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Article

The Role of Transcrust Magma and Fluid-Conducting Faults in the Formation of Mineral Deposits

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Abstract: The article considers the role of transcrustal magma- and fluid-conducting faults in the formation of mineral deposits, shows the importance of a deep source of heat and hydrothermal solutions in the genesis and history of the formation of these deposits. As a result of the impact on the lithosphere of mantle jets rising along transcrustal faults, intense block-and-clump deformations and tectonic movements are generated; rift systems and volcanic-plutonic belts spatially combined with them are formed; intrusive bodies are introduced. At ore deposits, these processes cause epithermal ore formation as a consequence of the impact of mantle jets rising along transcrustal faults on the lithosphere. At hydrocarbon fields, they play an extremely important role in conduction and convective heat and mass transfer to the area of hydrocarbon generation, determine the relationship between the processes of lithogenesis and tectogenesis, and activate the generation of hydrocarbons from oil and gas mother formations. Detection of transcrustal magma- and fluid-supporting faults was carried out by MMZ and MTZ in combination with other geological and geophysical data. Practical examples are given for mineral deposits under which subvertical transcrustal columns of increased permeability traced to considerable depths have been found. The nature of these unique structures is related to faults of pre-Paleozoic time of emplacement, which determined the fragmentation of the subcrystalline structure of the Earth and later developed inherited in the conditions of development of volumetric fluid dynamics. The residual forms of functioning of fluid-conducting thermohydrocolumns are granitoid batholiths and other magmatic bodies. Experimental modelling of deep processes allowed to reveal the quantum character of interactions of crystal structures of minerals with "inert" gases under elevated T-P conditions. The role of helium, nitrogen and hydrogen in changing the physical properties of rocks in connection with their intrastructural diffusion has been clarified. As a result of low-energy impact, stress fields are formed in the solid rock skeleton, the structure and texture of rocks are rearranged, and general porosity develops. With increasing pressure, energy interactions intensify, deformations, phase transitions and chemical bonds occur in an unstable geological environment, which increases with increasing gas saturation, pressure, and temperature. The process of heat and mass transfer along transcrustal magma- and fluid-supplying faults to the Earth's surface occurs in stages with energy release, which can manifest itself in the form of explosions on the day surface, in coal and ore mines, in earthquakes and volcanic eruptions.

Keywords: transcrustal magma- and fluid-conducting faults; microseismic and magnetotelluric sounding; ore genesis; hydrocarbon deposits

1. Introduction

In solid mineral geology, the concept of "endogenous deposit" implies the direct involvement of deep sources of heat and mineral components in the genesis and history of their formation. These sources may be located at different depths and may be single or composite and of different nature.

In the case of upper crustal sources of matter (e.g., near-surface magmatic sources or ore-rich host rocks), a deep subcrustal heat carrier is assumed to have caused melting of the crustal substrate or extraction of the useful component by hydrothermal solutions. Thus, the direct participation of mantle processes in the formation of endogenous deposits is obvious.

Developing this concept, it can be seen that ore mineralization is widespread in various geotectonic structures associated with deep processes in the Earth's lithosphere. A large, if not dominant role in these processes is played by deep faults, which control the location of ore provinces, belts and deposits, and concentrations of various compounds of volatile components are indicators of the manifestation of these faults [1].

For example, volatile components such as F, Cl, P, B, H₂O play a crucial role in the formation of magmas of different acidity, have a significant influence on the evolution of granitic magmas, granitic pegmatites, solidus and liquidus temperatures of melts, viscosity of silicate melts, crystallization sequence of mineral formation, as well as on the behaviour of dispersed, ore and rare elements and their partitioning between fluid and melt [1].

Access from the depths of the lithosphere to volatile components and hydrothermal solutions is provided by deep faults, which manifest themselves as tectonically weakened zones saturated with intrusive rocks, as well as linear systems of grabens, volcanoplutonic belts (VPP), etc., which provide [2, 3, 4, 5].

In continuation of this postulate, a comparison of the tectonic position of intracontinental ore belts with the schemes of geodynamic zoning and the deep structure of the territory shows that the main provinces are located in the zone of linear stretching of the Earth's crust [2, 6], and the most productive regions - for example, Transbaikal, Central Asian, South Kazakhstan and others - are characterized, in addition, by lithospheric decompression and are distinguished by the presence of upper mantle heterogeneities, forming the marginal parts of the Central Asian region, which is the most productive in the world [1].

An increase in the intensity of Palaeozoic and Mesozoic orogenesis from the inner parts to the periphery of these regions is observed; and a connection between the scale and formational affiliation of mineralization and thickness of the anomalous mantle and the depth of dipping of its edges is outlined [7].

As for platforms and shields, ore belts are confined directly to their marginal parts, and, more often than not, are combined with continental volcanogenic belts of marginal-continental (Pacific belt) or intracontinental (Transbaikal, Mongolian-Zabaikal, Beltau-Kuramin, South Kazakhstan, etc.) types. Epithermal ore formation is typical for these structures as a consequence of the impact of mantle jets [4] on the lithosphere rising along transcrustal faults, usually under weakened crustal zones, which are subsequently transformed into rifts.

On the contrary, stable areas of platforms and shields experience uplift without volcanic manifestations. With the decline of mantle activity, the process of vaulting (arcogenesis) is replaced by a stage of stress relaxation, stretching and differentiation of movements (vault collapse, taphrogenesis, hill-graben tectonics, etc.) [8].

Thus, the processes of hydrothermal orogenesis and endogenous metamorphism of rocks are closely related to the stages of the geological history of the region and are characterized by: a) intensive block-and-cliff deformations, tectonic movements with the renewal of existing and the embedding of new deep faults; b) formation of rift systems and spatially combined with them runways filled with sedimentary-volcanogenic formations (e.g., Devonian marginal volcanic belt of Central Kazakhstan); c) formation of magmatogenic focal-dome structures, intrusive massifs intrusion of small intrusions and dikes.

Transcrustal magma- and fluid-supporting faults also control the formation of hydrocarbon (HC) accumulations.

For more than 100 years, two hypotheses have played the role of independent scientific paradigms in oil and gas geology- sedimentary-migration and abiogenic- have been competing over the origin of hydrocarbons. The proponents of the former argued that oil and gas arise in the fields themselves from organic matter coming "from above" – from the earth's surface, while the latter

insisted that hydrocarbons enter the deposits “from above” – from the Earth’s surface, while the latter insisted that hydrocarbons enter the fields “from below”-from the deep Earth’s interior, where they are formed [5].

Each of the paradigms is supported by a large number of supporters and is based on the results numerous experiments and theoretical studies. Nevertheless, they have not eliminated the known difficulties inherent in the paradigms themselves and have not allowed the scientific community to make a definitive choice in favor of one of them.

The idea of endogenous origin of hydrocarbon deposits is being intensively promoted [5, 9, 10, 11]. Fluidodynamic [12, 13] and sedimentary- fluidodynamic [6, 7] concepts of the origin of oil and gas are being actively developed, according to which the relationship between the processes of lithogenesis and tectogenesis is carried out in different geodynamic settings. Conduction and convective heat and mass transfer occurs along mantle faults, accompanied by additional heating of sedimentary strata and, consequently, activation of HC generation from oil and gas mother formations.

Mixgenetic origin of hydrocarbons is based on the scheme of hydrocarbon synthesis with participation of dispersed organic matter and channels of deep heat and mass transfer from the position of lithospheric plate tectonics [14]. This hypothesis was developed by geologists-oilmen of Uzbekistan A.A. Abidov (2002), I.U. Atabekov, F.G. Dolgopolov, A.I. Khodjimetov in the beginning of 2000.

In recent years, an independent, actively developing concept of the origin of oil and gas has emerged, which competes very successfully with the ideas of the sedimentary-migration and abiogenic hypotheses [15, 16].

In accordance with this concept, the main mechanism oil and gas formation in the subsurface is polycondensation synthesis of hydrocarbons from carbon oxides and hydrogen, occurring in water-saturated mineral matrix of rocks, mechanically activated by natural seismotectonic processes (N.V. Chersky And etc., (1985).

In this mechanism, called geosynthesis (Zakirov et al., 2013), the hydrogen donor in HC is water, and carbon is organic matter, water-soluble CO₂ and easily soluble carbon-containing minerals.

Geosynthesis occurs in a water-saturated mineral matrix of rocks, mechanically activated by seismotectonic processes along fault planes, and is accompanied by the decomposition of a large mass of groundwater into oxygen and hydrogen.

Under the action of seismotectonic deformations, intracrystalline defects are generated in rock minerals (N.V. Chersky et. al., 1985). Diffusing to surface of mineral grains, these defects form an energy-rich layer that reduces the Gibbs energy of chemical reactions.

Such reactions, as shown by V.I. Molchanov (1981, 1992), N.V. Chersky, V.P. Tsarev et al. (1984, 1985, 1986), includes decomposition of H₂O with release of hydrogen, which participates in synthesis of HC from carbon oxides (CO and CO₂).

Consequently, all of the above concepts, hypotheses and facts unambiguously testify to the critical importance of deep transcrustal faults in heat and mass transfer from the mantle to the area of ore deposition or to the areas of emigration and generation of hydrocarbon accumulations.

It is this peculiar structural and tectonic phenomenon that is the subject of the author’s research, the contents of which are presented in this article.

2. Materials and Methods

The study of deep crustal structures beneath ore fields and HC deposits has traditionally been carried out using seismic methods – deep seismic sounding (DSS) and the reflected wave method in the modification of the common depth point (CDP-DWP).

