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Magmatogenic-hydrothermal formation model of fluid-dynamic structures and rare metal brine deposits in Siberian Platform cover

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Abstract. The enormous-scale processes of platform stages of magmatism and paleovolcanic activity on the Siberian Platform are characterized by the effusio of gigantic volumes of basaltic magma, the formation of kimberlite fields, iron, rare earth, and sulfide ores, as well as changes in the localization of hydrocarbon deposits. These processes, initiated by the passage of the craton over the “hotspot” of the giant super-plume encompassed many aspects of the evolution of hydrogeological, including magmatic-hydrothermal, paleosystems in the sedimentary cover of the ancient craton. This paper examines the nature and concept of «fluid–dynamic structure» as part of the magmatic-hydrothermal model of volcanogenic-sedimentary cover evolution using the Angara-Lena artesian basin as an example. The purpose of the study is to substantiate a magmatic-hydrothermal formation model of fluid-dynamic structures and transformation of rare-metal industrial brines in the volcanogenic-sedimentary cover of the Siberian Platform. This study uses archival and up-to-date seismic and electrical exploration data, deep-drilling geotechnical datasets, and hydrogeochemical brine sampling. The authors interpret the subvertical and associated subhorizontal zones of reflection loss observed in seismic sections at a number of sites as fluid-dynamic structures formed during the magmatic and postmagmatic pneumatolytic-hydrothermal stages. The impact of magmatic melts rising into the upper crust through deep crustal faults and areas of increased permeability of the tectonosphere led to the pulsed formation of vapor-dominated fluid pressure systems. According to the authors, the circulation of vapor-hydrothermal fluids through secondary filtration systems led to profound transformations in the hydrogeochemistry of the primary sedimentogenic brines of the sedimentary basin. At the same time, the reservoir rocks were transformed, with the development of high-capacity natural reservoirs driven by hydraulic fracturing, thermolift, and vapor-gas and fumarolic activity. The stages of platform magmatism and post-magmatic processes played a crucial ore-forming and ore-localizing role in the metallogeny and mineral genesis of industrial metal-bearing brines, determined the secondary concentration of the richest «liquid» ore of rare, dispersed elements, and mineral salts, including bromine, alkali metals – lithium, rubidium, cesium, potassium, and compounds with alkaline earth calcium and strontium.

Keywords: hydrothermal vents, volcanogenic-sedimentary cover, fluid-dynamic structures, vapor-dominated reservoirs, deep salt karst, metalliferous industrial brines

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Научная статья

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Магматогенно-гидротермальная модель формирования флюидодинамических структур и месторождений редкометалльных рассолов в чехле Сибирской платформы

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Резюме. Колоссальные по своим масштабам процессы платформенных этапов магматизма, палеовулканической деятельности на Сибирской платформе известны излиянием гигантских объемов базальтовой магмы, формированием кимберлитовых полей, железных, редкоземельных и сульфидных руд, а также изменениями в локализации месторождений углеводородов. Эти процессы, инициированные прохождением кратона над «горячей точкой» гигантского суперплюма, охватывали многие аспекты эволюции гидрогеологических, в том числе магматогенно-гидротермальных, палеосистем в осадочном чехле древнего кратона. Речь пойдет о природе и понятии «флюидодинамическая структура» как части магматогенно-гидротермальной модели эволюции вулканогенно-осадочного чехла на примере Ангаро-Ленского артезианского бассейна. Целью проведенного исследования являлось обоснование магматогенно-гидротермальной модели формирования флюидодинамических структур и преобразования редкометалльных промышленных рассолов в вулканогенно-осадочном чехле Сибирской платформы. В работе использованы архивные и новейшие материалы по сейсмо- и электроразведке, массивы геопромысловых данных глубокого бурения, гидрогеохимического опробования рассолов. Авторы трактуют наблюдаемые на сейсмогеологических разрезах субвертикальные и сопряженные с ними на ряде объектов субгоризонтальные зоны потери отражений как флюидодинамические структуры, сформированные в магматический и постмагматический пневматолитово-гидротермальный этапы. Воздействие поднимающихся через глубинные коровые разломы и узлы повышенной проницаемости тектоносферы в верхнюю кору магматических расплавов привело к импульсному формированию пародоминирующих флюидонапорных систем. По представлениям авторов, циркуляция парогидротерм по вторичным системам фильтрации привела к глубокому преобразованию гидрогеохимии первично-седиментогенных рассолов осадочного бассейна. Одновременно происходило изменение пород-коллекторов с формированием высокочемных природных резервуаров вследствие процессов гидроразрыва, термолифта, парогазовой и фумарольной активности. Этапы платформенного магматизма и постмагматические процессы сыграли важнейшую рудоформирующую и рудолокализирующую роль в металлогении – минерации промышленных металлоносных рассолов, обусловили вторичное концентрирование богатейшей «жидкой» руды редких, рассеянных элементов и минеральных солей, в том числе брома, щелочных металлов – лития, рубидия, цезия, калия, соединений со щелочноземельными кальцием и стронцием.

