

Article

The Roles of Transcrustal Magma- and Fluid-Conducting Faults in the Formation of Mineral Deposits

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Abstract: In this article, we consider the roles of transcrustal magma- and fluid-conducting faults (TCMFCFs) in the formation of mineral deposits, showing the importance of deep sources of heat and hydrothermal solutions in the genesis and history of deposit formation. As a result of the impact on the lithosphere of mantle plumes rising along TCMFCFs, intense block deformations and tectonic movements are generated; rift systems, and volcanic–plutonic belts spatially combined with them, are formed; and intrusive bodies are introduced. These processes cause epithermal ore formation as a consequence of the impact of mantle plumes rising along TCMFCF to the lithosphere. At hydrocarbon fields, they play extremely important roles in conductive and convective heat, as well as in mass transfer to the area of hydrocarbon generation, determining the relationship between the processes of lithogenesis and tectogenesis, and activating the generation of hydrocarbons from oil and gas source rock. Detection of TCMFCFs was carried out using MMSS (the method of microseismic sounding) and MTSM (the magnetotelluric sounding method), in combination with other geological and geophysical data. Practical examples are provided for mineral deposits where 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 emplacement, which determined the fragmentation of the sub-crystalline structure of the Earth and later, while developing, inherited the conditions of volumetric fluid dynamics, where the residual forms of functioning of fluid-conducting thermohydrocolumns are granitoid batholiths and other magmatic bodies. Experimental modeling of deep processes allowed us to identify the quantum character of crystal structure interactions of minerals with “inert” gases under elevated thermobaric conditions. The roles of helium, nitrogen, and hydrogen in changing the physical properties of rocks, in accordance with their intrastructural diffusion, has been clarified; as a result of low-energy impact, stress fields are formed in the solid rock skeleton, the structures and textures of rocks are rearranged, and general porosity develops. As the pressure increases, energetic interactions intensify, leading to deformations, phase transitions, and the formation of chemical bonds under the conditions of an unstable geological environment, instability which grows with increasing gas saturation, pressure, and temperature. The processes of heat and mass transfer through TCMFCFs to the Earth’s surface occur in stages, accompanied by a release of energy that can manifest as explosions on the surface, in coal and ore mines, and during earthquakes and volcanic eruptions.



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1. Introduction

In the literature [1–5], a prevailing concept has been identified concerning the existence of transcrustal zones that facilitate the formation of ore deposits.

The references [6–10] provide a detailed examination of the influences of deep transcrustal channels on heat–mass transfer to hydrocarbon and generation migration zones; these studies underscore the critical role of deep faults in the hydrocarbon migration process, as well as their significance in the formation and accumulation of hydrocarbon deposits.

In solid mineral geology, the concept of an “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 natures [11–13].

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 useful components by hydrothermal solutions; thus, the direct participation of mantle processes in the formation of endogenous deposits is obvious [13–16].

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 significant, if not dominant, role in these processes is played by deep faults, which control the distribution of ore provinces, belts, and deposits. The concentrations of various volatile compound components serve as indicators of these faults’ activities [17].

For example, volatile components, such as F, Cl, P, B, and H₂O, play a crucial role in the formation of magmas of varying acidity, significantly influencing the evolution of granitic magmas and pegmatites, the variation in melt solidus and liquidus temperatures, the viscosity of silicate melts, and the crystallization sequence of mineral formation, as well as the behavior of dispersed ore and rare elements and their partitioning between the fluid and melt [17–19].

The access of volatile components and hydrothermal solutions from the depths of the lithosphere is facilitated by deep faults, which manifest as tectonically weakened zones saturated with intrusive rocks, as well as linear systems of grabens and volcanic–plutonic belts (VPBs) [19–23].

In continuation of this postulate, a comparison of the tectonic positions of intracontinental ore belts with the schemes of geodynamic zoning and the deep structures of their territories shows that the main provinces are located in the zone of linear stretching of the Earth’s crust [20,24], and the most productive regions, such as Transbaikalia, Central Asia, South Kazakhstan, and others, are additionally characterized by lithospheric decompression and the presence of upper mantle heterogeneities, forming the peripheral parts of the Central Asian anomalous mantle domain [25–27].

An increase in the intensity of Paleozoic and Mesozoic ore genesis is observed from the central to the peripheral parts of the mentioned regions. A correlation is noted between the scale and formation affiliation of the mineralization and the thickness of the anomalous mantle, as well as the subduction depth of its edges [28,29].

As for platforms and shields, ore belts are directly associated with their marginal parts and are most often aligned with either marginal–continental (e.g., the Pacific Belt) or intracontinental (e.g., Transbaikalian, Mongol–Transbaikalian, Beltau–Kurama, South Kaza-

khstan, and others) VPBs, structures which are typically characterized by manifestations of epithermal ore formations, resulting from the impacts of mantle plumes rising through TCMFCFs [24], usually under weakened zones of the Earth's crust, which later transform into rifts [12,30].

In contrast, stable areas of platforms and shields experience uplift without volcanic activity; as the mantle activity decreases, the process of arch formation (arcogenesis) transitions into a stage of stress relaxation, accompanied by extension and differential movements (arch collapse, taphrogenesis, horst–graben tectonics, etc.) [31].

Thus, the processes of hydrothermal ore genesis and endogenous rock metamorphism are closely related to the stages of the geological history of the region and are characterized by the following properties: (a) intense fold–block dislocations along reactivated and newly formed deep fault structures; (b) rift systems formation and spatial association of them with volcano–plutonic belts (VPBs) filled with sedimentary and volcanogenic rocks (e.g., the Devonian marginal VPB of Central Kazakhstan); (c) the formation of magmatogenic focal–dome structures and the emplacement of intrusions, including dikes, stocks, batholiths, sills, and similar bodies [32,33].

TCMFCFs also control the formation of hydrocarbon (HC) accumulations. For more than 100 years, two hypotheses have represented independent scientific paradigms in oil and gas geology, namely the sedimentary–migrational and abiogenic hypotheses, which debate the origin of hydrocarbons. Each of the paradigms is supported by a large number of researchers and is based on the results of numerous experiments and theoretical studies; nevertheless, researchers have not eliminated the known difficulties inherent in the paradigms themselves, which has not allowed the scientific community to make a definitive choice in favor of one of them [34–39].

The supporters of the first theory argue that oil and gas are formed directly within fields from organic matter originating “from above”—from the Earth's surface—whereas the second group maintains that hydrocarbons migrate into fields “from below”—from the Earth's deep interior, where they are generated [23,35,37].

The idea of an endogenous origin of hydrocarbon fields is being intensively promoted [40–42]. The fluidodynamic [43,44] and sedimentary–fluidodynamic [24,28] concepts of oil and gas generation are being actively developed; according to these concepts, the interconnection of lithogenesis and tectogenesis processes occurs within various geodynamic settings; mantle faults facilitate conductive and convective heat–mass transfer, leading to additional heating of the sedimentary strata and, consequently, the activation of hydrocarbon generation from oil and gas source suites.

The mixed-genetic hydrocarbon origin theory is based on the scheme of petroleum synthesis, with the participation of dispersed organic matter and channels of deep heat–mass transfer from the position of lithospheric plate tectonics [45]; this hypothesis was substantiated by three Uzbek petroleum geologists [23].

In recent years, an independent and actively developing concept of oil and gas formation has emerged, successfully competing with the sedimentary–migrational and abiogenic hypotheses [46,47].

In accordance with this concept, the main mechanism of oil and gas formation in the subsurface is the polycondensation synthesis of hydrocarbons from carbon oxides and hydrogen, occurring in the water-saturated mineral matrices of rocks, mechanically activated through natural seismotectonic processes [48].

In this mechanism, referred to as geosynthesis, water acts as the hydrogen donor in hydrocarbons, while organic matter, water-dissolved CO₂, and easily soluble carbon-containing minerals serve as the carbon donors [49].

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

Under the influence of seismotectonic deformations, intracrystalline defects are generated in the minerals of rocks [48], which diffuse to the surface of the mineral grains to form an energy-enriched layer that reduces the Gibbs free energy of chemical reactions.

Such reactions, as shown by references [48,50–52] include the decomposition of H₂O with the release of hydrogen, which participates in the synthesis of hydrocarbons from carbon oxides (CO and CO₂).

Consequently, all of the above concepts, hypotheses, and experimental data highlight the crucial role of TCMFCFs as key agents of heat and mass transfer from the mantle interior to zones of ore formation and hydrocarbon generation.

These unique deep-seated geological structures have become the subject of research, the results of which are presented in this article.

2. Study Areas and Geological Setting

As the previous studies have demonstrated, TCMFCFs are established beneath deposits of solid minerals and hydrocarbons fields, regardless of their age, the structural and formational composition of the host rocks, tectonics, and geological evolution, which, in turn, directly indicates a paragenetic relationship between deep and near-surface conditions in the formation of these unique natural phenomena.

In order to facilitate the perception of the considered cases, later in the text of this article, in the form of annotations, information is presented on the geology of mineral deposit areas, under which TCMFCFs are reidentified.

2.1. Precaspian Depression

The Precaspian Basin (Figure 1) occupies the southeastern part of the East European Platform, with the Precambrian Basement subsiding to depths of 22–24 km; this region hosts major hydrocarbon fields, including Tengiz, Kashagan, Karachaganak, Zhanazhol, Kenkiyak, Alibekmola, and Urikhtau (subsalt), as well as Kenkiyak and Shubarkuduk (suprasalt).

The sedimentary cover (6–24 km) comprises the following three megacomplexes (levels): subsalt, salt-bearing (Lower Permian, Kungurian), and suprasalt (Meso–Cenozoic, Upper Permian). Drilling has penetrated rocks of Asselian, Sakmarian, Artinskian, and Carboniferous ages, as well as Devonian sediments [53–55].

The subsalt level is represented by carbonate massifs (organogenic limestones); in some areas, oil and gas occur in terrigenous reservoirs (Kenkiyak); the main types of deposits are reef protrusions, as well as dome-shaped and brachyanticline uplifts; the depths range from 2700 to 3600 m (Zhanazhol), 3900 to 4200 m (Astrakhan), and 3800 to 5500 m (Tengiz, Karashyganak) [54,55].

Subsalt hydrocarbon accumulations are characterized by extreme thermobaric conditions, including pressure ranges from 65 to 105 MPa and temperature variations between 110 and 120 °C. Gas condensate fields contain condensate (580–644 g/m³) and hydrogen sulfide (1–24%).

The suprasalt level is composed of terrigenous sandy–clayey sediments with carbonates; several dozen oil fields have been discovered there, small in terms of reserves in the Pliocene and Upper Jurassic sediments (Port Arthur, Airshagyl, Ushkultak). Oil and gas complexes of the suprasalt floor include the Permian–Triassic, Middle–Upper Jurassic, Lower Cretaceous, and Neogene. Additionally, there are fields in the Upper Permian, Upper Cretaceous, and Paleogene sediments (Kenkiyak, Karatobe) [54].

The main types of hydrocarbon accumulations are layer-uplifted, lithologically sealed, and tectonically trapped reservoirs.