In addition to the above mentioned methods, of combined KMPV-OGT method and a modification of the GSZ method (GSZ-OGT) were used to search for non-metallic minerals. However, all these methods allow for good identification of horizontal or slightly inclined boundaries, while steeply dipping and subvertical structures are practically not identified by them, or are identified by indirect signs (zones of loss of correlation).

Similar results, although with lower reliability, were obtained using the methods of regional magnetic and gravity reconnaissance, and DEWS (method of exchange waves from earthquakes) [17, 18]. At the same time, the models constructed from the data of these methods are beyond the scope of this paper and will be discussed in future publications. In the search for acceptable solutions, the MMZ and MTZ were chosen, which allow levelling the above mentioned limitations.

The microseismic sensing method (MSM) is a fundamentally new approach based on recording the spectrum of a low-frequency microseismic field represented by the fundamental modes of Rayleigh surface waves [19, 20].

Microseisms are natural elastic waves with frequencies from hundredths to first tens of hertz, caused by atmospheric phenomena, surf wave activity and other reasons. Studies in the low-frequency range (fractions of millihertz), can provide data on the structure of deeply buried and large structures.

The research methodology consists in measuring the frequency-amplitude characteristics of microseisms along a profile or along a network of profiles, varying the amplitude values by depth in accordance with the above dependence, and constructing 2D or 3D models of seismic field.

The advantages of the MMZ are that inhomogeneities of the Earth's crust distort the spectrum of the low-frequency microseismic field at the Earth's surface. Over high-velocity inhomogeneities, spectral amplitudes of a certain frequency f decrease, while over low-velocity inhomogeneities they increase. This effect is observed if the inhomogeneities lie at a depth equal to approximately half of the wavelength. In the case of inhomogeneities at other depths, they do not distort the amplitudes of seismic waves of a given frequency [21].

The frequency f , at which the interaction of the wave with the heterogeneity occurs most effectively, is related to the depth of occurrence of heterogeneous strata H and the velocity of the fundamental mode of Rayleigh wave $V_R(f)$ by the relation $H = KV_R(f)/f$. In other words, the rule $H \approx K\lambda$ is fulfilled (λ is the length of the fundamental Rayleigh wave mode for frequency f ; the wave of length λ is effective for a given depth) [7, 12].

The measurement results produce a section or volumetric model of geological heterogeneity, which is an estimate of the structure in terms of relative velocity parameters of transverse seismic waves. The size of geological heterogeneities should exceed the wavelength by at least 1.5 times.

We note that subvertical geological heterogeneities and velocity boundaries are preferred for MMZ, while subhorizontal boundaries are "inconvenient" objects. In this sense, MMZ can be regarded as a specific "orthogonal complement" to traditional seismic methods.

Now let's turn to electrical exploration by the method of magnetotelluric sounding (MTZ) – a tool capable of successfully solving a number of tasks, a wide range, including in the study of the geological structure of the lithosphere at depths up to many hundreds of kilometers; at depths from the first tens of metres to the first tens of kilometres for the search and exploration of deposits of ore, non-metallic and combustible minerals, for the regional study of geological structures.

There are several modifications of this method, in our case deep MTZ (DMTZ), used for investigations to depths of hundreds of kilometres in the low-frequency region.

The natural sources of the field in the MTZ are electromagnetic oscillations in the ionosphere (e.g., generated by the Earth's thunderstorm activity and the Sun's activity (solar wind)). The depth of penetration of the electromagnetic field into the medium depends on the electrical conductivity of the medium itself and the frequency of the field (the lower the frequency, the deeper the field penetrates) – the skin effect.

MTZ aims to calculate the resistivity and its dependence on depth. For this purpose, MTZ studies the frequency response $q_k(\omega)$ of a geological section, called apparent resistivity.

Two phases of work are highlighted:

1. stage - processing of measured data, which includes procedures of frequency analysis (filtering, obtaining Fourier series coefficients) and procedures of working with matrices (matrix inversion by Moore-Penrose method, or singular matrix decomposition);
2. stage - inversion (transformation) of response functions into a section consisting of earth layers. The solution of the inverse problem of MTZ usually includes the solution of the direct problem and one of the fitting methods. Response function transformation is used when a quick but

coarse estimate of the geoelectric section is required. Sometimes this assessment turns into an assessment of the quality of the measured data, in such cases the measurements have to be repeated.

Both stages may be accompanied by manual correction or rejection of data for a number of frequency and time parameters. In addition, the second stage introduces an a priori geophysical model due to the fact that the inverse MTZ problem has many different solutions, from which the interpreter selects the geophysically most reliable one.

Interpretation of MTZ data is performed within 1D, 2D, and more recently 3D models. Palettes and programmes for one-dimensional interpretation of TPM data are widely distributed and publicly available.

Currently, 2D inversion algorithms (Reboc, WinGlink, ZondMT2D) are the standard for interpretation. Despite the development of computer technology, the three-dimensional inverse problem is not yet widely used due to its high resource intensity.

MTZ is not included in the list of high-tech methods with increased resolution, which allow to get a detailed picture of the peculiarities of the geological structure of the studied sections.

As a rule, this technology is used in geotraverses mining. Nevertheless, the experience of using this method in Kazakhstan shows quite good results in identifying deep faults, including regional deep faults that can be considered as channels for heat and mass transfer, large anticlinal rises, and crystalline basement structures [22, 23].

3. Results

3.1. Ore Minerals Deposits

In this section of the paper, we consider a practical example of MMZ research for the construction of genetic models of ore deposits.

The application of MMZ at the unique molybdenum-uranium deposits of the Streltsovskoye ore field (SOF) in Eastern Transbaikalia allowed us to identify deep fault zones beneath them. Comparison of MMZ data with geomechanical parameters of rocks calculated from well cores showed that areas of more monolithic rocks correspond to relatively high velocity areas, while zones of tectonic faults with low values of geomechanical parameters are characterized by reduced velocities of elastic waves [7, 19].

Comparison of MMZ results with the results of other geophysical methods applied along the same profiles (AMTZ, gravity survey, magnetic survey) showed that MMZ is an order of magnitude more detailed, objective (not depending on a priori information and subjectivity of a specialist), deep (from the first meters to 50 km), operative and easily to perform method that does not require explosions, vibrators and wires [20].

As can be seen from the seismic section along the sublatitudinal profile PR-1 (Figure 1a), a transcrustal column with a radius of about 5 km, characterised by increased amplitudes (decreased velocities) of microseisms, was detected beneath the Streltsovskaya caldera.

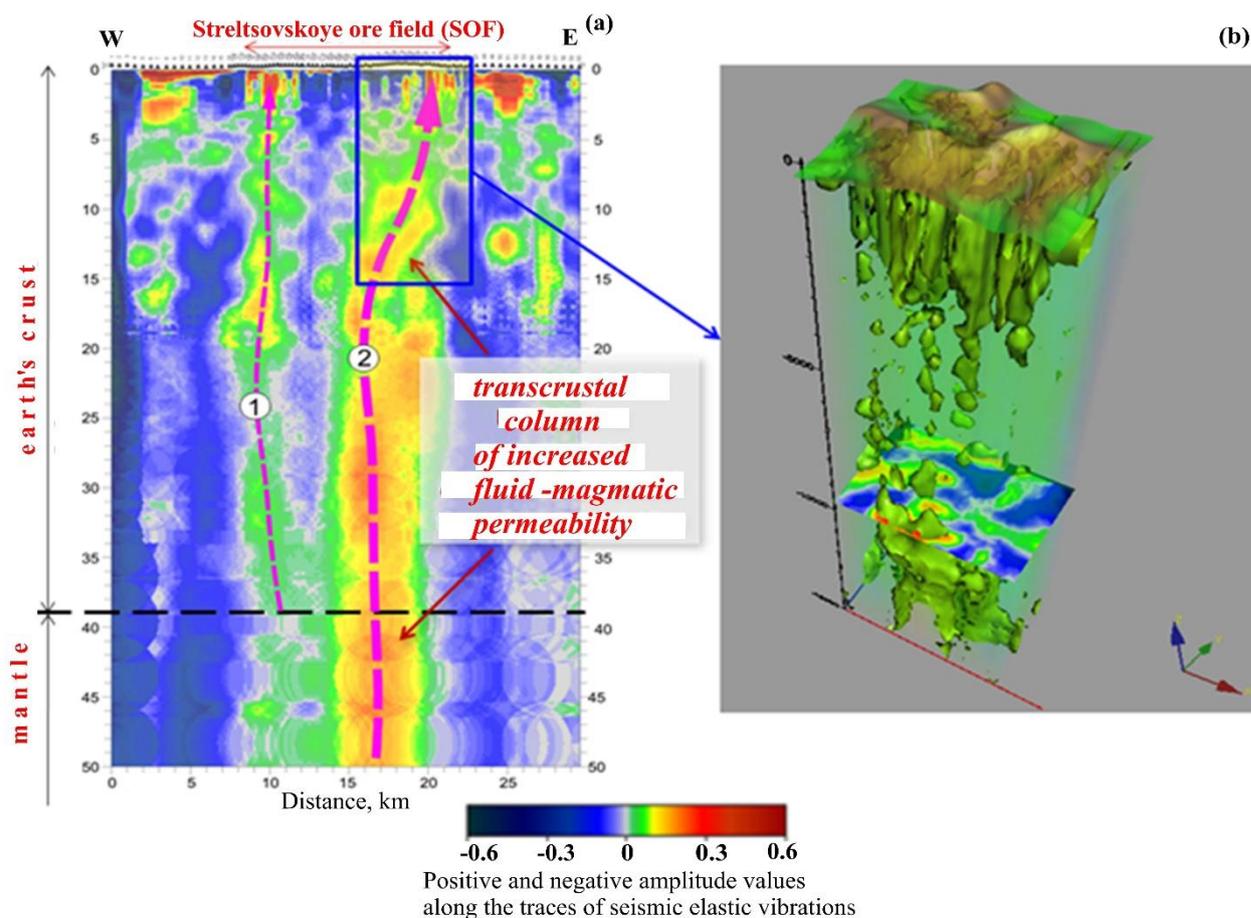


Figure 1. Microseismic section along profile PR-1 (a) and 3D seismic model to a depth of 15 km, constructed from detailed microseismic sounding data within the Gorny and Streltsovsky sections (b).