Ключевые слова: гидротермы, вулканогенно-осадочный чехол, флюидодинамические структуры, пародоминирующие резервуары, глубинный соляной карст, металлоносные промышленные рассолы



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Introduction

It is known that the key to solving the mystery of fluid-dynamic structures is a comprehensive analysis of the history of geological development of the volcanogenic-sedimentary cover of the craton in the Precambrian and Phanerozoic. Such structures are regularly observed in 2D and 3D seismic data from many exploration areas in the south of the Siberian Platform.

The works of V.S. Obruchev, I.I. Krasnov, V.S. Masaitis, M.M. Odintsov, G.M. Levinson-Lessing, L.G. Strakhov, G.D. Feoktistov, A.I. Al-mukhamedov, A.Ya. Medvedev, and many other geologists are devoted to the study of the geology and geochemistry of the platform magmatism of the trap intrusions of the Siberian Platform. At the end of the Paleozoic and the beginning of the Triassic, the Siberian Platform experienced a phase of main magmatism [1–4, etc.]. The most widely accepted opinion is that the magmatic melts that formed the dolerite intrusions, or sills, originated from the Kansk-Taseevskaya depression, a source zone of trap magmatism with a monoclinical rock dip. A number of the largest intrusions located in the lower part of the sedimentary cover have been identified within the Irkutsk region, including the Okinsky, Kupsky, Vikhorevsky, Bratsky, Sedanovsky, Tubinsky, Tushamsky, Sredne-Angarsky, Verkhne-Katansky, and Usolsky sills. According to petrographic, mineralogical, and structural features, three morpholog-

ical zones are conventionally distinguished in all intrusions: the central (or overrooted) zone, the peripheral zone, and the wedging area. The central zone of sills has a true thickness of up to 250 m; the peripheral zone is from 50 to 100 m, adapting to the general strike of the layered halogen-carbonate stratum; the thickness of the wedging areas is up to 50 m. In the work by D.P. Gladkochub and co-authors [5], three main stages of Phanerozoic plume mafic magmatism (500, 275–290, and 240–245 Ma) are identified for the southern flank of the Siberian craton. The Early Mesozoic trap magmatism in the south of the Siberian craton is represented by numerous basic intrusions of the Angara-Taseyevskaya syncline, including the Usolsky sill with an age of 240–245 million years.

By analogy with volcanic areas of recent volcanism, Eastern Kamchatka Peninsula, the Kuril Islands, New Zealand, the intrusion of the 1,200°C hot melt of basaltic magma resulted in the formation of intermediate magmatic foci in the sedimentary cover of the Siberian craton [3, 6–8]. The physical basis of the interaction process between the melt of basaltic magma, the host sedimentary rocks of the Lower Cambrian evaporites of the sedimentary cover, and the groundwater of deep aquifers, brines [9], is the high-temperature effect of the basaltic melt coming from the mantle [3, 4, 6, 10–12]. The system of aqueous solution of salts, natural chloride brines, is considered to be



the first and most actively responding to changes in temperature conditions during interaction with magma [12–16].