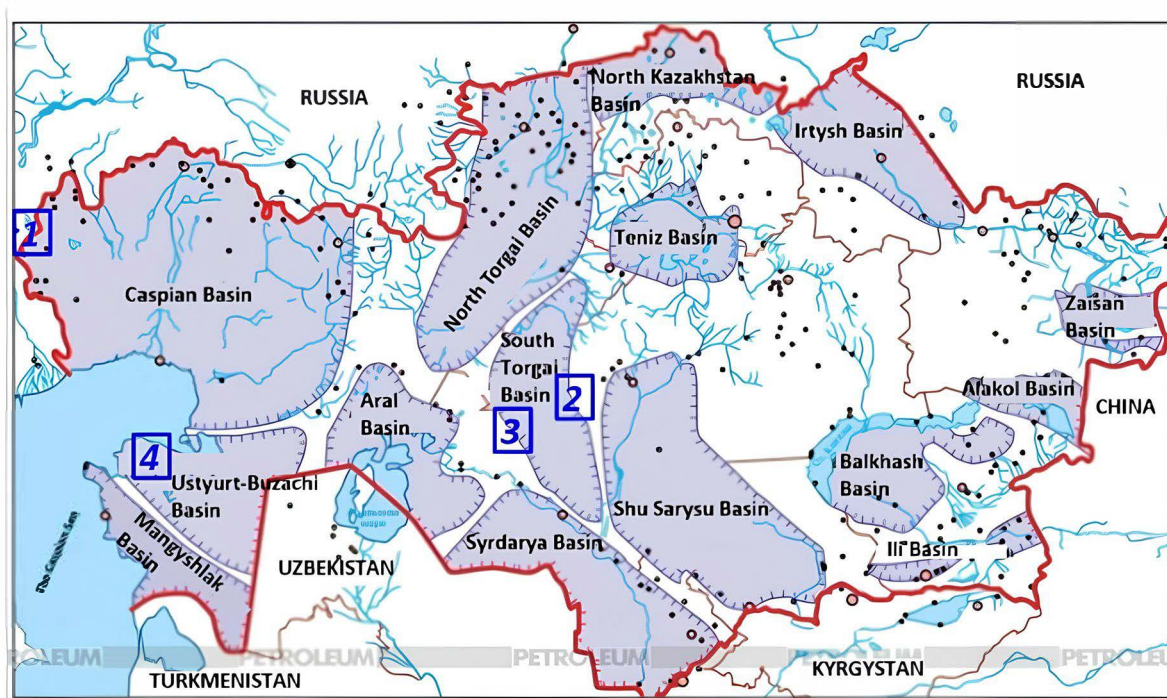


Figure 1. Overview map of the sedimentary basins of the Precaspian Depression and the Turan Plate. Legend: 1. Astrakhan Gas Condensate Field. 2. Kumkol Oil and Gas Field. 3. Kyzylkia Oil and Gas Field. 4. Northern Karazhanbas Oil Field.

2.2. Turan Plate

The Turan Plate occupies a vast area to the east of the Caspian Sea within the Turan Lowland, the Ustyurt Plateau, the Mangyshlak Peninsula, the Aral Sea, and adjacent territories (Figure 1).

Encompassing the sedimentary basins of Kazakhstan, the Turan Plate borders the Caspian Basin in the northwest. In the north, the border runs along the Hercynian Mugodzhar Range and then crosses the Turgai Trough; in the northeast, the plate is limited by the Caledonian outcrops of the Kazakh Uplands.

The Turan Plate has been extensively studied; geological and regional geophysical surveys have been conducted, along with a substantial volume of seismic investigations and hydrogeological studies.

The plate is formed by three structural levels, as follows: the lower one is a folded basement, overlain by an intermediate structural level, and, finally, there is a platform cover on top [56,57].

The basement of the Turan Plate is composed of highly metamorphosed and intensely deformed Precambrian and Paleozoic quartzites, crystalline schists, marbles, and Silurian flysch sequences, enriched with volcanogenic–sedimentary rock complexes and magmatic intrusions. In the northeastern part of the plate, the basement was formed by Caledonian orogeny (Precambrian, Lower Paleozoic, Silurian). The remaining territory is characterized by a Hercynian Basement, which is segmented by faults and features rigid massifs within major structural domains.

The intermediate (second) structural level of the Turan Plate lies with angular nonconformity on the basement and includes weakly dislocated (dip angles of 15–20°) volcanogenic–sedimentary rocks of the Devonian (andesites, dacites, sandstones, and

conglomerates up to 7 km thick), salt-bearing, and coal-bearing strata (Upper Famennian–Tournaisian) up to 4 km. The upper horizons are composed of sandy–conglomerate strata (Middle Carboniferous–Lower Triassic) up to 3.5 km [57]. In the Hercynian Region, the floor is of Early Permian–Late Triassic age, and its thickness ranges from hundreds of meters to 11 km (Mangyshlak), consisting of marine and continental suites, as follows: at the base, there are compacted sandstones, siltstones, argillites, and limestones (Permian–Middle Triassic); at the top, there are black limestones, shales, and argillites with ammonites (Upper Triassic).

The platform cover of the Turan Plate comprises oil- and gas-bearing Lower, Middle, and Upper Jurassic, as well as Cretaceous–Miocene, rock complexes. The Lower Jurassic complex is composed of sandy–clayey deposits, while the Middle and Upper Jurassic complex consist of terrigenous, coal-bearing, and carbonate formations, reaching thicknesses of up to 1000 m. Cretaceous deposits include both marine and continental facies, with thicknesses of up to 3 km. The Paleogene unconformably overlies the Upper Cretaceous and is represented by limestones, marls, and clays [57].

Middle Miocene–Upper Pliocene deposits are widely developed in the western part of the plate, comprising both marine and continental facies. Upper Pliocene–Quaternary sediments include marine, alluvial, and aeolian formations, with increased thicknesses in depressions.

2.3. The Astrakhan Gas Condensate Field

The Astrakhan Gas Condensate Field (AGCF) is located in the southwestern part of the Precaspian Depression, 60 km northeast of Astrakhan (Figures 1 and 2). The field measures 100×40 km, with production occurring at a depth of 4100 m; it is associated with the central, most elevated part of the Astrakhan Arch. Reserves are estimated at 2.5 trillion m³ of gas and 400 million tons of condensate, characterized by high hydrogen sulfide (26%) and carbon dioxide (16%) contents [58,59].

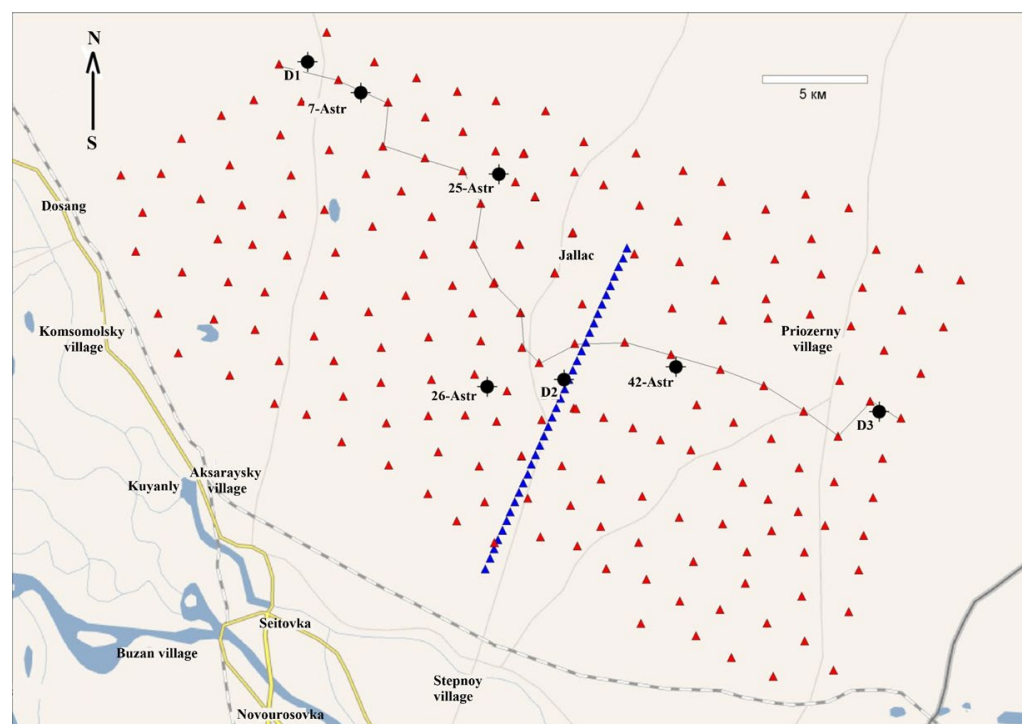


Figure 2. MMSS profile and area surveys at the AGCF (modified after [58,59]). Legend: ▲ —MMSS pickets on the network, ——detailed profile of MMSS.

The AGCF was discovered in August 1976, and pilot exploitation began in 1987. This field is the largest in the European part of Russia and is unique in terms of its reserves and fluid composition [58].

The formation of the AGCF was driven by paleotectonic, geochemical, and thermodynamic processes occurring in the carbonate strata of the Middle and Lower Carboniferous. The lithological and tectonic isolation of the Astrakhan Arch served as a favorable factor for the development of a closed, isolated gas–hydrodynamic system with specific conditions for hydrocarbon accumulation, hydrogen sulfide and carbon dioxide formation, and the establishment of extreme thermobaric conditions for reservoir fluids [58,59].

2.4. The Kumkol Oil and Gas Field

The Kumkol Oil and Gas Field belongs to the Turan Oil and Gas Province; it was discovered in February 1984 and is located 230 km from the Pavlodar–Shymkent oil pipeline and 200–250 km north of the city of Kyzylorda, within the Ulytau Region (Figure 3).

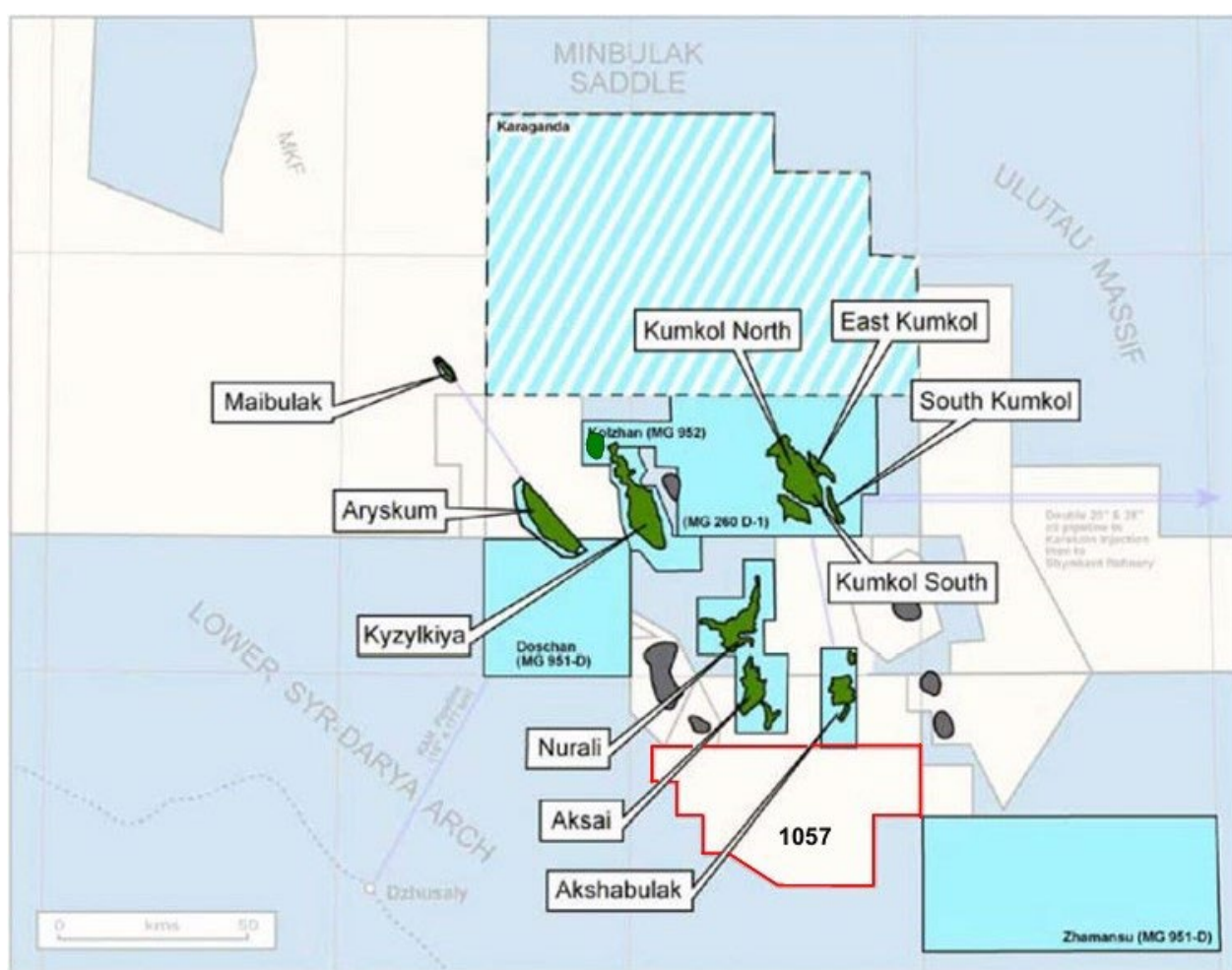


Figure 3. Diagram of the distribution of oil fields in the South Turgay Petroleum Basin (modified after [60,61]).