Symbols: areas of increased amplitudes (decreased velocities) of microseisms are shown in yellow-red colours, and areas of decreased amplitudes (increased velocities) in blue. At a depth of 10 km, the 3D model shows, a horizontal section of the isosurfaces of microseism amplitudes. The Y-axis (green) is directed to the north, the X axis (red)- to the east. Dotted arrows on the regional profile show the direction of movement of magmatic masses and fluid -thermal flows.

This column is interpreted as a zone of increased decompaction and permeability, along which melts of basaltic, dacite and rhyolite compositions rose during the Late Mesozoic tectonomagmatic activation, which caused the subsequent collapse of the upper part of the Earth's crust over the devastated centre of Li - F uranium-bearing acidic melt and the formation of the Streltsov caldera [20].

A detailed area survey in the regional profile allowed us to build a 3D seismic model (Fig. 1b). The upper part of the identified transcrustal column is a pipe-like body localized at the junction of sublatitudinal and submeridional faults traced to depths of 10-15 km [7, 19]. This column comes to the surface beneath the highest cone-shaped hills of the Argun Range. A detailed geological survey with measurements of the dip angles of rhyolites, as well as data from drilling deep (up to 1200 m) boreholes allowed us to identify the main center of acid volcanism in this place, consisting of several fissure-cone volcanoes, called the Streltsovsky volcanic center [24].

Thus, microseismic sounding allowed us to detect under the Streltsovskoye ore field a transcrustal column of increased fluid -magmatic permeability, which is the main channel for the flow of different- depth magmatic melts into the upper part of the Earth's crust, and through the movement of high-temperature uranium-bearing hydrothermal solutions into the area of ore deposition.

The MMZ also helped identify the main center of acid volcanism controlling the position of most of the Mo - U deposits in the central and eastern parts of the caldera.

3.2. Hydrocarbon Deposits

The study of transcortical fluid- and magma-induced faults in hydrocarbon fields by microseismic and magnetotelluric soundings is carried out on the examples of genetically different oil and gas basins.

Symbols: yellow-red tones show areas of increased amplitudes (decreased velocities) of microseisms, and blue tones show areas of decreased amplitudes (increased velocities). The areas of increased amplitudes on the 3D model (a) and on its horizontal slice at a depth of 6.5 km are marked with Latin letters. On the 3D model of the Astrakhan gas condensate field up to a depth of 50 km (c), a deep zone of increased amplitudes (deep fault) located beneath productive oil wells is visible (b). The latter are marked with black dots, the size of which is proportional to productivity.

At the Astrakhan gas condensate field (AGCF), explored on the western side of the Caspian depression, the measurement network consisted of 200 points, and the average distance between measurement points was 2-2.5 km. In addition, a profile with a distance between points of 500 m was performed [7, 25].

The obtained three-dimensional model for the field area (Figure 2) was compared with geological and geophysical data of independent studies. The results of the 3D seismic model for the field area were compared with the geological and geophysical data from independent studies. Thus, areas of salt domes are labelled in the seismic model with lower microseismic amplitude values, which reflects higher elastic wave velocities in salts compared to the host Mesozoic terrigenous sediments. There is also a good agreement between microseism amplitude values (based on MMZ data) and reservoir porosity values (based on well drilling data) at 4-4.1 km depth of the productive horizon.

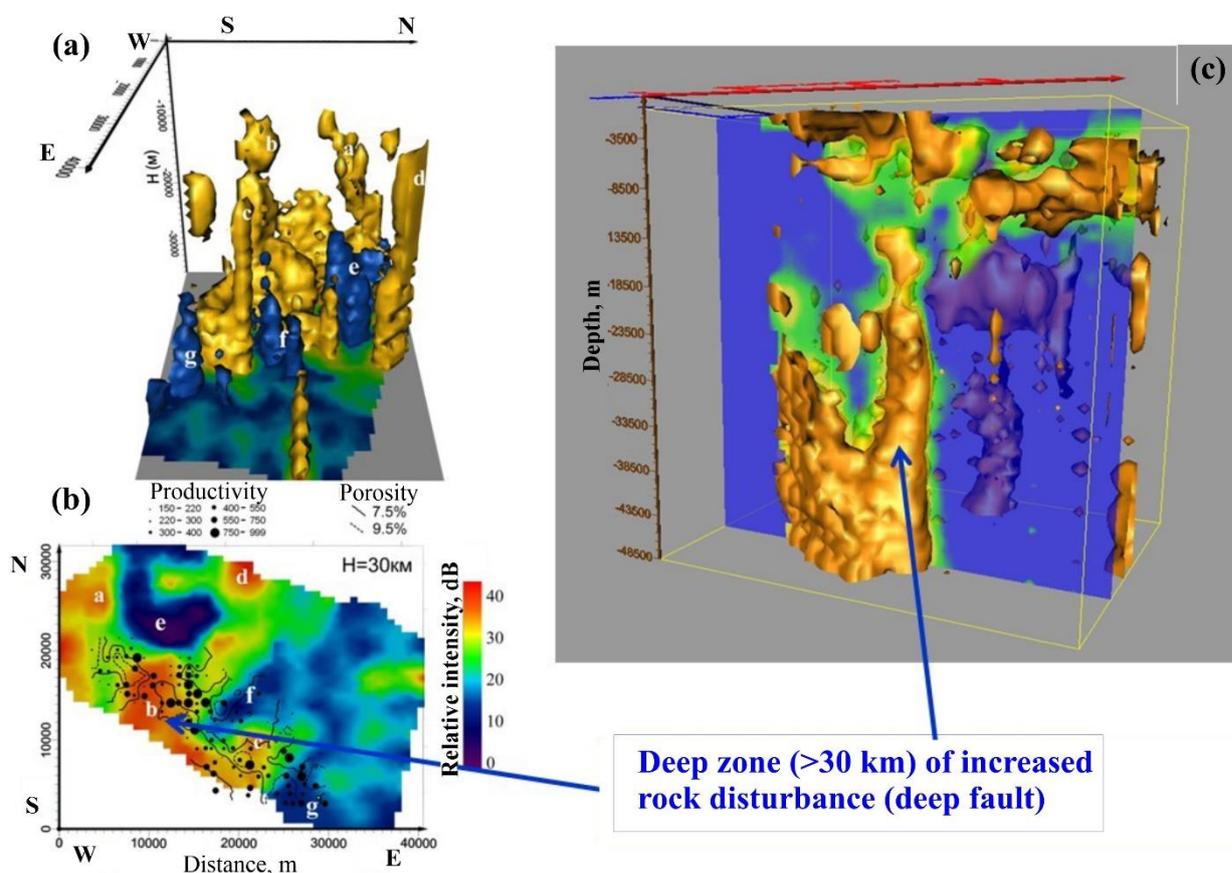


Figure 2. Three-dimensional seismic model of the Astrakhan GCF based on MMZ data.

Top left and right - volumetric models of areas (Figure 2a and Figure 2c) with increased microseismic amplitudes (inside yellow-orange bodies). Bottom left - horizontal section of a volumetric seismic model at of 30 km depth with an orange region of increased permeability (high amplitudes). Above this region are oil productive wells (black circles, size corresponds to productivity) and areas of increased porosity (7.5 and 9.5% porosity isolines) (Figure 2b). On the left pictures letters show the correspondence of permeable (yellow) and dense (blue) volume bodies (above) and their position on the horizontal slice (below).

It can be assumed that low seismic velocities are caused by increased fluid conductivity of: a) subhorizontally elongated zones; b) subvertically oriented bodies associated with the system of deep faults, along the planes of which, probably, huge volumes of high-temperature aggressive vapour-gas mixtures, including those containing hydrocarbons, have been and are being lifted and carried away. These mixtures react chemically with dispersed organic matter, activate catagenesis processes and form hydrocarbon accumulations.

The fault system we have identified is in direct contact with three high-velocity subvertical bodies e, f and g (Figure 2 a, b), which are marked in the gravity field by increased density anomalies and apparently, represent deep intrusions.

Consequently, MMZ can be an effective tool for mapping independent and additional (to the CDP) petrophysical characteristics - porosity and fracturing of the medium, as well as steeply inclined (subvertical) boundaries beyond the resolution of reflected-wave seismic.

Thus, the use of MMZ at ore and oil and gas deposits allows to reveal under them transcrustal zones of increased fluid -magmatic permeability, which provide heat and matter flow into the area of ore deposition and generation of hydrocarbon accumulations.

The following examples of tracer fluid- and magma-supporting faults are associated with hydrocarbon deposits in the South Turgai oil and gas basin in Kazakhstan.

For example, in the Kumkol oil and gas field, the MTZ results revealed a good correlation between the anomalies of increased resistivity and deep zones of endogenous heat inflow. On the geoelectric section (Figure 3) these anomalous zones are manifested by reduced resistivity values. Above them, zones of sharp increase in electrical resistivity of rocks laterally, associated with the presence of an oil deposits, are revealed [26].