In the southern part of the Siberian Platform, the mass intrusion of basaltic melt into the supra-source spaces along the system of deep magmatic faults, to the level of the Lower Cambrian carbonate-halogen complex of the rocks of the sedimentary cover, led to the formation of magmatic peripheral foci that were split along their flanks. The thermal effect of the melt on the lateral rocks was accompanied by granulation and radial invasion through the least stable layers, that is, in layers. Subhorizontal zones associated with them were formed. In the central part of the structure, there was “complete liquefaction of the host evaporite stratum, intensive mixing of the newly formed carbonate-salt melt with granular silicate, accompanied by the release of the ore phase” [11]. All processes took place under the screen of the overlying halogen strata.

At the subsequent stage, hydraulic fracturing (HF) of the silicate-carbonate and ore-carbonate emulsion mixtures took place into layered cracks with the formation of sill-like bodies. The intrusion of emulsions in the sedimentary strata proceeded with a constant inflow of brines from deep horizons of the sedimentary cover, that is, with the participation of the aqueous phase. Ahead of magma, a horizon/layer of water-salt deposits consisting mainly of halite and its saturated solution was formed at this depth due to the vapor-gas front [17]. Later in relation to the magmatic stage is the hydrothermal-metasomatic stage. Recently, this stage in the deposits of the Angara province has been considered the leading one in ore formation, therefore, a number of special studies have been devoted to the processes associated with it [2–4, 18, 19]. Thus, the monograph by A.I. Almukhamedov and G.V. Neshterenko [19] is devoted to the study of the geochemistry of rare elements in the processes of basalt magma differentiation. The work is based on the example of traps of the Siberian platform. It shows the main geochemical patterns of distribution, location, and behavior of 28 elements

characteristic of both basic magma (iron group elements) and other types of magmas (silver, zinc, lead, lithium, rubidium, strontium, barium, tantalum, niobium, and others). It should be noted that the role of deep fluid-dynamic processes of fluid migration, as well as ore transfer processes in the Earth's crust, have been considered from different perspectives by many well-known geologists – I.M. Gubkin, F.A. Letnikov, Zh.V. Seminsky, E.B. Chekalyuk, L.A. Abukova, N.A. Kudryavtsev, A.N. Dmitrievsky, A.A. Nezhdanov, A.V. Migursky, V.I. Nikulin.

The purpose of this work is to substantiate the volcanogenic-geothermal model of the formation of fluid-dynamic structures, which are recorded based on the results of detailed seismic surveys using the method of volumetric seismic exploration and deep drilling in the sedimentary cover, using the example of the studied territory of the southern Siberian platform. With a certain degree of conventionality, following Yu.A. Zagorovsky¹ and A.A. Nezhdanov [20], we distinguish two types of fluid-dynamic structures:

- subvertical, well-studied structures of increased permeability of the tectonosphere in combination with deep crustal faults [21, 22], structures of diatreme association and diatremes, as a rule, these are through hydrogeological structures in the upper structural stage of the platform, draining the cover or part of it;

- subhorizontal and slightly inclined zones of an active karst fractured reservoir, to which numerous “rapa sills” are confined, detected by high-yield inflows from deep wells of extremely saturated magnesium-calcium metalliferous polycomponent brines with abnormally high reservoir pressure comparable in magnitude to the rock pressure at these depths.