Tectonically, the field is associated with the Sorbulak Basement uplift, which complicates the northeastern segment of the Aryskum Depression. The block uplift of the basement is reflected in the overlying sediments as a horst, and in the Cretaceous–Cenozoic deposits as a swell. The Kumkol structure, within the Jurassic–Cretaceous productive complex, represents a brachyanticlinal fold of complex shape, with an amplitude of 50 m in Neocomian sediments and 150 m in Jurassic sediments [60].

The reservoirs in the Cretaceous sediments are oil-bearing, and in the Jurassic sediments they are oil-and-gas-bearing and purely oil-bearing. They are classified as stratified and anticlinal, with tectonic and lithological sealing [60].

2.5. The Kyzylkiya Oil and Gas Field

At another field (Kyzylkiya), located west of Kumkol (Figure 3), the MTSM results also showed a similar increase in specific resistance (see below in the text), associated with deep faults and heat and mass transfer processes [60,61].

The Kyzylkiya Oil and Gas Field is located 40 km to the west of the Kumkol Oil and Gas Field; it was explored through seismic surveys in 1984–1985, and the first oil product was obtained in 1986. The oil and gas accumulations were explored in the sediments of the Aryskum horizon of the Lower Neocomian (at depths ranging from 1467 to 1600 m), and a small amount of oil was obtained from the basement rocks.

In the example of the electric exploration works of MTSM in the South Turgai Depression, one can observe the paragenesis of subvertical conductive zones (channels) and areas of development of porous bodies (reservoirs) saturated with hydrocarbons [60,61].

2.6. Northern Karazhanbas

Now, we consider the identification of TCMFCFs using the example of the Northern Karazhanbas Field in the North Ustyurt Sedimentary Basin.

Northern Karazhanbas is a field with heavy oil, located in the Tupkaragan district of the Mangistau Region of Kazakhstan, on the Bozashy Peninsula (Figure 4); it was discovered in 1981 and belongs to the North Bozashy petroliferous region [60,61].

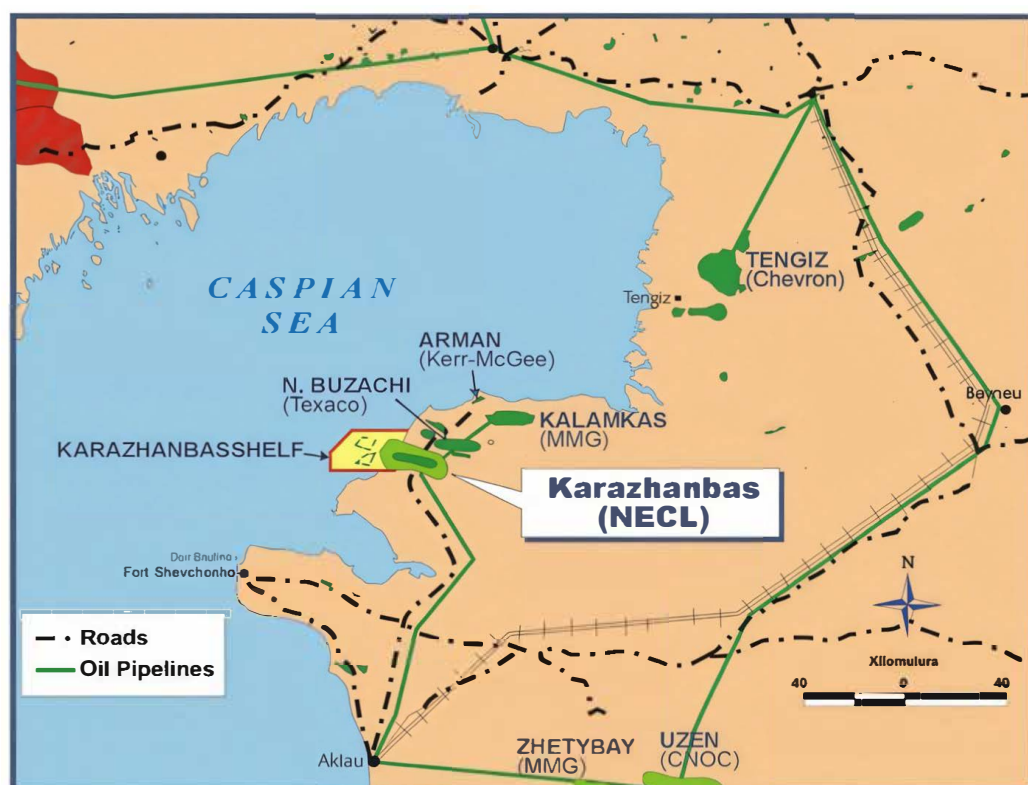


Figure 4. Location of the Northern Karazhanbas Heavy Oil Field in Western Kazakhstan (modified after [60,61]).

The Upper Paleozoic, Triassic, Jurassic, and Lower Cretaceous sediments have been uncovered through the drilling of parametric, exploratory, and appraisal wells. Lithologically, they are composed mainly of clays with interlayers of sandstone.

Structurally, the Northern Karazhanbas Field is represented by two hemianticlines: the southwestern and northeastern, bounded on the south and southwest by faults. Two oil accumulations have been identified in the Bathonian stage of the Middle Jurassic; the accumulations are stratified, anticlinal, and tectonically sealed, and the depth of occurrence is 548–569 m (Figure 5) [60].

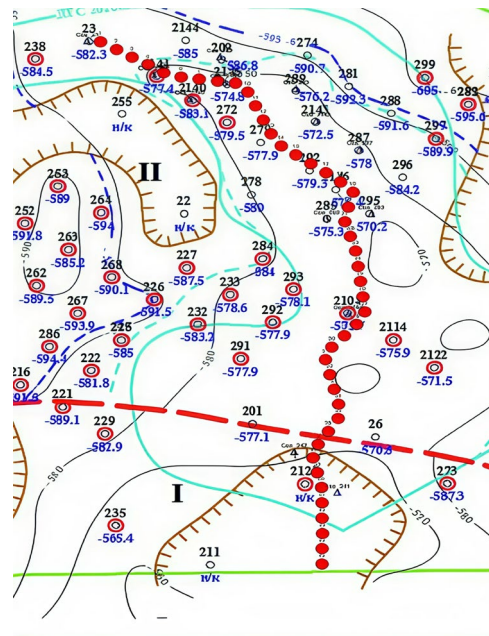


Figure 5. Location of the MTSM profile on the reflecting horizon structural map at the top of the Barremian stage.

2.7. The Streltsovskoye Ore Field

The Streltsovskoye Ore Field is located in the marginal part of the Urulyunguyev Massif within the Mongol–Priargun Volcanic Belt. Uranium deposits were formed as a result of the intense processes of Late Mesozoic tectono-magmatic activation and are confined to a volcanic–tectonic depression (subsidence caldera) (Figure 6); the caldera measures 15 × 10 km and covers an area of 120 sq. km [62,63].

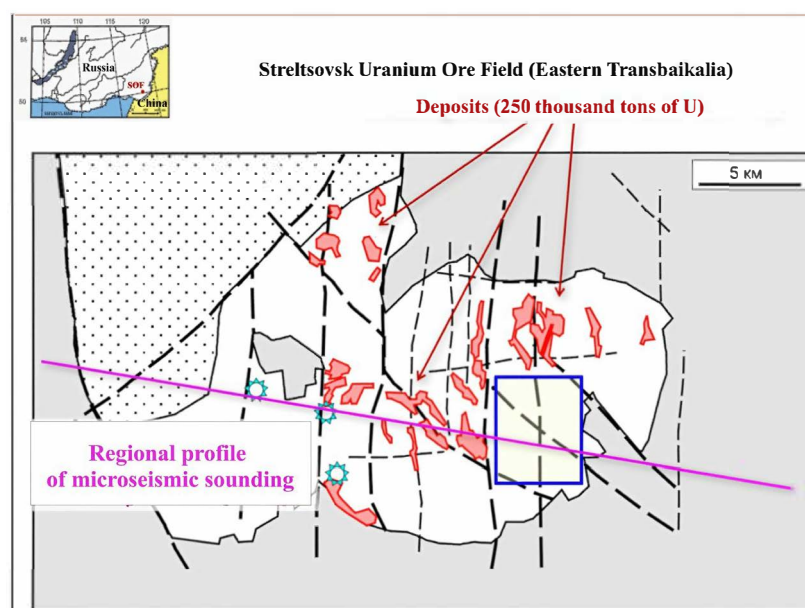


Figure 6. Location of the Streltsovsk Uranium Ore Field (Eastern Transbaikalia) (modified after [43]).

The caldera's structure is divided into two structural levels: the lower level, referred to as the “basement”, and the upper level, which consists of sedimentary–volcanogenic rocks. The “basement” of the caldera is composed of Paleozoic granites containing xenoliths of Early Proterozoic metamorphic rocks, represented by dolomitized limestones, crystalline schists, amphibolites, quartzites, and phyllite-like schists [62,63].

The upper structural level is composed of a complex of sedimentary and volcanogenic rocks from the Upper Jurassic–Lower Cretaceous period, with a total thickness of 500–600 m; this level includes three alternating basalt flows and three trachydacite flows, interspersed with layers of sedimentary and tuffogenic–sedimentary rocks [63].

Commercial uranium and molybdenum–uranium ores were formed both in the rocks of the “basement”—granites, dolomitized limestones—and in all the rocks composing the upper structural level, including basal conglomerates, basalts, trachydacites, felsites, and, in some cases, in horizons of sedimentary rocks enriched with organic material. The ore bodies in the Streltsovskoye Field occur in the forms of stockworks, veins, and stratiform bodies [63].

2.8. Uzon Geyser Volcanic–Tectonic Depression and the Kikhpinych Volcanic Massif

The Uzon–Geyzernaya Volcanic–Tectonic Depression and the Kikhpinych Volcanic Massif (Figure 7) can be considered a classic example of deep energy outbreak associated with heat and mass transfer occurring during volcanic eruptions. These large tectonic features are part of the Eastern Kamchatka Volcanic Belt [64].