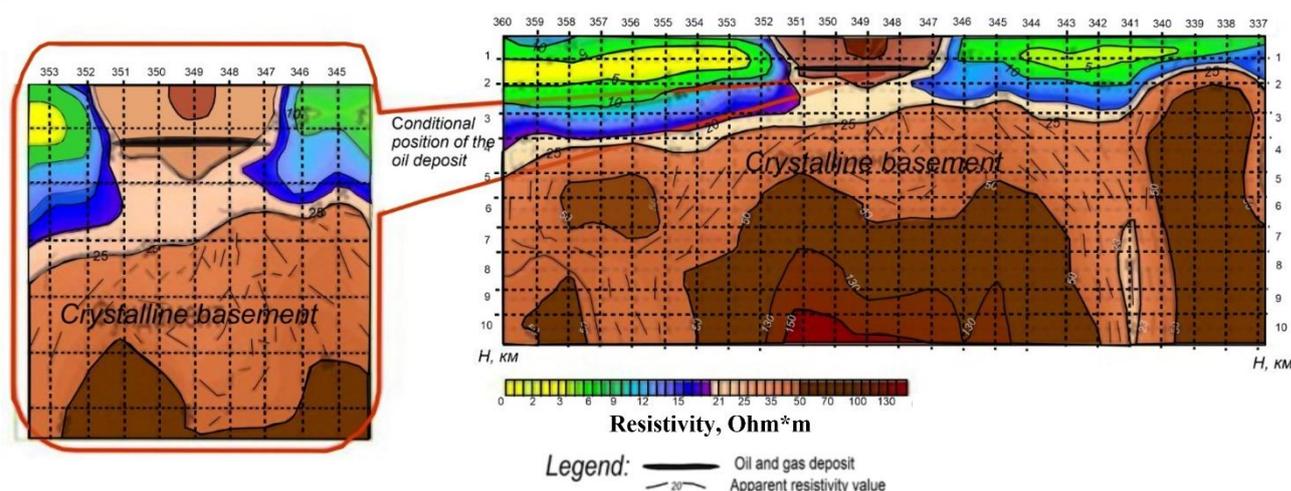


Figure 3. Geoelectric section through the Kumkol field according to MTZ data.

We can assume a direct impact of the predicted transcrustal magma- and fluid-conducting structures on the processes of hydrocarbon accumulation formation in the Kumkol field.

In another field located west of Kumkol, the results of MTZ also showed a similar increase in resistivity (Figure 4), which has a connection with deep faults and heat-mass transfer processes.

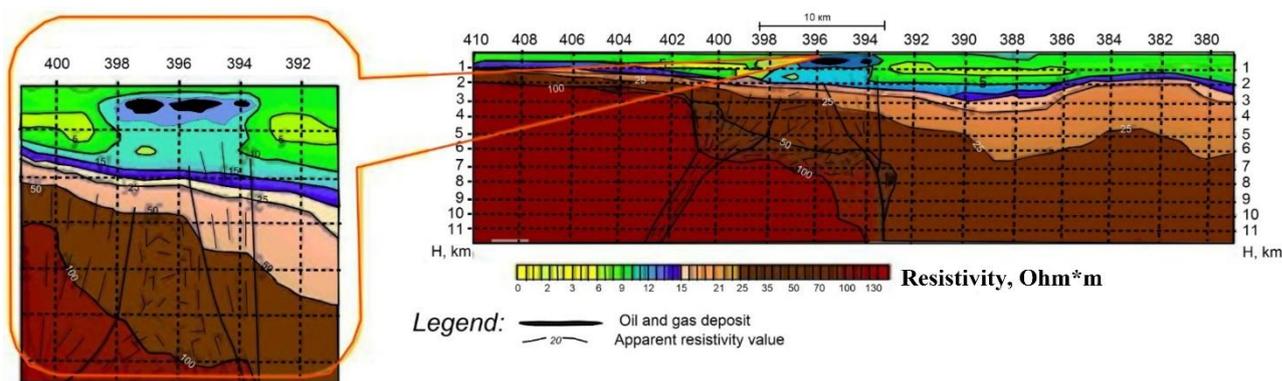


Figure 4. An example of a similar manifestations of an oil deposit in another field in the South Turgai Trough.

On the example of electric exploration works of MTZ in the South Turgai Trough, one can observe the paragenesis of subvertical conductive zones (channels) and areas of development of porous bodies (resevoirs) saturated with hydrocarbons (Figure 5).

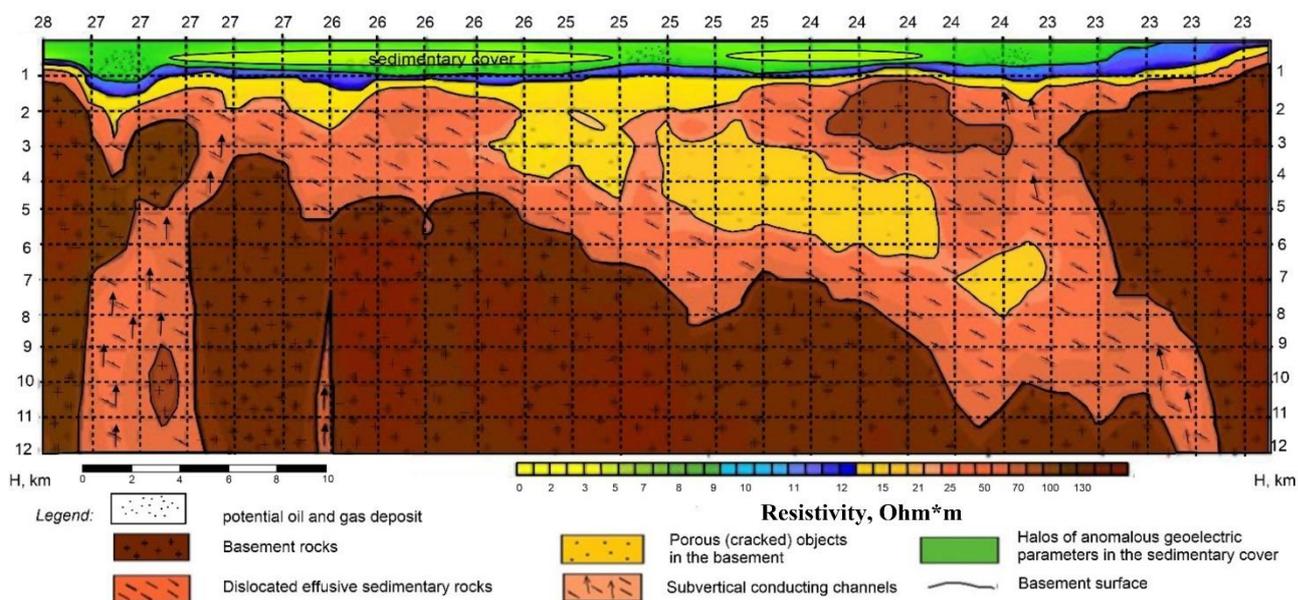


Figure 5. Delineation of subvertical zones and conductive channels on geoelectric section.

Thus, Figures 3-5 show that the conductive objects are bodies penetrating the Earth's crust to depths of up to 15-20 km, possibly deeper. Presumably, the processes occurring in these zones are associated with heat and mass transfer and movements of deep fluids, the nature of which remains to be studied.

By the way, researchers have repeatedly pointed out the controlling role of deep faults in the crystalline basement of platforms in the formation of hydrocarbon deposits in the sedimentary cover [27, 28, 29, 30].

Subvertical transcrustal channels with increased permeability may be agents of transfer of deep thermal flow and fluid transport. It is possible that these subvertical structures provide a link between deep and surface conditions of oil reservoir formation.

4. Discussion

The use of MMZ and MTZ at ore and oil and gas deposits allowed to reveal under them transcrustal zones of increased fluid -magmatic permeability of the mantle level of embedding agents of heat and mass transfer to the area of ore deposition and formation of HC accumulations.

To date, extensive geophysical material has been collected on the possible flow of mantle fluids through transcrustal channels. According to MTZ data, these channels are identified by values of reduced electrical conductivity.

Thus, under the Bezymyanoye deposit, which is one of the large, shallow (250-500 m) deposits of Western Kazakhstan, deep faults were revealed, complicating its geological structure. The deposit is characterized by the absence of salt tectonics, stratigraphic discrepancies, and lithological and facies variability of Middle Jurassic-Neocomian rocks.

Additionally, studies were carried out in the Lower Paleozoic part of the section along two experimental profiles crossing the field in areas characterized by different geological structures [3]. Two-dimensional inversion was performed along these profiles. To increase reliability, the reflecting horizons identified by 3D seismic survey and the results of induction logging, which is the closest to the MTZ method in terms of physical and geological basis, were used.

As a result, promising hydrocarbon zones were identified in the upper part of the section, and in the lower, Paleozoic part- a positive high-resistivity structure in the central part of the pilot profile, and two steeply sloping zones of reduced resistivity were identified beneath it. (Figure 6), rooted deep into the basement.