Materials and methods

The work uses archival and the latest materials on seismic and electrical exploration, arrays of geofield data from deep drilling, hydrogeochemical sampling of brines. In order to take into account as much as possible the significant large-scale geodynamic processes that influ-

¹ Zagorovsky Yu.A. *The role of fluid-dynamic processes in the formation and distribution of hydrocarbon deposits in the north of Western Siberia: dissertation for the degree of Ph.D. in Geology: 25.00.12.* Tyumen; 2017, 201 p.



enced the formation of fluid-dynamic structures in the sedimentary cover of the Siberian platform through magma fluid flows into the upper crust [23], the authors used the analogy method to draw on the experience of studying geothermal fields [6, 24, 25, etc.] of modern magmatic and high-temperature hydrothermal systems of Eastern Kamchatka (Russia). Experimental data are extremely important, based on which it is concluded that evaporation of solvent water over time is the basis for lithium concentration in brines, while high-temperature pneumatolite-hydrothermal processes are key to the formation of lithium brine deposits with a low magnesium-lithium ratio [12].

Results and discussion

The process of studying the sedimentary cover of the Siberian Platform by hydrotherms, which took place both during and after the catastrophic period of active basic volcanic activity, was very long and, according to some estimates, took up to 60 million years [7]. Under hydrotherms, the authors understand both the mantle and crustal components of magma degassing, as well as chloride fluids, brines from deep horizons of the sedimentary cover involved in active circulation in the paleoprocess of the thermolift [25]. Hydrotherms of mantle and crustal genesis formed active filtration zones, “hydrogeological windows”, which received the lower (relative to the position of the intermediate magmatic focus) hydrodynamic groundwater systems of deep horizons of the sedimentary cover (brines). The accumulation of reservoir pressure under halogen screens led to the injective penetration of hydrotherms into fractured reservoirs of the sedimentary cover and the activation of auto-hydraulic fracturing (auto-HF) processes, they were also significantly discharged into surface watercourses and entered the World Ocean [16]. The regional stratum of the Cambrian salt basin [26] played the role of a regional impermeable bed. Intersalt fractured carbonate reservoir formation of the Vendian–Cambrian and Early Cambrian strata on the Siberian platform as a complex drainage-channel system were the most important factors in the process of redistribution of high-pressure hydrodynamically active fluid systems.

According to this model, fluid-dynamic structures were formed during the intrusion of liquid high-temperature (up to 1,200°C) basic magma into the halogen-carbonate-volcanogenic stratum of the cover of the salt basin. According to Yu.A. Zagorovsky¹, A.A. Nezhdanov [20], fluid-dynamic processes include the migration (movement) of fluids in the Earth’s subsurface. Fluid-dynamic anomalies of the seismic record are considered evidence of jet migration through caprocks, linking them to the oil and gas content and abnormally high reservoir pressure of the fluid systems of the upper crust.

Today, the use of new technologies and geophysical methods for oil and gas exploration has allowed geologists to take a fresh look at these territories with a long, complex history of geological development, and at a number of sites with an unclear genesis. One of the tasks that requires explanation, solution and geological interpretation is the so-called “fluid-dynamic structures”, which are recorded (Fig. 1) based on the results of detailed seismic surveys of the three-dimensional seismic exploration in the sedimentary cover. The fluid-dynamic structures are detailed based on the materials of wide-azimuth 3D seismic exploration [27], including using artificial intelligence tools.

According to one hypothesis, the fluid-dynamic structures are volume-planar subvertical or inclined to subhorizontal cavernous-fractured fault zones, decompression zones [28–30], which at the stages of tectonic and magmatic activation of the craton were presumably channels of deep degassing [20]. Fluid-dynamic structures are often also associated with zones of development of local structural and compositional heterogeneities, subsidence troughs, in the halogen-carbonate strata of the sedimentary cover. According to one hypothesis, their formation is determined by the manifestation of deep salt karst [7, 31, 32] as a result of “hydraulic cutter”, the lateral movement of diluted groundwater along one of the regionally continuous fluid-bearing horizons at the base of the karst strata, in this case presumably the Osinsky horizon [32]. This hypothesis is based on the fact of the invasion of the giant Usolsky sill along the Osinsky horizon or, in some areas, in the immediate vicinity under or above it [27, 30, 32]. The subvertical fluid-dynamic structures served as