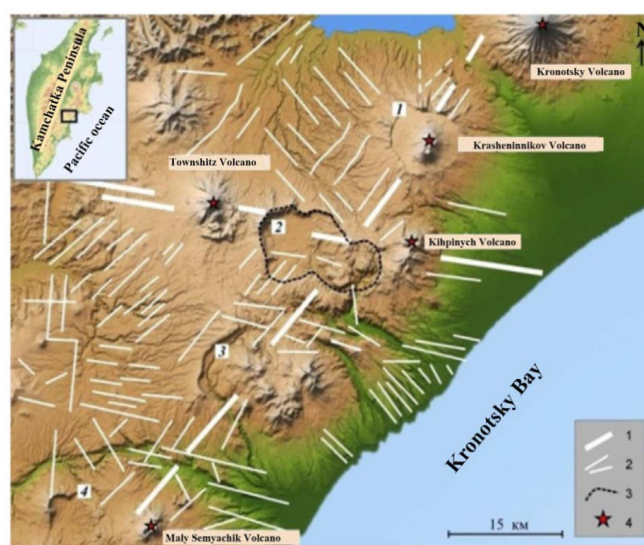


Figure 7. Map of volcanic features and fault structures in the central part of the Eastern Kamchatka Volcanic Belt. The map uses numbers to indicate calderas and volcanic–tectonic depressions: 1—Krashenninnikova, 2—Uzon–Geyzernaya, 3—Bolshoi Semyachik, 4—Stena–Soboliny (modified after [64]). Legend: 1—axial lines of regional fault zones trending northeast (volcanic rift) and sublatitudinally (Uzon–Valaginsky deep strike–slip fault) intersecting the Uzon–Geyzernaya area; 2—fault structures; 3—boundary of the Uzon–Geyzernaya Volcanic–Tectonic depression.

The Uzon Geyser Volcanic–Tectonic Depression is a volcanic structure with oval outlines, elongated in the latitudinal direction, with dimensions of approximately 9×18 km along the edge of the surrounding scarps (Figure 7); tectonically, it is located in a large depression with a Cretaceous–Paleogene Basement, predominantly filled with Neogene volcanic–sedimentary deposits.

The Kikhpinych volcano is poorly studied; little is currently known about its seismic activity, as local seismological observations were not previously conducted there. The

history of Kikhpinych's eruptive activity, however, has been sufficiently covered in the scientific literature.

In the eastern part of Uzon Geyser Volcanic–Tectonic Depression, based on the data of independent geological and geophysical studies (interferometric synthetic aperture radar (InSARS), thermohydrodynamic observations, aerial thermal and ground infrared photography, temporary seismological observations, and slope instability processes), collected between 2000 and 2014, local geodynamic activation was observed, which was confirmed by the deformation of the Earth's surface, seismicity, heating of the young cone of the Kikhpinych Volcanic Massif, catastrophic landslide and rockslide manifestations, changes in the thermodynamic parameters of hydrothermal systems, and the appearance of new hot and boiling springs according to the materials of aerothermal and ground-based infrared imaging [64].

3. Materials and Methods

The study of deep crustal structures under ore deposits and HC fields has traditionally been carried out using seismic methods, such as deep seismic sounding (DSS) and the Reflection Method modification of the common depth point (RM-CDP).

In addition to the above, the combined method of correlation refraction seismic–common depth point (CRS-CDP) and a modification of the DSS method, namely the deep seismic sounding–common depth point (DSS-CDP) method, were used for prospecting and exploration of the hydrocarbon field [65,66].

However, all of the above methods are effective at identifying horizontal or slightly sloping boundaries, while steeply dipping and subvertical structures are either not identified at all or are detected only through indirect signs (areas of lost correlation).

Similar results, although with lower reliability, were obtained using the methods of regional magnetic and gravimetric prospecting [67,68] and the earthquake converted-wave method (ECWM) [69,70]; however, the models constructed from the data obtained using these methods are beyond the scope of this paper and will be discussed in future publications. In the search for acceptable solutions, the method of microseismic sounding (MMSS) and the magnetotelluric sounding method (MTSM) were chosen, which level the abovementioned limitations.

To enhance reliability, the research was based on data from regional field geophysical surveys using the MMSS and MTSM methods, as well as their processing across various sedimentary basins in Kazakhstan. The authors were directly involved in the geological interpretation and modeling of these datasets, which is reflected in references [28,71].

For the Streltsovskoye Ore Field, joint scientific publications [62,63] were utilized to identify transcrustal columns of increased decompression and permeability, through which basaltic, dacitic, and rhyolitic melts ascended during the Late Mesozoic tectono-magmatic reactivation [71].

For the Uzon Geyser Volcanic–Tectonic Depression [64], which reveals the structure of the magmatic system of long-lived volcanic centers, mechanisms of ancient and modern magma chamber generation, crystallized magma reservoirs of various compositions and depths, and independent deep magmatic feeding channels and their migration trajectories were used.

Overall, in the process of writing the article on the models, types, and conditions of magma- and fluid-conducting transcrustal faults, an extensive list of scientific publications by domestic and foreign authors was used in combination with experimental data from field geophysical surveys.

The method of microseismic sounding (MMSS) is a fundamentally new approach, based on the recording of the spectrum of low-frequency microseismic waves, represented by the fundamental modes of Rayleigh surface waves [71,72].

Microseisms are natural elastic waves, with frequencies ranging from hundredths of a hertz to tens of hertz, caused by atmospheric phenomena, wave-induced activities, and other factors; in low-frequency studies (fractions of millihertz), it is possible to obtain data on the structures of deeply buried large-scale structures.

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 in accordance with the above dependence, and constructing 2D or 3D models of the seismic field.

The advantage of MMSS lies in the fact that heterogeneities in the Earth’s crust distort the spectrum of the low-frequency microseismic field on the Earth’s surface. Over high-velocity heterogeneities, the spectral amplitudes of a specific frequency (f) decrease; meanwhile, over low-velocity heterogeneities, they increase, an effect which is observed when the heterogeneities are located at a depth approximately equal to half the wavelength. If the heterogeneities are located at other depths, they do not distort the amplitudes of seismic waves at that frequency [73].

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 layers (H) and the velocity of the fundamental mode of the Rayleigh wave $V_R(f)$ with the relation $H = KV_R(f)/f$. In other words, the rule $H \approx K \times \lambda$ is fulfilled (λ is the length of the fundamental Rayleigh wave mode for the frequency (f); the wave of length λ is effective for a given depth) [28,43].

Based on the measurement results, a cross-section or 3D model of the geological heterogeneity is constructed in terms of relative shear wave velocity parameters. The dimensions 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 MMSS, while subhorizontal boundaries are “inconvenient” objects. In this sense, MMSS can be regarded as a specific “orthogonal complement” to traditional seismic methods.

The MMSS depends on the fulfillment of postulates that are valid only as a first approximation [74]. For this reason, there are two obvious statistical approaches to assessing the accuracy of values presented in seismic sections; these methods have their own advantages and complement each other.

The first method involves evaluating accuracy based on internal consistency; in this case, the standard deviation (SD) is calculated relative to the mean of the unweighted sample of values obtained for each spatial point, where analyzing the internal consistency of the results allows for consideration of measurement-specific features at each point, including errors introduced by short-term external factors.

The second method is associated with examining the theoretical capabilities of the MMSS method under optimal conditions for seismic station deployment, which involves the statistical analysis of long-term recordings (ranging from a day to several months) from closely spaced stationary seismic stations; this method enables the determination of the expected mean standard deviation values for velocity sections, as well as the study of key patterns influencing result accuracy, including the measurement duration, the distance between the measurement point and the reference station, the amplitude of the useful signal (such as storm microseisms), and the distance to its source [74].

Both of these accuracy assessment methods are essential for the correct and well-founded interpretation of velocity sections obtained using the MMSS, as they help pre-

vent the misinterpretation of amplitude variations that are smaller than the accuracy of their determination.

Now, we turn to electrical exploration via the method of magnetotelluric sounding (MTSM), a tool capable of successfully solving a wide range of tasks, including the study of the geological structure of the lithosphere at depths of up to several hundred kilometers; research at depths from tens of meters to tens of kilometers is conducted for the exploration and prospecting of ore, non-ore, and combustible mineral deposits, as well as for the regional study of geological structures [75].

There are several modifications of this method; in our case, deep MTSM (DMTSM) was used for investigations to depths of hundreds of kilometers in the low-frequency domain [76].

The natural sources of the field in the MTSM are electromagnetic oscillations in the ionosphere (e.g., generated by the Earth's thunderstorm activity and the Sun's solar wind activity). The electromagnetic field's depth of penetration 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). This is known as the skin effect [75].

MTSM is aimed at determining the specific electrical resistivity and its dependence on depth. To achieve this, MTSM analyzes the frequency response ($\rho_k(\omega)$) of the geological section, known as the apparent resistivity.

Two phases of work are highlighted, as follows.

Stage 1: The processing of measured data, which includes procedures for frequency analysis (filtering and obtaining Fourier series coefficients) and matrix operations (matrix inversion using the Moore–Penrose method, or the singular value decomposition of matrices) [76].

Stage 2: Inversion (transformation) of the response functions into a cross-section consisting of Earth layers. The solution to the inverse MTSM problem typically involves solving the forward problem and one of the fitting methods. Response function transformation is used when a quick but rough estimate of the geoelectrical cross-section is required; sometimes, this estimate turns into an evaluation of the quality of the measured data, and, in such cases, the measurements may need to be repeated [75,76].

Both stages may be accompanied by manual correction or rejection of data based on a range of frequency and time parameters. Additionally, in the second stage, an a priori geophysical model is introduced, as the inverse MTSM problem has multiple solutions, from which the interpreter selects the most geophysically reliable one.

Interpretation of MTSM data has been performed within 1D, 2D, and, more recently, 3D models. Patterns and software for one-dimensional interpretation 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 [77].

MTSM is not included in the list of high-tech methods with increased resolution which enable researchers to obtain a detailed understanding of the geological structure characteristics of the studied areas.

However, the application of this technology under the geological conditions of Kazakhstan has proven highly effective in identifying major uplifts and depressions, delineating crystalline basement structures, and detecting deep-seated faults interpreted as potential channels of heat and mass transfer [78,79].

When discussing the accuracy or reliability of the deep MTSM, it is important to recognize that its development has faced both theoretical and practical challenges. Some of these challenges have been successfully addressed, as follows:

- The physical validity of the Tikhonov–Cagniard plane–wave model, which provides a sufficiently accurate approximation of magnetotelluric relationships.
- The development of methods ensuring stable impedance estimation.
- The transition from scalar to tensor definitions due to the influence of horizontal geoelectrical inhomogeneities.
- The elimination of industrial and model-induced noise, enabling the determination of magnetotelluric transfer functions with high accuracy.

One-dimensional interpretation presents certain challenges, as it ignores the distorting effects of horizontal inhomogeneities in the Earth’s structure, an issue which has necessitated the development of a theory that accounts for typical distortions in MT curves and methods for their normalization [80].

By applying the criteria and methods of distortion theory, it is possible to eliminate, or at least mitigate, lateral effects, thereby enabling one-dimensional interpretation of MT curves; however, such curve normalization is not always reliable and is almost always associated with the loss of some information.

Therefore, the primary challenge of the modern deep MTSM is the transition to two- and three-dimensional interpretation models—an area that is currently undergoing active development.

Finally, regarding the effectiveness of deep MTSM, the inverse problem of magnetotelluric sounding is unstable and, as a consequence, contains uncertainty; however, this is also typical for any other method of electrical or electromagnetic sounding.

Solving this problem is meaningful if the search space is constrained using prior knowledge of the subsurface, for example, based on seismic data. Clearly, the effectiveness of magnetotelluric interpretation is directly related to the amount of available prior geological and geophysical information [81].