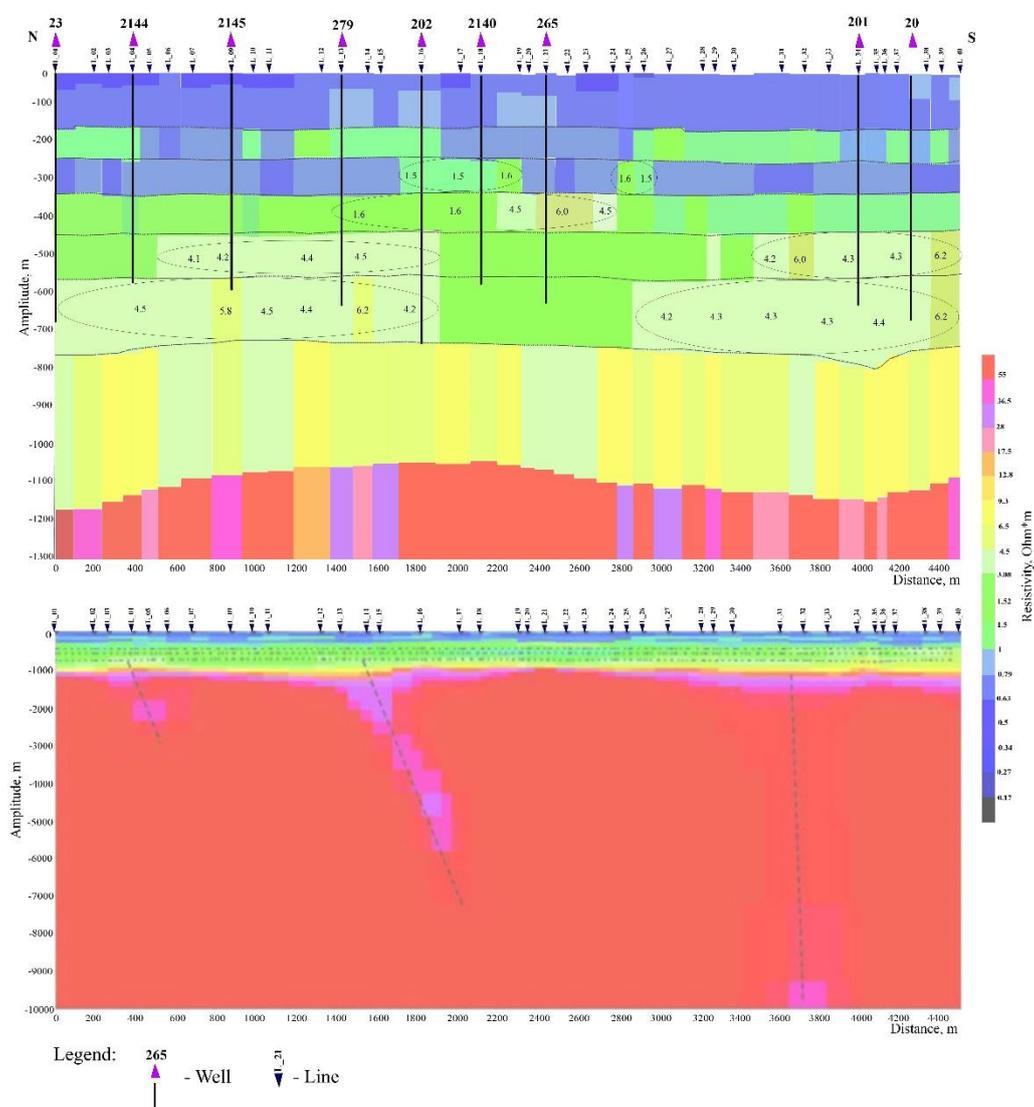


Figure 6. Identification of transcrustal channels in the Paleozoic part of the section on the example of the Bezymyanoye deposit.

The nature of this structure is not clear, but it should be noted that these decompacted zones are similar to the subvertical structures shown in Figures 3-5. The results of detailed MRS allowed us to

reliably link them with conductive (fracture) channels along which heat and mass transfer and hydrocarbon migration may occur.

The works of Sysoev B.K. and Khudyakov D.S. also note the existence of a relationship between the deep structure of the earth and the presence of HC deposits (Figure 6) [31].

Nature of Transcrustals Fluid- and Magma- Conducting Channels

As for the nature of transcrustals fluid and magma conduits, they are believed to be confined to faults of ancient (Archean-Proterozoic) age that determined the fragmentation of the Earth's subcrystalline structure.

Later, these faults functioned inherited, which is natural not only for shields and ancient denuded folded regions, but also for platforms, to which much attention was paid in due time by academicians N. S. Shatsky and A. V. Peive. The formation of consolidated rigid blocks proper occurred at the early stages of megastructures formation [32] under the conditions of volumetric fluid dynamics development. The residual forms of functioning of large-scale fluid-conducting Korzhinsky -Pospelov thermohydrocolumns are batholiths of granitoids that served as consolidation cores. Such structures serve as fluid conductors even nowadays [33].

Iskandarov M.Kh., Abdullaev G.S., Mirzaev A.U., Khakimzyanov I.N., Umarov Sh.A. (2022), develop ideas similar in content, but taking into account plate tectonics on the example of the South Ustyurt region. According to these researchers, the regmatic network of crustal faults was historically formed and permanently activated by cyclically acting tectonic forces of tension-displacement-compression associated with changes in the rotational regime during the galactic year, the polar radius of the Earth and the position of its rotation axis.

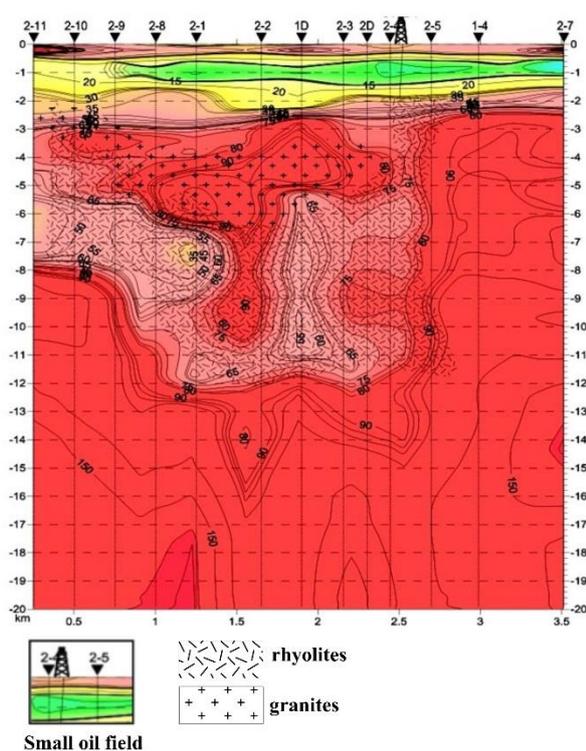


Figure 7. Deep geoelectric section.

As a result, three multilevel regmatic systems of inclined and shear discontinuities were formed in the South Ustyurt region for the crystalline basement, Paleozoic and Mesozoic rock complexes. The character of attenuation of regmatic systems and changes in the configuration of blocks in the Paleozoic, Paleozoic and Mesozoic (lower horizons) structural floors has been established [5].

Taking into account the latest data of seismology and structural analysis, the special role of hydrodynamic mechanisms in the formation of sectorial structures of the Earth's "crust" and "mantle" can be considered proved. It has been established that the uppermost crustal layers have a pronounced structure of "pounded ice" or even "chain mail".

The existence of transcrustal fluid- and magma-conducting channels is confirmed by experimental modeling of deep processes performed by E.K. Gerling (Radium Institute), L.L. Shanin (IGEM), V.V. Cherdyn'tsev (GIN), K.P. Florensky (GEOHI), A.Y. Namiot (MNI) and others. Multicomponent systems (rocks, minerals, salts on water, and even on water-hydrocarbon basis) were studied in autoclaves during both increasing and decreasing T-P conditions. Experiments with the introduction of inert gases - helium and argon - into the investigated complexes were of particular interest. The main result was the conclusion about the stepwise (quantized) nature of interactions of crystal structures of minerals and rocks with "inert" gases under elevated T-P conditions, which clearly reflected covalent and even transitional to chemical phenomena [34].

The previously available data on the special role of helium and hydrogen in changing the physical properties of rocks due to their intras-structural diffusion (without chemical interaction with the material) have been clarified.

As a result of low-energy impact, stress fields, structural rearrangements, deformation textures are formed in the solid rock skeleton, and general porosity develops. As formation pressures increase, their interactions intensify, phase transitions and chemical bonds occur.

As a result, a concept was formulated, which is based on the ideas of a mountain environment as a system located at depths of more than 3-5 kilometers in an unstable (metastable) state. The region of maximum stability approaches only near-surface, energetically background conditions. The instability increases with increasing gas saturation and temperature. Helium, nitrogen, and hydrogen can be indicators of deep heat and mass transfer.

The process of heat and mass transfer during the rise of deep substance to the Earth's surface (thermofluid dynamics) occurs stepwise with energy release, which is most clearly manifested in the foci of crustal earthquakes according to the heat- and gas dynamic model of A.S. Ponomarev [35, 36].

Energy release occurs through fluid-conducting thermohydrocolumns (in the terminology of D. S. Korzhinsky and G. L. Pospelov in the 50-70s). These processes are directly related to the mechanism of hydrothermal ore formation. In our case, we call such structures transcrustal magma- and fluid-suppressing faults.

It is thermofluidodynamics that determines the local instability factor, which is a function of the Earth's deep regime. On this basis, the features of the block structure of the lithosphere, seismicity regime and other forms of transition of the rock medium into an unstable state up to the stage of destruction and energy release are considered.

Examples of energy release would include explosions on the day surface, in coal and ore mines, in earthquakes and volcanic eruptions.

Methane explosions in coal mines, according to I.N. Yanitsky [32], often occur not in active faces (faces), where gas saturation of coal and rocks is higher, but in the rear of sinking and excavation. Emission in the latter case occurs from long ago opened and degassed faults in the mines. And the time of the emission appears to be synchronous with geodynamic activation, registered by other methods.

The intensity of emissions increases progressively with the depth of penetration. In the productive strata, emission-hazardous faults are represented by subvertical zones of strongly crushed coals with traces of increased temperature effects.

In the opinion of this researcher, methane to the active horizons of the mine comes from the lower, possibly even multi-kilometre, productive strata. The most striking fact is a major disaster in the coal industry (Shevyakov mine, 1 December, 1992, Kuzbass).

