstones, granite-gneisses and with some contribution of mantle heat [Gordienko et al., 2011]. In the LVZ-I the temperature varies from 160 to 260 °C, therefore, this zone is of the thermobaric nature [Korchin, 2017] and consists of decompaction granite-gneiss with schists which are vulnerable to destructive external influences.

Below the LVZ-I the temperatures are low because of the decrease in radiogenic heat. Besides, the mantle component of HF is controlled by the physical state of the underlying rocks that causes the formation of a layer with high velocity because of the dominance of P over T. This horizon consists of basic rocks. At depth of 18–26 km temperature regimes produced a new LVZ-II. The input of heat from the mantle warms up the rocks up to 600 °C at 18–26 km depth (Fig. 8, *d*). The zone is composed of diorites, gabbroides, basaltoides and other products of volcanic activity. The ruptured structure of Moho allows us to suppose the occurrence of crust-mantle mixture here [Korchin et. al., 2019a,b].

There are two voluminous domains in the LVZs along the profile. The first occurs in the Vygorlat-Guta volcanic ridge area which is apparently related to an intense inflow of mantle heat along the fault. The second one is located at a 90–120 km depth. The Chop-Mukachivsky basin is localized within the Transcar-pathian mantle fault zone where volcanism was wides-pread. It now descends due to the powerful cooling of volcanogenic formations of low elastic parameters in the lower crust [Gordienko et al., 2011; Tretyak et al., 2015]. Additional decompaction of basified formations above the Moho discontinuity and the velocity decrease are associated with shear stresses directed along the TD [Tretyak et al., 2015] which causes the dilatant decompaction of rocks [Nikolaevsky, 1966].

An intense warming up of the rocks zone is a characteristic of Solotvinsky basin, which formed a large LVZs above the M discontinuity (in turn, here the latter ascends to 18–21 km). The constant heat inflow from the mantle heats the rocks at depths of 13-18 km and a new LVZ-II zone is formed. Some contribution to the increase in T in the zone is made by the rocks of low thermal conductivity of the LVZ-I above the zone LVZ-II that reduces the outflow of the mantle heat from the LVZ-II.

This is the region of transition from acidic rocks to rocks of intermediate composition, and gabbroids and diorites seem to underlie it. There is the development of LVZs in the Earth's crust in active zones of quite intense stresses. In the process of destruction of the mineral matter at certain depths, the development of LVZs can be associated with the action of the dilatancy effect [Nikolayevsky, 1996; Milanovsky, Nikolaevsky, 2009; Milanovsky, Nikolaevsky, 2010]. Theoretically, it means the linear proportionality of inelastic increases in volume and shear, or in other words, the volumetric and shear inelastic deformations are functions of pressure and tangent stress. In crystalline rocks, the effect of the development of microcracks is manifested when the stresses satisfy the criterion for the onset of dilatant pre-destruction or, more simply, the elastic limit. It is assumed that the characteristic changes of types of brittle fractures observed in laboratory experiments on rocks occur within the crust. On this basis the relevant models are developed for defects of the deep horizons of the crust. A certain disadvantage of our model is the requirement of the presence in the Earth's crust of shear stresses that reach the strength limits of the rocks. However, these phenomena are possible for the territory of Transcarpathia under study. Additional decompaction of basified formations above the M discontinuity and reduction of the velocity are associated with dilatant decompaction of the rocks due to shear stresses directed along the TD and the presence of the mantle Transcarpathian fault [Chekunov, 1994; Tretyak et al., 2015]. Moreover, earthquakes are concentrated at a shallow depth of the TD (Fig. 8, d), which, in our opinion, is closely associated with the thermobaric zones of the upper crust decompaction. Here, the seismic activity contributes to the widening of the channels for motion of fluid from the asthenosphere lens below the Carpathian region, which is described in [Chekunov 1994; Gordienko, Gordienko, 2019].

Under thermodynamic conditions of the LVZs at depths from 3-5 km to 12–20 km the rocks are subject to change when their cataclastic transformation occurs and increases fracture and porosity of rocks [Korchin, 2017; Korchin et al, 2013a,b]. The migration of free water and gas through the rock microcracks accelerates. It destroys the rock, forming secondary pores and cavities. Thus, the “degassing tube” is formed which is the pathway for the migration of abiogenic hydrocarbons to be accumulated in the crystalline crust. Under high pressure and decompression hydrocarbons penetrate into the subsurface horizons of the sedimentary cover where they form several fields.

Originality

It has been shown for the first time that the LVZs in the Earth’s crust (the region of thermobaric decompression of mineral matter) are its integral part (especially, in areas of the present-day and ancient geodynamic activation, accompanied by the increased deep heat flows), providing the lithosphere stability. The study showed that the active heating of the Earth's interior inevitably causes the development of the LVZs, as a result of mantle cataclysms and the localization of radioactive elements. The horizons of thermobaric decompression of the rocks, which under the influence of stresses, multidirectional deformations, and vibrations acquire the properties of strongly dislocated media, form vast migration channels of fluids, "degassing pipes". In turn, they provide the movement of useful mineral matter to the surface and also provoke intense relaxation of tectonic stresses, in particular, in the form of earthquakes.

Practical significance

At present, when interpreting geophysical survey materials, it is necessary to take into account the presence of crustal thermobaric decompression zones (LVZ). In our view, such zones are almost a worldwide occurrence in the Earth's crust. This changes outdated ideas on the geological and structural features of the regions under study.