4. Findings

4.1. Ore Mineral Deposits (Streltsovskoye Ore Field)

In this section of the article, we consider a practical example of microseismic sounding (MMSS) for constructing deep geological and genetic models of ore deposits.

The application of MMSS at the unique molybdenum–uranium deposits of the Streltsovskoye Ore Field (SOF) in Eastern Transbaikalia enabled us to identify deep fault zones beneath them. Comparing the MMSS data with the geomechanical properties of the rocks, calculated from core samples, showed that areas of more monolithic rocks corresponded to relatively high-velocity regions, while tectonically disturbed zones with low geomechanical values were characterized by reduced elastic wave velocities [28,71].

Comparison of the MMSS results with the results of other geophysical methods applied along the same profiles (audio-magnetotelluric sounding (AMTS), gravity and magnetic surveys) showed that MMSS is an order of magnitude more detailed, objective (not depending on a priori information and the subjectivity of a specialist), deep (from surface-level meters to 50 km), operative, and easy-to-perform method that does not require explosions, vibrators, and wires [72].

From the seismic section along the sublatitudinal profile PR-1 (Figure 8a), a transcrustal column with a radius of about 5 km, characterized by increased amplitude (decreased velocity) in microseisms, was detected beneath the Streltsovskoye Caldera.

The 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 tectono-magmatic activation, which caused the subsequent collapse of the upper part of the Earth’s crust over the devastated center of the Li-F uranium-bearing acidic melt and the formation of the Streltsovskoye Caldera [72].

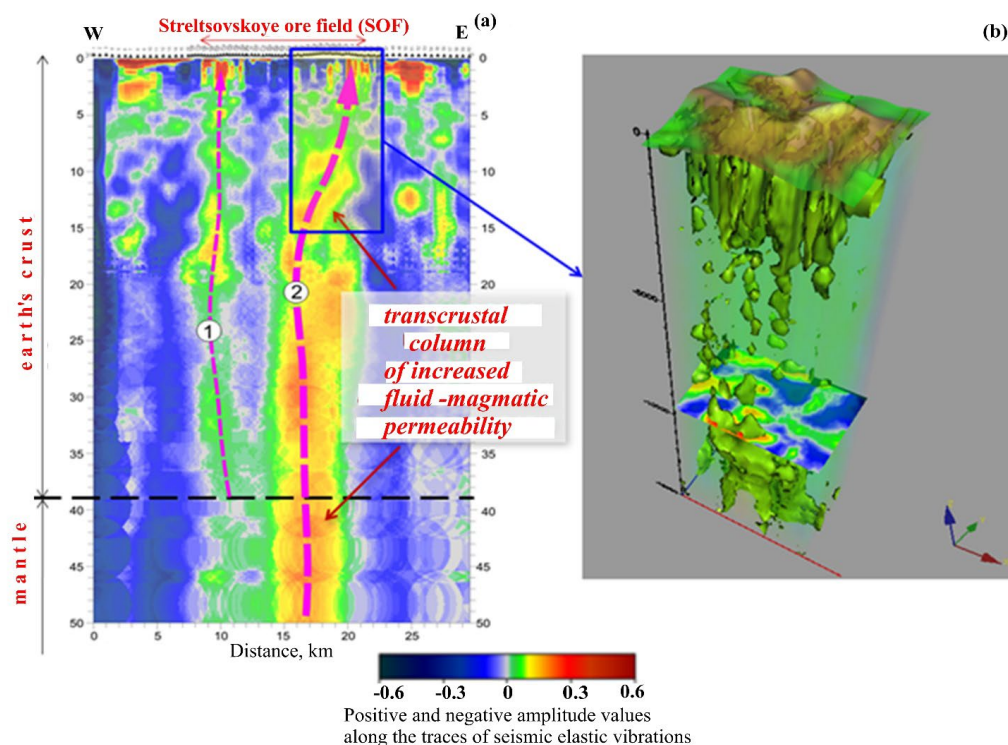


Figure 8. Microseismic section along profile PR-1 (a) and 3D seismic model to a depth of 15 km, constructed from detailed microseismic sounding data within the Gornyy and Streltsovskoye areas (b). Legend: areas of increased amplitude (decreased velocity) of microseisms are shown in yellow–red, and areas of decreased amplitude (increased velocity) are shown 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, and the X axis (red) is directed to the east; dotted arrows on the regional profile show the directions of movement for magmatic masses and fluid–thermal flows.

A detailed area survey along the regional profile alignment enabled the construction of a 3D seismic model (Figure 8b), in which the upper part of the identified transcrustal column represents a pipe-shaped body localized at the intersection node of sublatitudinal and submeridional faults, which can be traced to depths of 10–15 km [28,71]. This column reaches the Earth’s surface at the highest conical hills of the Argun Ridge.

Detailed geological mapping, including measurements of rhyolite dip angles, along with data from deep drilling (up to 1200 m), revealed the primary center of acidic volcanism at this location, a center consisting of several fissure–cone volcanoes, which has been named the Streltsovskoye Volcanic Center [82].

Thus, MMSS enabled the detection of 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 MMSS also helped us to 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.

4.2. Hydrocarbon Fields

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

4.2.1. The Astrakhan Gas Condensate Field

At the AGCF, 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 [28,83].

The obtained three-dimensional model for the field area (Figure 9) was compared with geological and geophysical data from independent studies, while the results of the 3D seismic model for the field area were compared with the geological and geophysical data from independent studies. In a seismic model, salt dome areas are marked by reduced microseismic amplitude values, reflecting the higher velocities of elastic waves in salts compared to in the surrounding Mesozoic terrigenous deposits.

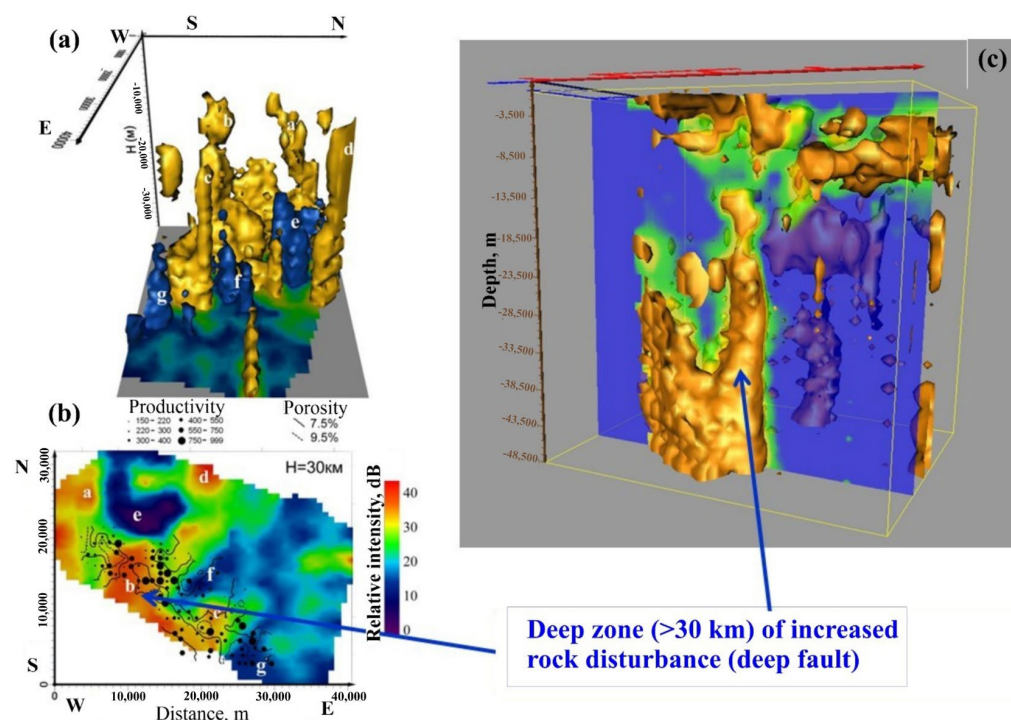


Figure 9. Three-dimensional seismic model of the Astrakhan Gas and Condensate Field (AGCF) based on MMSS data. Legend: yellow–red tones show areas of increased amplitude (decreased velocities) of microseisms, and blue tones show areas of decreased amplitudes (increased velocities). The areas of increased amplitude 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 amplitude (deep fault) located beneath productive oil wells is visible (b). The oil wells are marked with black dots, the sizes of which are proportional to their productivity.

A strong correlation has also been established between the microseismic amplitude values (based on MMSS data) and reservoir porosity values (based on well drilling data) at the productive horizon depth of 4–4.1 km.

The top of the figure, in the upper left and right corners, shows 3D models of areas (Figure 9a, c) with increased microseismic amplitudes (inside yellow–orange bodies). At the bottom of the figure, on the left, there is a horizontal slice of the 3D seismic model at a depth of 30 km, with an orange area indicating increased permeability (high amplitudes).

Above this domain are oil-producing wells (black circles, with size corresponding to productivity) and areas of increased porosity (with 7.5 and 9.5% porosity isolines) (Figure 9b). In the left side of the figure, letters show the correspondence of permeable (yellow) and dense (blue) volume bodies (above), and their positions on the horizontal slice (below).

It can be assumed that low seismic velocities are caused by the increased fluid conductivity of (a) subhorizontally elongated zones or (b) subvertically oriented bodies, associated with a system of deep faults, along which the uplift and expulsion of massive volumes of high-temperature aggressive vapor–gas mixtures, including those containing hydrocarbons (HCs), likely occurred and continue to occur; these mixtures chemically react with dispersed organic matter, activating catagenetic processes and forming hydrocarbon accumulations.

The fault system we have identified is in direct contact with three high-velocity subvertical bodies—e, f, and g (Figure 9a,b)—which are marked in the gravity field with increased density anomalies, apparently representing deep intrusions.

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

Thus, the use of MMSM at ore fields, as well as oil and gas fields, enabled us to reveal TCMFCF zones, with increased fluid–magmatic permeability, under them, providing heat and mass flow into the area of ore deposition, or the generation of hydrocarbon accumulations.

The following examples of tracer fluid- and magma-supporting faults are associated with hydrocarbon deposits in the South Turgai Petroleum Basin in Kazakhstan (Figures 10–12).

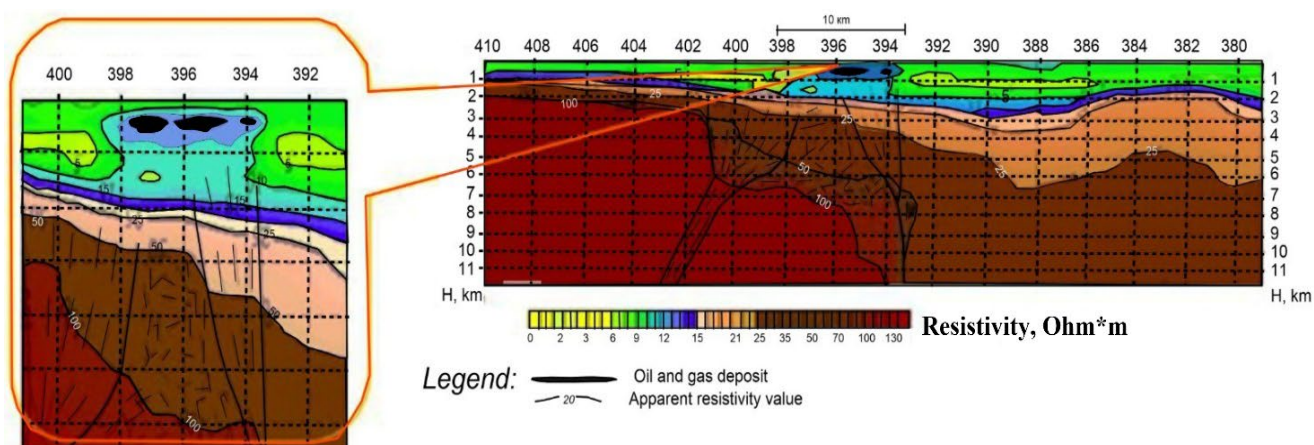


Figure 10. An example of a similar manifestations of an oil deposit in another field in the South Turgai Depression.