There are known explosions in ore mines, where the conditions for methane formation generally accepted for coal and oil regions are absent at all (gold and uranium deposits of Northern Kazakhstan, gold and uranium mines of Witwatersrand, South Africa, etc.). All this leads to the

conclusion about triggering their energy sources of plasmoid type with explosion temperatures of tens of thousands of degrees [32, 34].

Ground, or near-surface explosions (high-temperature, plasmoid type), which E. V. Barkovsky (OIFZ RAS) qualified as a phenomenon - discharge of the Earth's deep energy along a fault with a complex of preceding electromagnetic, gravitational, acoustic and light effects [32]. According to this researcher, the signs of gravitational explosion are observed during multifactorial processes of deep energy unloading, including in the epicenters of some earthquakes (e.g., Sochi, 1970, Spitak, 1986, etc.).

Volcanic eruptions can also be considered as a manifestation of the discharge of deep energy during heat and mass transfer. The Uzon -Geysernaya volcanotectonic depression and the Kikhpinych volcanic massif, which are part of the East Kamchatka volcanic belt, are considered as example [37].

In the eastern parts Uzon -Geysernaya volcano-tectonic depression according to the data of independent geological and geophysical studies (SAR- interferometry, thermohydrodynamic observations, thermal and infrared imaging, temporary seismological observations, slope instability processes) in 2000-2014 local geodynamic activation was observed, which is confirmed by : deformation of the earth surface, seismicity, heating of the young cone of the Kikhpinych volcanic massif, catastrophic landslide manifestations; changes in the thermodynamic parameters of hydro-thermal systems, the appearance of new hot and boiling springs according to the materials of aerothermal and ground-based infrared imaging [37].

The work on the permafrost allowed us to build a model of their deep structure (up to 30 km), clarify the existing ideas about the magmatic centre and reveal new features of the crustal structure.

Interpreting the MMZ results in comparison with the available geological understanding, the following main elements of the magmatic system of the Kikhpinych long-lived volcanic centre are manifested (Figure 8). Identified:

- an ancient shallow-depth crystallized magmatic source (intrusive) of acidic composition of irregular shape in the depth range from 2–3 to 10–12 km beneath the eastern part of the Uzon -Geysers Depression (structures 3 and 4, outlined with white dashed lines);
- magma chamber (basaltic melts concentration area) in the depth range of 15–20 km beneath the ancient crystallised hearth (structure 8);
- modern peripheral magmatic centre (area of basaltic melt concentration) beneath Kikhpinych volcano in the depth of 5–10 km (structure 7, outlined by white dashed line);
- crystalline basement from deeper horizons (subvertical heterogeneities, which are marked by white dashed lines with arrows).

The geometry of the detected deep structures agrees with the local weak seismicity and the model of magma intrusion into the upper crustal horizons, which allows us to specify the possible position of an irregularly shaped magma sill at depth 4–8 km deepening to the northwest [37].

Thus, on the basis of these studies, it was possible to analyse the peculiarities of the structure of the magmatic system of the long-lived volcanic centre. The different- aged magma chambers that caused the migration of eruption centres, as well as feeding isolated deep magma channels, were localized.

Discharge of excessive energy in the form of earthquakes may occur during deep degassing processes. According to V.L. Syvorotnikov (2023), this is indicated, firstly, by spatial coincidence of the epicenters of earthquakes and zones of intensive degassing in the axial parts of rift zones and in faults. Secondly, the direct connection between volcanic eruptions and seismic events, already mentioned above. Thirdly, numerous data on the correlation of fluctuations of gas flows (radon, helium, hydrogen) and earthquakes.

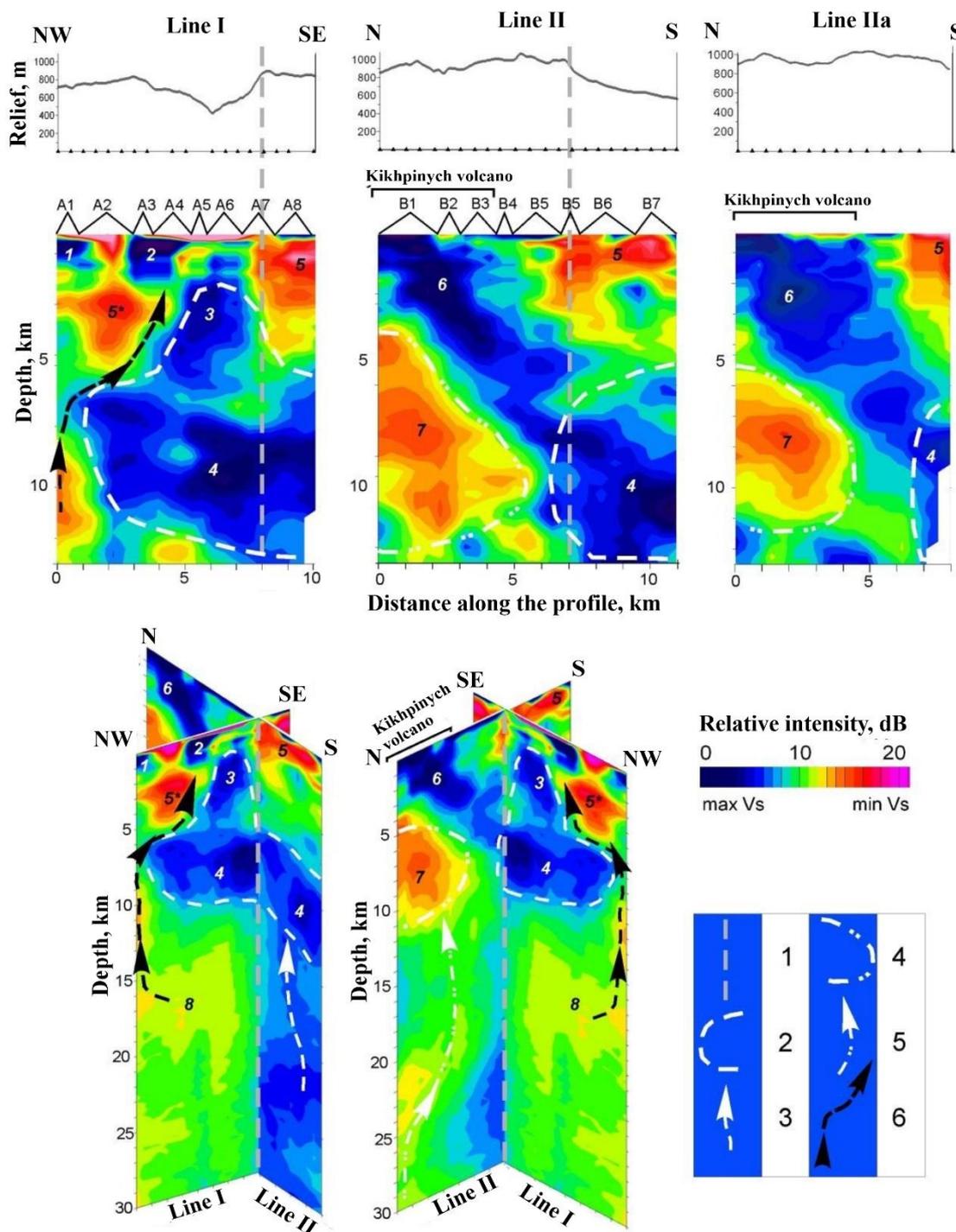


Figure 8. Depth sections along microseismic profiles in parameters of relative velocities of transverse seismic waves (with interpretation elements) according to [37].

Symbols: Top: up to a depth of 12 km. Bottom: quasi-3D representation to a depth of 30 km.

The sections are labelled with numbers: 1 – area of the extrusive dome of Belaya Mountain, partially overlain by lake sediments; 2 - field of extrusive domes development in the eastern part of the depression; 3, 4 - interconnected parts of the upper crustal crystallized magma source under the Uzon -Geysernaya depression; 5, 5* – blocks of undissected sediments of the pre-caldera complex (volcanogenic- sedimentary cover); 6 - magma propagation paths along the system of sublatitudinal discontinuities controlled by the regional Uzon-Valagin fault; 7 - peripheral source feeding Holocene

basaltoid eruptions of the Kikhpinych volcanic centre; 8 - basalt melt accumulation area formed due to the shielding role of acidic intrusion 4 located above.

Dotted lines in the legend: 1 - intersection line of sections I and II; 2 - conditional boundary of the crystallized magmatic hearth under the Uzon -Geysernaya depression; 3 - "root" that fed the hearth under the Uzon -Geysenayar depression; 4 - conditional boundary of the peripheral magmatic hearth of the Kikhpinych volcano; 5 - "root", feeding the hearth of Kikhpinych volcano ; 6 - presumed position of the magmatic sill , intruding from deeper horizons along the boundary of magmatic intrusions 3 and 4 (crystallized magmatic hearth) and volcanogenic-sedimentary stratum 5*.

The Institute of Geochemistry SB RAS (V.L. Syvorotnikov, 2023) created a model of the explosive origin of earthquakes during the rise of deep fluids. Heavy hydrocarbons play a special role in fluid detonation: alkanes, alkenes, alkadienes, alkynes, naphthenes and arenas. They are formed in the liquid core and are unstable outside it, but in fluid flows rising rapidly from the core, their migration to the upper mantle and the Earth's crust becomes possible, where their paths are controlled by transcrustal faults.

The rapid explosive transformation of heavy hydrocarbons into stable light hydrocarbons is accompanied by the release of a huge amount of energy capable of generating seismic events within the East European platform, e.g., in the White Sea -Baltic zone, on the Kola Peninsula, and the Voronezh Anticline.