The practical significance of the present studies is as follows. The research established thermobaric genesis and the corresponding features of the structure of the LVZs, their places and roles in the structure and geodynamics of the crust of the regions, including Transcarpathia. It makes possible to clarify the geological and structural features of the crust of the region, to adequately interpret distribution of geophysical fields and decipher the peculiarities of local geodynamics and seismic-tectonic process, to clarify the level and nature of geo-ecological hazards, to more effectively predict and investigate deep spatial distribution of mineral resources.

Conclusions

The LVZs are the most active horizons of the present-day transformation of the mineral environment and changes in the structural features of the Earth's crust. The LVZs in the crystalline crust are its integral part stabilizing the lithospheric state. In our opinion, active heating of the Earth's interior, as a result of mantle cataclysms and the localization of radioactive elements, inevitably facilitates the formation of the LVZs which are the horizons of thermobaric decompression of the rocks. Such zones under the influence of fluid migration, stress, multi-directional deformations, and vibrations become strongly dislocated media, provoking intense relaxation of tectonic stresses in the form, for example, of earthquakes. In turn, seismic activity causes widening migration channels for the mantle fluids producing the so-called "degassing tubes". Such tubes are the essential elements of the formation of hydrocarbon accumulations.

Based on geological-geophysical data, geodynamic researches and PTBM the TD is considered to be a region of the present-day active geological processes where mineral deposits are formed and earthquakes occur. Among known deep anomalies of the geophysical fields, LVZs are the most accessible to study using different geological-geophysical methods, including superdeep drilling. Taking into consideration the present analysis of the nature and origin of LVZs in the crust of Transcarpathia, it is possible to fulfil the most detailed and perspective study aiming at searching for mineral resources and clarifying the deep structure of the Earth, as well as explaining and predicting crustal earthquakes. Detailed further study of the deep structure of the TD and especially the position of the LVZs can significantly expand the possibilities for hydrocarbons searching. Moreover, legends in Fig. 8 show hydrocarbon fields.

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ПОХОДЖЕННЯ ЗОН НИЗЬКОЇ ГУСТИНИ В КРИСТАЛІЧНІЙ КОРІ ЗАКАРПАТСЬКОГО ПРОГИНУ (УКРАЇНА) ЗА ДАНИМИ ПЕТРОФІЗИЧНОГО ТЕРМОБАРИЧНОГО МОДЕЛЮВАННЯ

Мета. На основі матеріалів лабораторних РТ-досліджень гірських порід і геофізичних даних щодо регіонального профілю РП-17 і їх сумісного аналізу передбачалось розкрити генезис зон низьких швидкостей у корі Закарпатського прогину як горизонтів термобаричного розущільнення мінеральної речовини та простежити зв'язок цих зон із землетрусами і родовищами вуглеводнів. **Методика.** Суть такого підходу полягає у порівнянні інформації ГСЗ і експериментальних даних про фізичні параметри гірських порід за високих тисків і температур. Для цього використано результати лабораторних досліджень у високих РТ-режимах петрофізичних характеристик зразків гірських порід, аналогічних тим, які притаманні досліджуваному району. **Результати.** На основі аналізу вивчення даних лабораторних РТ-досліджень характеристик порід Українського щита і результатів спільної інтерпретації цих та сейсмічних даних по регіональних сейсмічних профілях ГСЗ на УЩ розроблено метод петрофізичного термобаричного моделювання. Напрацьовані підходи і методики застосовано для аналізу даних щодо Закарпаття, зокрема, вздовж регіонального профілю РП-17. Тут виявлено дві зони розущільнення термобаричного походження, які збігаються із зонами низьких швидкостей, аналогічні зафіксованим лабораторними методами в зразках гірських порід у різних РТ-умовах. Зони прогнозуються як ефективні регіональні пастки мантійних флюїдів, зокрема вуглеводнів, які під дією високих тиску, температури і декомпресії проникають у земну кору, а потім у приповерхневі шари осадового чохла, де сформують певні родовища. У зонах розущільнення активізуються приповерхневі землетруси із малими магнітудами, що розширює області розущільнення і сприяє переміщенню у них глибинних, наприклад, вуглеводнів до зон їх локалізації. **Наукова новизна**. Зони низьких швидкостей (області термобаричного розущільнення мінеральної речовини) обов'язкові за певного тиску і температур у земній корі будь-яких регіонів. Вперше показано, що для Закарпаття вони є її невід'ємною частиною і обов'язково формуються в процесі прогрівання земних надр під час їх "термогеоактивізації". Горизонти термобаричного розущільнення порід під впливом тектонічних напружень, різноспрямованих деформацій і вібрацій набувають властивостей сильно дислокованих середовищ, формують великі канали міграції флюїдів, так званих "труб дегазації", які, своєю чергою, забезпечують рух корисних мінеральних середовищ до поверхні, а також є зонами релаксації тектонічних напружень, зокрема, у вигляді землетрусів. **Практична значущість.** Результати описаних досліджень дають можливість уточнити геолого-структурні особливості будови земної кори Закарпаття, адекватно інтерпретувати просторовий розподіл геофізичних полів та розшифровувати особливості місцевої геодинаміки і сейсмотектонічного процесу, уточнювати рівень та характер геоекологічних небезпек, ефективніше прогнозувати та досліджувати глибинно-просторовий розподіл корисних копалин.

Ключові слова: Закарпатський прогин (Україна); зони низьких швидкостей і густини; петрофізичне термобаричне моделювання; термобаричні пастки вуглеводнів; приповерхневі землетруси.

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