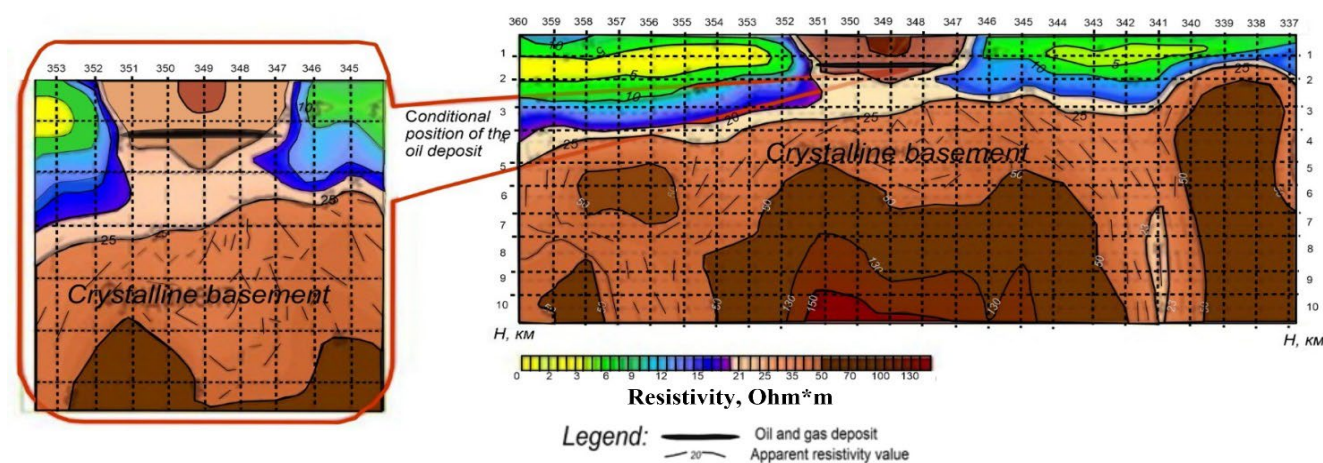


Figure 11. Geoelectric section through the Kumkol Field according to MTSM data.

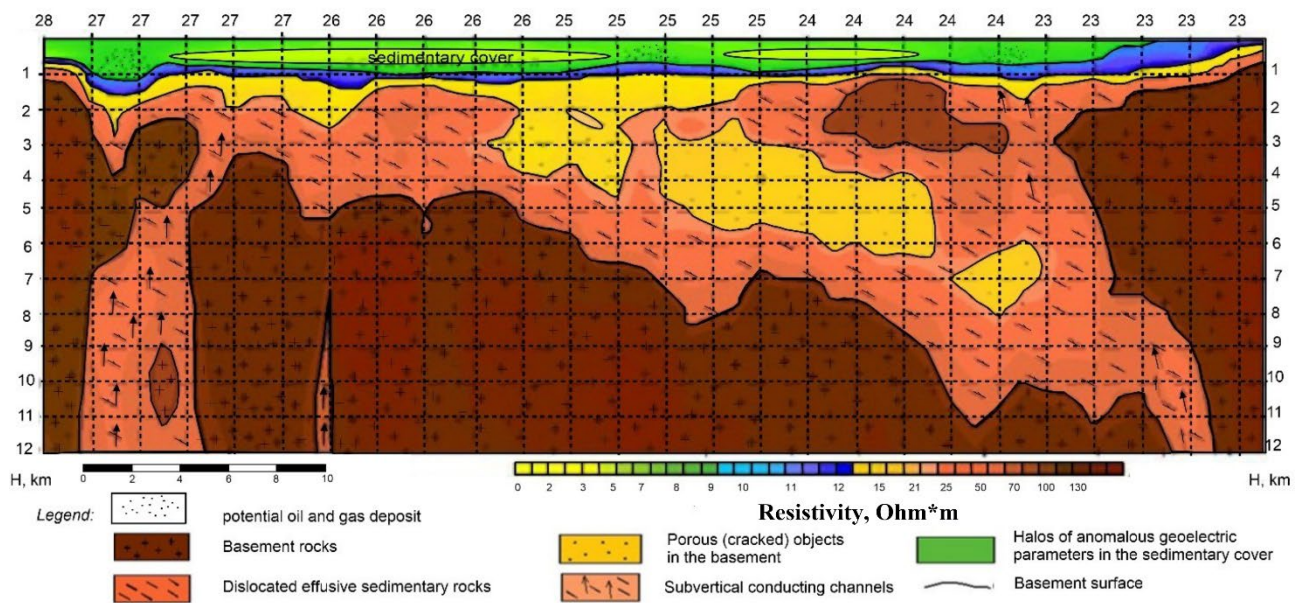


Figure 12. Identification of subvertical zones and conductive channels on a geoelectrical section.

4.2.2. The Kumkol Oil and Gas Field

At the Kumkol Oil and Gas Field, the MTSM results revealed a good correlation between the anomalies of increased resistivity and deep zones of endogenous heat inflow.

On the geoelectric section (Figure 11), these anomalous zones are manifested as reduced resistivity values; above them are zones of sharp increase in the electrical resistivity of rocks.

It can be assumed that the predicted TCMFCFs have direct impacts on the processes of hydrocarbon accumulation formation at the Kumkol Field.

4.2.3. The Kyzylkiya Oil and Gas Field

In the example of MTSM in the South Turgay Depression, the paragenesis of subvertical conductive zones (channels) and porous body areas of propagation (reservoirs), saturated with hydrocarbons, can be observed (Figures 10–12).

Thus, Figures 10–12 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–mass transfer, as well as movements of deep fluids, the nature of which remains to be studied.

4.2.4. Northern Karazhanbas Oil Field

Now, we consider the identification of TCMFCFs using the example of the Northern Karazhanbas Field in the North Ustyurt Sedimentary Basin.

Beneath this large, shallow (250–500 m) field in Western Kazakhstan, deep faults have been identified, complicating its geological structure; the field is characterized by the absence of salt tectonics, stratigraphic unconformities, and the lithological–facies variability of Middle Jurassic to Neocomian formations (Figures 13 and 14).

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. Two-dimensional inversion was performed along these profiles and, in order to increase reliability, the reflecting horizons identified through 3D seismic survey and the results of induction logging, the closest to the MTSM method in terms of its physical and geological basis, were used.

As a result, prospective hydrocarbon zones were identified in the upper part of the section, while, in the Lower Paleozoic part, a positive high-resistivity structure was delineated in the central portion of the pilot profile. Beneath it, two steeply dipping low-resistivity zones were identified, extending deep into the basement (Figure 13).

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 10–12 and 14, and the results of detailed MTSM studies made it possible to reliably correlate them with conductive (fracture) channels, along which heat–mass transfer, as well as hydrocarbon migration, may occur.

One article [41] also highlights the correlation between the deep structure of the Earth and the presence of hydrocarbon accumulations.

Additionally, researchers have repeatedly pointed out the controlling role of deep faults in the crystalline basements of platforms in the formation of hydrocarbon deposits in the sedimentary cover [84–87].

Subvertical transcrustal channels with increased permeability may be agents of transfer for deep thermal flow and fluid transport, and it is possible that these subvertical structures provide a connection between the deep and surface conditions for the formation of oil accumulations.

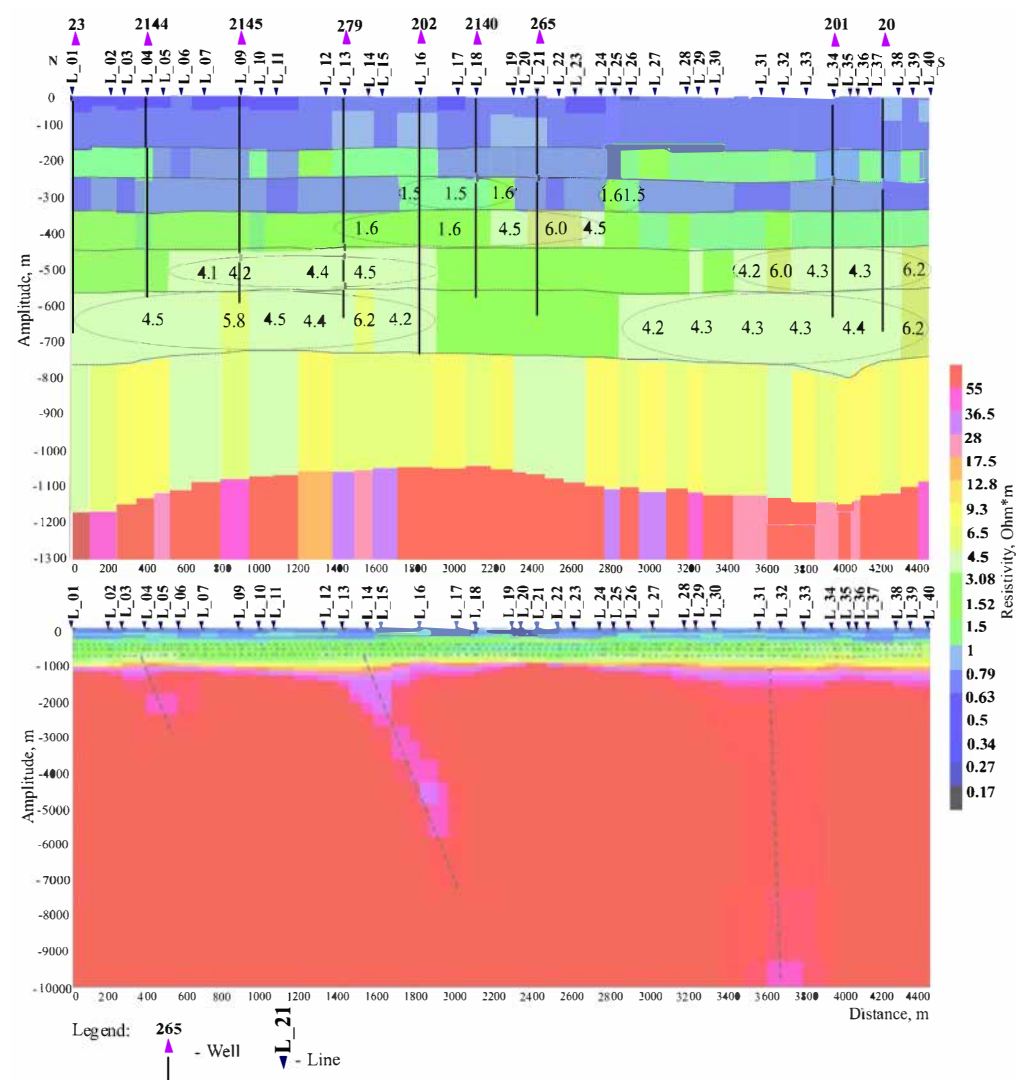


Figure 13. Identification of transcrustal channels in the Paleozoic part of the section for the example of the Northern Karazhanbas Field.