The Earth Physics Institute of the Russian Academy of Sciences is developing (I.L. Gufeld, 2015) a model of seismic events occurrence when deep fluids (helium, hydrogen, methane) pass through rock volumes. Within the framework of the model it is postulated that the degassing impulse leads to the inhibition of mutual movement of blocks, i.e. to the blocking of boundaries. This process is possible due to the increase in the volume of crystalline structures of boundaries and blocks when hydrogen and helium are implanted into rock materials in concentrations corresponding to the lithosphere [38].

According to A.A. Marakushev (2010), the concept of global seismicity is based on a new (petrological) concept, according to which the processes of processing of mantle and crustal matter under the influence of fluid, essentially hydrogen flows rising to the surface from the molten core. Thus, the orogenic structure of the Andes with andesite volcanism is projected onto the epicenters of earthquakes of medium depth (up to 300 km), and while deep-focus (300-700 km) earthquakes occur beneath the platform depressions framing it.

On platforms, fluid deep flows lead, as a result of complex geochemical processes, to redistribution of matter between the crust and mantle with a thinning of the former and accretion of the latter. Thus, isometric platform depressions appear, within which degassing impulses provide phases of crustal substrate uplift and subsidence accompanied by seismic events [39].

5. Conclusions

Depth faults control the location of ore provinces, belts and deposits with which ore mineralization is associated. These faults manifest themselves as tectonically weakened zones saturated with intrusive rocks, as well as linear systems of grabens, volcanic-plutonic belts, etc., which provide access from deep within the lithosphere for volatile components and hydrothermal solutions.

The article considers the role of a deep source of heat and useful components in the genesis and history of ore deposits formation. It emphasizes the location of intracontinental ore belts in zones of linear crustal stretching (in the band of deep faults) with lithospheric decompaction and the presence of upper mantle heterogeneities.

On platforms and shields, ore belts are confined to their marginal parts, and, more often than not, are combined with continental volcanogenic belts of the marginal-continental or intracontinental types, which are characterised by an increase in the intensity of Paleozoic and Mesozoic ore genesis from the inner parts to the periphery.

These structures are characterized by epithermal ore formation as a consequence of the impact on the lithosphere of mantle jets rising along transcrustal faults, usually beneath weakened zones of the Earth's crust, which are subsequently transformed into rifts.

Thus, the processes of hydrothermal ore genesis and endogenous metamorphism of rocks are closely related to the stages of the geological history of deep faults, along which occur: a) intense block and clastic deformations, tectonic movements; b) formation of rift systems and spatially combined with them runways; c) formation of magmatic focal-dome structures, intrusive massifs, introduction of small intrusions and dikes.

Transcrustal magma- and fluid-supplying faults also control the formation of hydrocarbon accumulations regardless of the hypotheses of their origin – sedimentary-migration, abiogenic or geosynthetic.

For all three concepts, such faults play an extremely important role in conductive and convective heat and mass transfer from the mantle to the area of emigration and generation of hydrocarbon accumulations, determine the relationship between the processes of lithogenesis and tectogenesis in various geodynamic settings, and also accompany the additional heating of sedimentary strata and, consequently, activation of hydrocarbon generation from oil and gas mother formations.

The use of MMZ and MTZ at ore and oil and gas deposits allowed to reveal under them transcrustal zones of increased fluid -magmatic permeability - a kind of channels of heat and mass transfer to the area of ore deposition and the formation of HC accumulations.

The microseismic sounding method (MSM) is based on recording the spectrum of a low-frequency microseismic field represented by fundamental modes of Rayleigh surface waves, which are distorted around seismic (geological) inhomogeneities of the Earth's crust.

The research methodology consists of measuring the frequency-amplitude characteristics of microseisms along a profile or along a network of profiles, varying the amplitude values by depth, and constructing 2D or 3D seismic field models. In this case, subvertical geological heterogeneities and velocity boundaries are preferred for MMZ.

Magnetotelluric probing (MTZ) is able to successfully solve a number of problems of regional study of the geological structure of the lithosphere. The sources of the electromagnetic field in MTZ, the depth of electromagnetic field penetration and dependence on the electrical conductivity of the medium itself and on the field frequency, the skin effect, the stages of work and the geological problems to be solved are considered. Interpretation of MTZ data is carried out in the framework of 1D, 2D and 3D models.

5.1. *Ore minerals Deposits*

Application of MMZ on unique molybdenum-uranium deposits of the Streltsovskoye ore field (SRF) in Eastern Transbaikalia allowed to detect a transcore column of increased fluid -magmatic permeability of “cylindrical shape” with a radius of about 5 km, localised at the junction of sublatitudinal and submeridional faults traced to depths of 10-15 km.

The column is the main channel for the flow of multi-depth magmatic melts of basaltic, dacitic and rhyolite compositions into the upper part of the Earth's crust and for the movement of high-temperature uranium-bearing hydrothermal solutions into the area of ore deposition.

5.2. *Hydrocarbon Fields*

A system of subvertically oriented deep faults with increased fluid conductivity has been identified beneath the Astrakhan gas condensate field, along the planes of which huge volumes of high-temperature aggressive vapour-gas mixtures, including those containing hydrocarbons, have probably been and are being lifted and carried away. These mixtures react chemically with dispersed organic matter, activate catagenesis processes and form HC accumulations. Oil producing wells with reservoirs of increased porosity are located above this area at low velocities.

According to the MTZ results, the hydrocarbon fields of the South Turgai oil and gas bearing basin are also characterized by steeply inclined transcrustal fluid- and magma-supporting faults,

which are bodies penetrating the Earth's crust. We can assume their direct impact on the processes of HC accumulation formation.

5.3. Nature of Transcrustal Fluid- and Magma -Conducting Channels

Transcrustal fluid and magma conduits are thought to be confined to faults of ancient (Archean-Proterozoic) emplacement time, which determined the fragmentation of the Earth's subcrystalline structure.

Later, these faults the residual forms of functioning of large-scale fluid-conducting thermohydrocolumns are batholiths of granitoids that served as consolidation cores.

Such structures serve as fluid conduits even nowadays. Their existence is confirmed by experimental modeling of deep processes. The character of quantized interactions of crystal structures of minerals and rocks with inert gases under elevated T-P conditions was revealed, which clearly reflected covalent and even transient to chemical phenomena. The previously available data on the special role of helium and hydrogen in changing the physical properties of rocks due to their intrastructural diffusion were clarified.

As a result of low-energy impact in the solid skeleton of minerals, stress fields, structural rearrangements, deformation textures are formed, and general porosity develops. With increasing pressure, energy interactions intensify, phase transitions and chemical bonds occur in unstable geological environment. With increasing gas saturation, pressure, and temperature, instability increases. Helium, nitrogen, and hydrogen can be indicators of deep heat and mass transfer.

The process of heat and mass transfer during the rise of deep substance to the Earth's surface occurs in stepwise with energy release, which manifests itself most clearly in the foci of crustal earthquakes according to the thermal-gas-dynamic model.

Energy release occurs transcrustal magma- and fluid-supporting faults that are directly related to the mechanism of hydrothermal ore formation. Examples of energy release would include daylight surface explosions, coal and ore mines, during earthquakes and volcanic eruptions.

6. Patents

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References

1. Kotova N.P. Geotectonic features of formation and mineralogenic zoning of Eastern Transbaikalia for fluorite // *Vestnik of ZabsU*. 2011. No. 12. URL: <https://cyberleninka.ru/article/n/geotektonicheskie-osobennosti-formirovaniya-i-mineragenicheskoe-rayonirovanie-vostochnogo-zabaykalya-na-flyuorit>.
2. Samsonov Ya.P., Savelyev A.K. *Geology of deposits of fluorine-containing raw materials*. – M.: Nedra, 1980. – 216 p.
3. Alieva O.Z., Koplus A.V., Evolutionary model of ore potential formation of fluorite epithermal mineralization // III International Conference "New Ideas in Earth Sciences": report summary. - V. 2. - M., 1997.
4. Harland W.B., Armstrong R.L., Cox A.W., A. *Geologic Time Scale* // Cambridge University Press. – 1989.
5. Iskandarov M.Kh., Abdullaev G.S., Mirzaev A.U., Khakimzyanov I.N., Umarov Sh.A. Scientific and innovative research of oil and gas formation processes in Ustyurt oil and gas region - Oil province. 2022. No. 3(31). P.23-55. <https://doi.org/10.25689/NP.2022.3.23-55>.
6. Laverov N.P., Velichkin V.I., Vlasov B.P., Aleshin A.P., Petrov V.A. Uranium and molybdenum-uranium deposits in areas of development of continental intracrustal magmatism: geology, geodynamic and physicochemical conditions of formation. Moscow: IFZ RAS, IGEM RAS, 2012. 320 p.