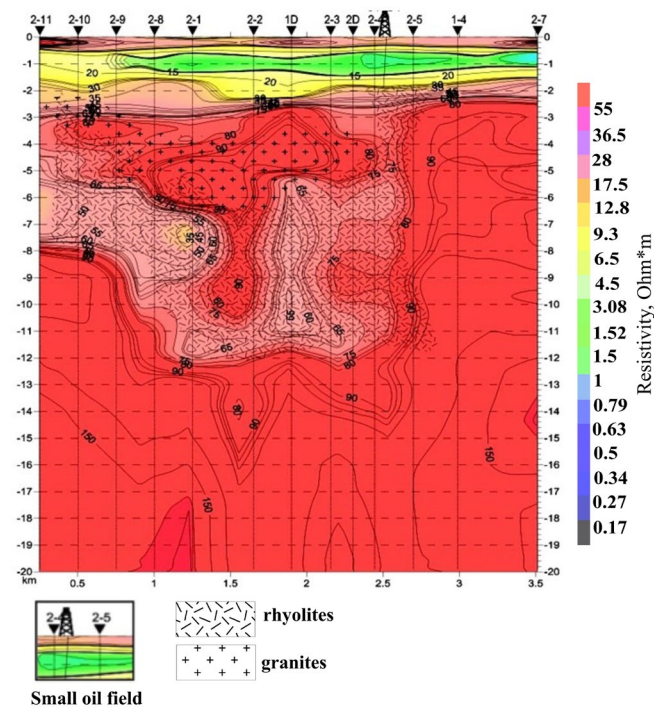


Figure 14. Deep geoelectric section of the Northern Karazhanbas Field.

5. Discussion

The use of MMSS and MTSM at ore deposits and oil and gas field enabled the detection of transcrustal zones of increased fluid–magmatic permeability of the mantle level of heat–mass transfer embedding agents to the area of ore deposition and HC accumulation formation [13,18,19,29,38,52].

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

5.1. Nature of TCMFCFs

As for the nature of TCMFCFs, they are believed to be associated with faults of ancient (Archean–Proterozoic) origin, which determined the fragmentation of the Earth’s sub-crystalline structure [19,52,88].

After their formation, the faults functioned in an inherited manner, a pattern observed not only in shields and ancient denudated folded regions, but also in platforms—a phenomenon extensively studied by the academicians N.S. Shatsky and A.V. Peive. The formation of consolidated rigid blocks occurred in the early stages of megastructural development [89] under conditions of volumetric fluid dynamics. Residual forms of large-scale fluid-conducting thermohydrocolumns, as described by Korzhinskii-Pospelov, include granitoid batholiths, which served as consolidation nuclei; such structures continue to function as fluid conduits to this day [90].

Similar ideas, but with consideration of the plate tectonics concept, were developed by the authors of [15] in relation to the South Ustyurt Region; according to these researchers, the regmatic fault network of the Earth’s crust was historically formed, and is permanently activated, by cyclically acting tectonic forces of extension, shear, and compression, associated with changes in the rotational regime over the course of a galactic year, the Earth’s polar radius, and the position of its rotational axis.

As a result, in the South Ustyurt Region, three-level regmatic systems of oblique and strike–slip fault disturbances formed for the crystalline basement, Paleozoic, and Mesozoic

rock complexes. The nature of the attenuation of regmatic systems and changes in block configuration in the Paleozoic and Mesozoic (in the lower horizons) structural levels have been established [23].

The special role of hydrodynamic mechanisms in the formation of sectoral structures of the Earth's "crust" and "mantle" can be considered proven, taking into account the latest data from seismology and structural analysis, which have established that the uppermost layers of the crust exhibit a pronounced structure resembling "broken ice" or even "chainmail" [91,92].

The existence of TCMFCFs was confirmed via experimental modeling of deep processes, performed by the authors of [18,43,93–95], among others. Multicomponent systems (rocks, minerals, salts on water, and even water–hydrocarbon emulsions) were studied in autoclaves under both increasing and decreasing pressure and temperature conditions. Of particular interest were the results of experiments with the injection of the inert gases helium and argon.

Conclusions were drawn about the stepwise (quantized) nature of interactions between the crystalline structures of minerals and rocks in the Earth's crust with "inert" gases under elevated T-P conditions, which clearly reflected covalent, and even transitional, chemical phenomena [91].

The previously available data on the special role of helium and hydrogen in changing the physical properties of rocks, due to their intrastructural diffusion (without chemical interaction with the material), have been clarified [15,96].

As a result of low-energy impacts, stress fields, structural rearrangements, and deformation textures, formed within the solid framework of rocks and accompanied by the development of overall porosity, with increasing reservoir pressures, the above interactions intensify, leading to phase transitions and chemical bonding.

Another concept, which was formulated based on the idea of the geological environment as a system in an unstable (metastable) state at depths exceeding 3–5 km, stated that the region of maximum stability is limited to near-surface, energetic background conditions; with increasing gas saturation and temperature, instability grows, and helium, nitrogen, and hydrogen can serve as indicators of deep heat–mass transfer [15].

The ascent of deep substances to the Earth's surface (thermofluid dynamic processes) occurs in a stepwise manner with energy release, which is most clearly manifested in the earthquake "crustal" sources, according to A.S. Ponomarev's thermo-gas-dynamic model of the Earth [97,98].

Energy release occurs along fluid-conducting thermohydrocolumns (as termed by D.S. Korzhinskii and G.L. Pospelov in the 1950s–1970s); these processes are directly related to the mechanism of hydrothermal ore formation, in which TCMFCFs play decisive roles [16].

Further developing this concept, one can conclude that thermofluidic dynamics determine the instability factor, which is a function of the Earth's endogenous regime that manifests in the block structure of the lithosphere, the specific nature of seismic activity, and other forms of the geological environment transitioning into unstable states, until the stage of medium geological destruction [19].

Examples of energy release can include explosions on the Earth's surface, in coal and ore mines, during earthquakes, and in volcanic eruptions.

5.1.1. Methane Explosions in Coal Mines

According to the author of [89], methane emissions often occur not in active faces, where the gas saturation of coal and rocks is higher, but in the rear of tunnels and coal extraction areas, i.e., they occur from long-exposed and degassed faults in the mines;

moreover, the timing of methane releases is found to be synchronous with geodynamic activation, which is registered using other methods.

With the depth of the mine, the intensity of methane emissions progressively increases; in the productive layers, the gas emission hazardous faults are represented by subvertical zones of highly disturbed coal with signs of increased thermal effects [89].

According to this research, methane enters the active horizons of the mine from the lower, possibly multi-kilometer, productive layer, the most striking example of which resulted in a major catastrophe in the coal industry.

5.1.2. Explosions in Ore Mines

In ore mines, the conditions commonly associated with methane formation in coal regions are completely absent (gold and uranium deposits in Northern Kazakhstan, gold–uranium mines in the Witwatersrand, South Africa, etc.). Explosions in ore mines are due to the activation of plasmoid energy sources, with explosion temperatures reaching tens of thousands of degrees [89,91].

5.1.3. Surface or Near-Surface (High-Temperature, Plasmoid) Explosions

High-temperature, plasmoid surface or near-surface explosions are quite common, with many variations in both the intensity and mechanism of their occurrence, but their description in the literature is accompanied by intense debates.

An interesting piece of information comes from the famous Sasov explosion, which occurred near Ryazan (RF) in 1991 and which V. Barkovsky (2000) classified as a phenomenon of deep energy release from the Earth along a fault, with a complex of electromagnetic, gravitational, acoustic, and light precursors [99]. According to this researcher, signs of gravitational explosions are observed in multifactorial processes of deep energy discharge, including in the epicenters of certain earthquakes [92,98,100].

5.1.4. Volcanic Eruptions

Volcanic eruptions can be interpreted as a consequence of deep energy release associated with heat and mass transfer processes. The Uzon–Geysernaya Volcanic–Tectonic Depression and the Kikhpinych massif represent a characteristic examples of such geodynamically active regions.

The results of studies conducted using MMSS are shown, with subsequent interpretation and modeling of the data obtained. This made it possible to build a model of the deep structure (up to 30 km), to clarify existing ideas about the magmatic source, and to identify new features of the Earth’s crust in the study area (Figure 15).

Interpreting the MMSS results in comparison with the available geological understanding, the following main elements of the magmatic system of the Kikhpinych long-lived volcanic center are manifested (Figure 15). They were identified as follows:

- An irregularly shaped ancient shallow-depth crystallized magmatic source (intrusive) of acidic composition in the depth range from 2 to 3 to 10 to 12 km beneath the eastern part of the Uzon–Geizernaya Volcanic–Tectonic Depression (structures 3 and 4, outlined with white dashed lines);
- A magmatic chamber (area of basalt melt concentration) within the depth range of 15–20 km beneath the ancient crystallized source (structure 8).
- A modern peripheral magmatic source (area of basalt melt concentration) beneath the Kikhpinych volcano, within the depth range of 5–10 km (structure 7, outlined by white dotted dashed lines).

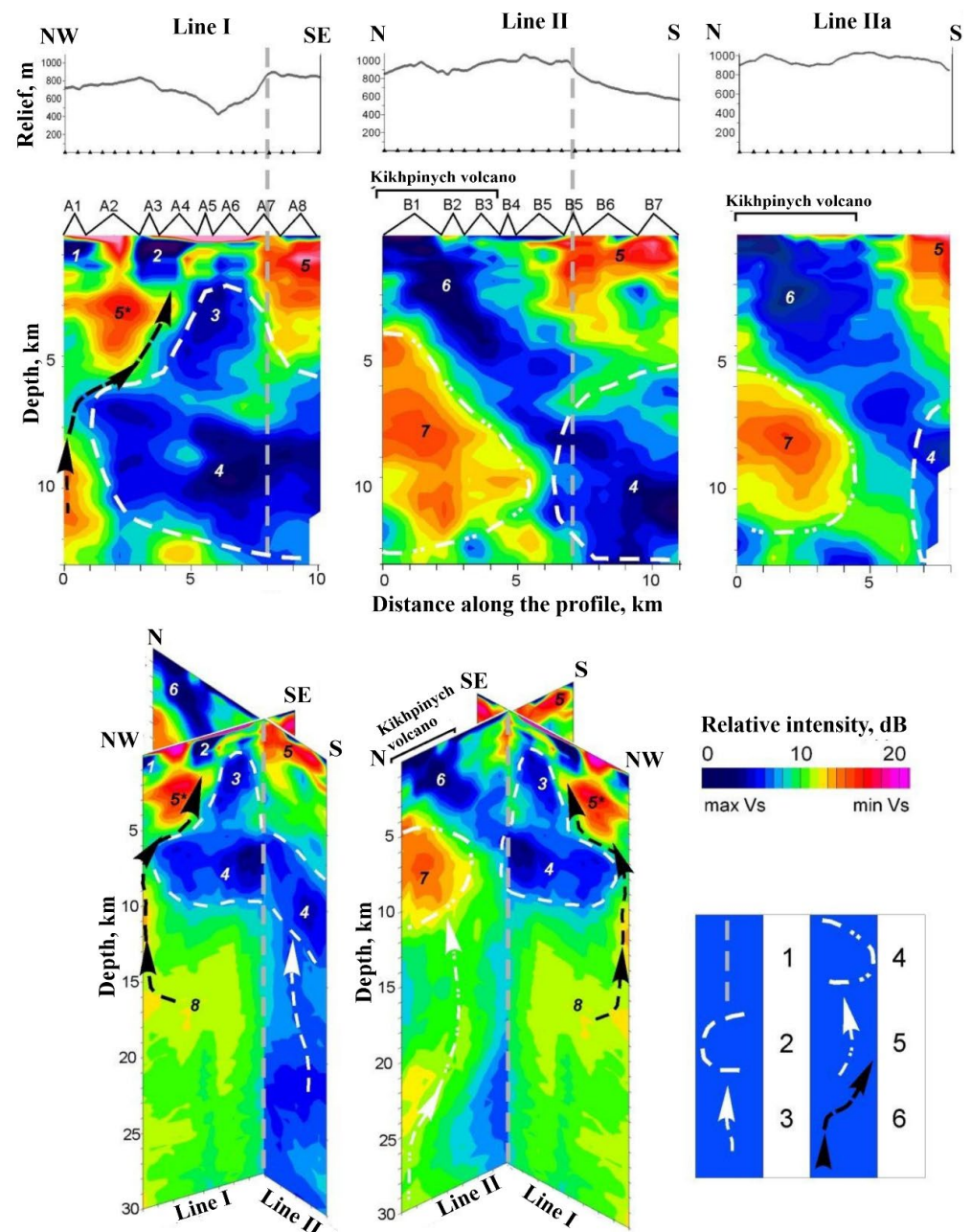


Figure 15. Upper section: depth profiles (up to 12 km) along microseismic lines in terms of the relative velocities of shear seismic waves (with elements of interpretation), based on data from reference [64]. Lower section: quasi-3D models down to depths of 30 km. The profiles are annotated with the following numbers: 1—area of the extrusive dome of Mount Belaya, partially covered with lake deposits. 2—field of extrusive domes in the eastern part of the depression. 3, 4—interconnected parts of the upper-crustal crystallized magmatic source beneath the Uzon Geyser Depression. 5, 5*—blocks of undivided deposits of the pre-caldera complex (volcanic–sedimentary cover). 6—pathways of magma propagation along the system of sublatitudinal faults controlled by the regional Uzon–Valaginsky fault. 7—Peripheral source feeding the Holocene basaltic eruptions of the Kikhpinych volcanic center. 8—Area of basalt melt accumulation, formed due to the shielding effect of acidic intrusion, 4, located above. Dashed lines in the legend: 1—intersection line of profiles I and II. 2—conventional boundary of the crystallized magmatic source beneath the Uzon Geyser Depression. 3—“Root” that fed the source beneath the Uzon Geyser Depression. 4—conventional boundary of the peripheral magmatic source of the Kikhpinych volcano. 5—“Root” that fed the source of the Kikhpinych volcano. 6—hypothetical location of the magmatic sill intruding from deeper horizons along the boundary of magmatic intrusions 3 and 4 (crystallized magmatic source), and the volcanic–sedimentary sequence 5*.

- Possible pathways for magma ingress into magmatic sources, gravitating toward the upper boundary of the crystalline basement from deeper horizons (subvertical heterogeneities marked by white dashed lines with arrows).

The geometry of the boundaries of the identified deep structures was found to correspond with local weak seismicity and the model of magma intrusion into the upper horizons of the Earth's crust, which enabled us to outline the possible location of an irregularly shaped magmatic sill at a depth of 4–8 km, dipping to the northwest [64].

Thus, based on the conducted research, the structural features of the magmatic system of a long-lived volcanic center were analyzed, and magmatic chambers of different ages were localized, which determined the migration of eruption centers, in addition to feeding separate deep magmatic channels.

5.1.5. Discharge of Excess Energy in the Form of Earthquakes

The discharge of excess energy through earthquakes may occur during processes of deep degassing; according to the authors of [100], this is indicated by, firstly, the spatial coincidence of earthquake epicenters and zones of intense Earth degassing (radon, helium, and hydrogen fluxes) in the axial parts of rift zones and deep faults, and, secondly, by the aforementioned direct relationship between volcanic eruptions and seismic events.

A model of explosive earthquake genesis during the ascent of deep-seated fluids has been developed [100]; in fluid detonation, a special role is played by heavy hydrocarbons, such as alkanes, alkenes, alkadienes, alkynes, naphthenes, and arenes, in that these compounds form in the liquid core and beyond, where they are unstable, but their migration becomes possible in rapidly ascending fluid flows from the core; these flows can then transport them into the upper mantle and the Earth's crust, where their pathways are controlled by TCMFCFs.

According to the authors of [91,100], 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 Kolskyi Peninsula, and on the Voronezh Anticline.

I.L. Gufeld and O.N. Novoselov (2022) developed a model for the generation of seismic events caused by the passage of deep-seated fluids, such as helium, hydrogen, and methane, through rock volumes. Within this model, it is postulated that a degassing impulse leads to the inhibition of mutual block displacement, i.e., to the blocking of boundaries, a process which is possible due to the increase in crystalline structure volume at the boundaries and blocks as hydrogen and helium are implanted into rock materials at concentrations corresponding to those in the lithosphere [14].

According to [101], the concept of global seismicity is based on a new petrological model, which suggests that the reprocessing of mantle and crustal material occurs under the influence of fluid flows, predominantly hydrogen-rich flows, ascending to the surface from the molten core. Thus, the orogenic structure of the Andes, characterized by andesitic volcanism, corresponds to the epicenters of intermediate-depth earthquakes (up to 300 km), while deep-focus earthquakes (300–700 km) occur beneath the platform depressions framing it.

On platforms, the circulation of deep fluids, combined with complex geochemical processes, leads to the redistribution of material between the crust and mantle, resulting in the thinning of the crust and the thickening of the mantle, which give rise to isometric platform depressions, within which degassing impulses drive phases of the uplift and subsidence of the crustal substrate, accompanied by seismic events [101].

6. Conclusions

In this article, we examine the role of transcrustal magma- and fluid-conducting faults (TCMFCFs) in the formation of mineral deposits, using examples from the Precaspian Depression, Turan Plate, Transbaikalia, and Kamchatka.

Upwelling heat flows and hydrothermal fluids from mantle sources along TCMFCFs induce intense tectonic deformations, the formation of rift systems, and volcano–plutonic belts, which, in turn, influence the formation of epithermal ores and hydrocarbon generation.

Moreover, TCMFCFs control the distribution of ore deposits, acting as conduits for volatile components (F, Cl, P, B, and H₂O), which affect the evolution of magmatism and mineralization processes. In tectonic zones of lithospheric extension (rifts), decompression and mantle heterogeneities enhance mineralization. On platforms and shields, hydrothermal processes are associated with magmatogenic structures and tectonic evolution.

TCMFCFs also play key roles in hydrocarbon accumulation through both conductive and convective heat–mass transfer from the mantle, regardless of the correct theory behind their origin (the sedimentary–migrational or abiogenic hypotheses or the geosynthesis concept), with increasing attention to fluid dynamic and mixed-genetic models.

Studies around TCMFCFs beneath ore deposits and hydrocarbon reservoirs have been conducted using microseismic sounding (MMSS) and magnetotelluric sounding (MTSM), which have proven effective in detecting steeply dipping and subvertical deep structures controlling ore formation and hydrocarbon accumulation.

MMS records low-frequency microseismic waves interacting with deep heterogeneities, correlates spectral amplitudes with velocity spectra, and is particularly effective in detecting subvertical TCMFCFs; its reliability is assessed using statistical methods considering internal consistency and long-term recordings.

Deep MTS analyzes natural electromagnetic field oscillations to determine rock resistivity at significant depths; it is used for regional geological studies and the identification of large-scale structures, including TCMFCFs. Data processing involves frequency filtering, matrix inversion, and the construction of inversion models.

At the Streltsovskoye Ore Field in Transbaikalia, TCMFCFs have been identified beneath uranium deposits at the intersections of major faults. According to MMS and rock geomechanics data, a transcrustal column (radius ~5 km) has been detected that has been interpreted as a high-permeability conduit for ascending magmatic melts and uranium-bearing hydrothermal fluids, extending to depths of 30 km and associated with Late Mesozoic acidic magmatism.

Beneath the Astrakhan Gas Condensate Field (Precaspian Depression), high-fluid-conductivity TCMFCFs have been identified, facilitating the ascent of high-temperature vapor–gas mixtures that influence hydrocarbon generation, migration, and accumulation. Moreover, three high-velocity subvertical bodies have been detected, spatially coinciding with gravitational anomalies, interpreted as intrusions.

In the South Turgai Petroleum Basin (beneath the Kumkol and Kyzylkia Fields) and the North Ustyurt Basin (beneath the Northern Karazhanbas Field), steeply dipping TCMFCFs have been identified, functioning as heat–mass transfer conduits. Zones of anomalously low resistivity correlate with deep heat flow channels and active faults, traced to depths of 15–20 km.

TCMFCFs control the distribution of ore provinces, belts, and deposits associated with ore mineralization, as well as hydrocarbon accumulation processes in oil- and gas-bearing provinces, basins, and regions, structures which represent tectonically weakened, permeable zones saturated with intrusive bodies, linear grabens, and high-permeability blocks (HPBs) that facilitate the upward migration of volatile components and hydrothermal solutions.

Ore belts are often localized along deep faults associated with lithospheric decompression and mantle heterogeneity; on platforms and shields, they are confined to marginal zones, frequently associated with continental volcanogenic belts.

Through TCMFCFs, the structures demonstrate hydrothermal ore formation and endogenous rock metamorphism, closely linked to the activities of deep faults, intense block–fault deformations, rift formations, and the development of volcanic–plutonic belts.

The nature of TCMFCFs is associated with ancient (Archean–Proterozoic) faults that fragmented the subcrustal structure of the Earth and remained active throughout geological history within shields, fold belts, and platforms, forming rigid blocks under the influence of volumetric fluid dynamics.

The faults persisted as active conduits for magma and fluid migration, influencing the structure of the Earth’s crust and its interaction with the upper mantle; they were cyclically reactivated by tectonic forces, forming fault systems and affecting hydrothermal ore formation.

Experimental modeling in TMFR zones achieved the following:

1. Demonstrated that heat–mass transfer and gas emission processes occur in a stepwise manner with energy release, altering the porosity and permeability of rocks under the influences of reservoir pressures and intrastructural diffusion.
2. Revealed quantum interactions between crustal minerals and inert gases (helium, nitrogen, and hydrogen) under high temperatures and pressures, leading to stress field formation, rock reorganization, and increased porosity.
3. It confirmed the stepwise migration of fluids (helium, nitrogen, and hydrogen as indicators of deep-seated heat–mass transfer) and mechanisms of deep energy release along transcrustal fluid- and magma-conducting faults during earthquakes, volcanic activity, and the formation of magmatic chambers, as well as explosions in coal and ore mines and surface outbursts due to deep energy emissions correlated with degassing zones.

In conclusion, it can be confidently stated that studies using the microseismic sounding and the magnetotelluric sounding methods produce highly reliable evidence confirming the existence of a geological phenomenon whereby deposits of solid mineral resources and accumulations of hydrocarbons are generally associated with deep-seated fluid- and magma-conducting fault systems. These faults are accompanied by zones of enhanced permeability, through which the continuous circulation of heat and deep fluids occurs.

These deep geodynamic systems represent unique natural phenomenon formations that exert a fundamental influence on ore-forming and hydrocarbon generation processes. Their role is decisive regardless of a region’s specific tectonic settings, deformation styles, metamorphic level, structural–formational composition, deposit type, or its geological evolution history.

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Data Availability Statement: Part of the data used in this study is publicly available, published in various years, and is thoroughly listed in the references section. These materials have undergone verification through peer-reviewed scientific publications and serve as a representative basis for the reproducibility of the results. An additional portion of the information base was formed through the generalization and analysis of empirical data obtained from defended doctoral dissertations in

the relevant scientific field, as well as from completed research, experimental-methodological, and initiative-based projects. These data encompass a wide range of geological and geophysical studies and have passed through internal scientific review, verification, and interpretation procedures using modern geographic information systems and geostatistical processing methods. A separate set of data was obtained by the authors through targeted work, including the integration of geological and geophysical data. All source files and accompanying metadata have been prepared in accordance with the journal's editorial policy, structured in machine-readable formats, and are available through the sources indicated in the article. Upon request, the authors are prepared to provide a detailed description of the methodology for data collection, processing, normalization, and storage, including the architecture of the databases used and a description of the software solutions employed in the study.

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