7. Abetov A.E., Alyoshin A.P., Akhmetov E.M., Gorbatiykov A.V., Erdyakov I.L., Malyshev O.A. Innovative method of microseismic sounding as an effective tool for studying the structures of oil and ore deposits - Abstracts for the forum " KGF, Oil & Gas, 2015", Astana, 2015.
8. Thomson I.N., Krivtsov V.S., Kochneva N.T. et al. Ore-bearing capacity of continental volcanic belts. – Moscow: Nedra, 1982.
9. Zubkov V.S. Tendencies in the distribution and hypotheses of the genesis of condensed naphthides in magmatic rocks from various geodynamic environments. *Geochem. Int.* 47, 741–757 (2009), no. 8. <https://doi.org/10.1134/S0016702909080011>.
10. Lurye M.A., Schmidt F.K. Sulfur content, metalliferousness, carbon and sulfur isotopy of oils as genetic characteristics // *Electronic journal "Deep Oil"*, 2013. Vol. 1. No. 4. Pp. 448-459. URL: http://journal.deepoil.ru/images/stories/docs/DO-1-4-2013/4_Lurije-Shmidt_1-4-2013.pdf.
11. Balitsky V.S., Bondarenko G.V., Pironon J., Penteley S.V., Balitskaya L.V., Golunova M.A., Bublikova T.M. On the causes of vertical zoning in hydrocarbon distribution in earth interior: experimental evidence of crude oil cracking in high-temperature aqueous-hydrocarbon fluids. *Superkriticheskie Flyuidy: Theory i Praktika*, V8, 2, 39-60 (2013). https://scf-tp.ru/articles/2013_02/3_r.html.
12. Abetov A.E., Alyoshin A.P., Akhmetov E.M., Gorbatiykov A.V., Erdyakov I.L., Malyshev O.A. Identification of transcrustal magmatic and fluid -conducting ore-generating structures using an innovative method of microseismic sounding (MSS). To the meet "Modern problems of geology, geophysics and metallogeny", Tashkent, 2015, pp. 13-18.
13. Bazhenova O.K., Burlin Yu.K., Sokolov B.A., Khain V.E. *Geology and Geochemistry of oil and gas*. Moscow, Moscow State University, 2012. 432 p.
14. Abidov A.A. Mixgenetic scheme of natural hydrocarbon synthesis of HC and its significance for prediction oil and gas content of regional oil and gas bearing structures and geodynamic conditions of oil and gas formation and oil and gas accumulation in the Earth's crust. // Tashkent. 2002.
15. Barenbaum A.A. New ideas about the origin of oil and gas in connection with the discovery of the phenomenon of replenishment of reserves of exploited fields - *Georesources / Georesources*, 2019. Vol. 21. No. 4. pp. 34-39. <https://doi.org/10.18599/grs.2019.4.34-39>.
16. Iktisanov V.A. Synthesis rate during field development. *Oilfield Business*, No. 4, 2017, pp. 49-54.
17. Tleubergenova A.K., Umirova G.K., Portnov V.S., Mausimbaeva A.D. High-precision aeromagnetic survey on the Shu-Sarysu geotraverse // *Oil and Gas*. - Almaty, 2023, No. 3 (135), pp. 52-67, ISSN 1562-2932. <https://doi.org/10.37878/2708-0080/2023-3.04>.
18. Tleubergenova A., Umirova G., Maussymbayeva A., Portnov V. Comprehensive analysis of magnetic and gravity data based on volumetric gravity-magnetic modelling along the geotraverse in the Shu- Sarysu sedimentary basin // Vol. 3 No. 102 (2023): *Visnyk of Taras Shevchenko National University of Kyiv. Geology*, pp. 31-37. <https://doi.org/10.17721/1728-2713.102.05>.
19. Gorbatiykov A.V., Stepanova M.Y., Korablev G.E. Microseismic field affected by local geological heterogeneities and microseismic sounding of the medium. *Izv., Phys. Solid Earth* 44, 577–592 (2008). <https://doi.org/10.1134/S1069351308070082>.
20. Gorbatiykov A.V., Tsukanov A.A. Modelling of Rayleigh waves near scattering velocity inhomogeneities. Investigation of possibilities of the method of microseismic sounding // *Physics of the Earth*. 2011. No. 4. P. 96-112.
21. Abkadyrov I.F., Gorbatiykov A.V., Stepanova M.Yu., Bukatov Yu.Yu. Experience of application of the method of microseismic sounding of geothermal fields on the example of Nizhne- Koshelevskaya / thermoanomaly (South Kamchatka) / *Proceedings of the 19th regional youth scientific conference "Natural environment of Kamchatka"*, Petropavlovsk-Kamchatsky, 2010. P.49-59.
22. Pospeev A.V., Seminski, I.K., Nemtseva D.B. First results of magnetotelluric soundings for mapping the Riphean sediments of the Baikal foredeep. *Geodynamics and Tectonophysics*, 2021, 12(3S): 769-775. <https://doi.org/10.5800/GT-2021-12-3s-0553>.
23. Tleubergenova A., Umirova G., Karpenko O., Maussymbayeva A. Geoelectrical model of the earth's crust along the Shu-Sarysu geotraverse according to magnetotelluric soundings. *Naukovyi Visnyk Nationalnoho Hirnychoho Universytetu*, 2023, (3), pp.3-10, <https://doi.org/10.33271/nvngu/2023-3/005>.
24. Petrov V.A., Andreeva O.V., Poluektov V.V., Kovalenko D.V. Uraniferous volcanogenic structures: Streltsovskaya (RF), Xianshan (China) and McDermitt (USA). Comparative analysis of the petrology of acid volcanics and the composition of near-ore metasomatites. *Geology of ore deposits*, 2022, Vol. 64, No. 1, pp. 7-36. <https://doi.org/10.31857/S0016777022010063>.
25. Gorbatiykov A.V., Stepanova M.Yu., Tsukanov A.A., Tinakin O.V., Komarov A.Yu., Odintsov S.L., Tokman A.K. New technology of microseismic sounding for studying the deep structure of oil and gas fields // *Oil industry*, 2010. No. 6. P. 15-17. https://oil-industry.net/en/Journal/archive_detail.php?ID=8978&art=186801.

26. Madisheva R.K., Portnov V.S., Amangeldiyeva G.B. et al. Geochemical prerequisites for the formation of oil and gas accumulation zones in the South Turgay basin, Kazakhstan. *Acta Geochim* 43, 520–534 (2024). <https://doi.org/10.1007/s11631-023-00660-4>.
27. Wang, S.M., Di, Q.Y., Zou, G.A. et al. Electrical resistivity imaging in Shibaozhai area using magnetotelluric sounding: Enlightenment of hydrocarbon reservoirs on the eastern edge of the Sichuan Basin. *Appl. Geophys.* 19, 294–305 (2022). <https://doi.org/10.1007/s11770-022-0979-6>.
28. He Meixing, PEI Fagen, FANG Hui, et al. Electrical structure and geological controlling factors of natural gas hydrates in Muli, Qilian Mountains[J]. *Journal of Central South University (Science and Technology)*, 2022, 53(3): 879-889. <https://doi.org/10.11817/j.issn.1672-7207.2022.03.010>.
29. He Faqi, YU Wenhui, MA Chao, ZHANG Shihui, LI Xiaowei, LI.U. Demin.2024. Deep structure and genesis of Sanmenxia fault basin and its adjacent area: Evidence from deep seismic reflection and magnetotelluric sounding[J]. *Acta Geologica Sinica*, 98(4):1088-1100, 2024. <https://doi.org/10.19762/j.cnki.dizhixuebao.2023167>.
30. Abdullaev G.S., Dolgoplov F.G., Tukhtaev K.M., Toshkulov A.Zh. Multilevel regmatic systems and fault-block structure of the South Ustyurt depression. // *Actual problems of oil and gas*. Moscow. 2020. Issue. 1(28). <http://doi.org/10.29222/ipng.2078-5712.2020-28.art1>.
31. Sysoev B.K., Yagafarov A.K., Arsan S.A., Khudyakov D.S., Savina M.E. Features of magnetotelluric scanning of the Earth's crust while searching and exploring hydrocarbon deposits. *Oil and Gas Studies*. 2019;(5):40-45. (In Russ.) <https://doi.org/10.31660/0445-0108-2019-5-40-45>.
32. Yanitsky I.N. Fluid regime of the Earth in the light of high-frequency geodynamics/Proceedings of the International Conf. "Degassing of the Earth: geodynamics, geofluids, oil and gas" Moscow: "GEOS", 2002. Pp. 281-283).
33. Bashorin V.N., Borodzich E.V., Korobeynik V.M. et al. Heliometric and prognostic studies at estimation the reliability of industrial sites of responsible engineering constructions. - Collection. "Assessment of seismo-tectonic conditions of nuclear power plant construction sites of ". Moscow: Energoatomizdat, 1987. Pp. 28-37.
34. Yanitsky I.N. About fluid-conducting thermohydromassives in the Earth interior (scientific and applied aspects of fluid dynamics) / Proceedings of the conference "Tectonics, geodynamics and magmatism processes" Moscow: RAS, 1999. Pp. 332-336.
35. Ponomarev A.S. Thermal and gas -dynamic model of crustal earthquakes// *Physics of the Earth*, 1990, No. 10. P. 100-112.
36. Yanitsky I.N. The concept of N.S.Shatsky "About modern faults on platforms in the light of heliometric and prognostic studies" / Materials of meeting "General issues of tectonics" M.: "GEOS", 2000. P. 633-637.
37. Kugaenko Yu. A., Saltykov V. A., Gorbatikov A. V., Stepanova M. Yu. Development of the model of the Uzon -Geysernaya volcano -tectonic depression area and the Kikhpinych volcano (Kamchatka) based on the results of a joint analysis of microseismic sounding data and local geodynamic activity – Moscow, *Physics of the Earth*, 2015, No. 3, pp. 89–101. <https://doi.org/10.7868/S0002333715030096>.
38. Gufeld I.L. Geological consequences of amorphisation of the lithosphere and upper mantle structure caused by hydrogen degassing. *Geodynamics and Tectonophysics*. 2012;3(4):417-435. <https://doi.org/10.5800/GT-2012-3-4-0083>.
39. Marakushev A.A., Marakushev S.A. Fluid Evolution of the Earth and Origin of the Biosphere. in "Man and the Geosphere." Chapter 1", p. 3-31, Florinsky I.V. (Ed.), 2010. <https://www.webofscience.com/wos/WOSCC/full-record/000283640000001>, Nova Science Publishers, Inc. New York, 385 p.

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