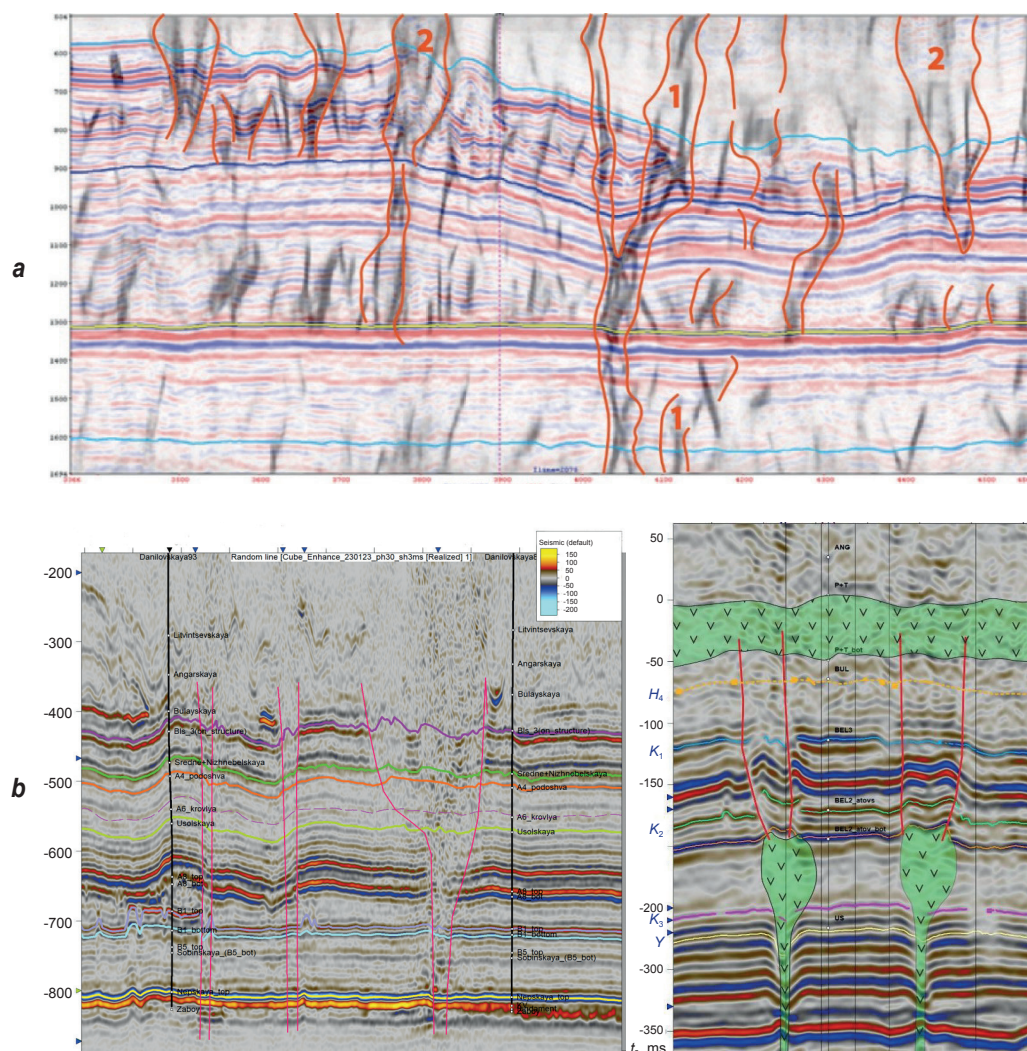


Fig. 1. Fluid-dynamic structures on the time section of seismic exploration using the common depth point method (A.V. Levin's interpretation):

- a* – fragment of the time section from the Kovyktinskaya area, Angara-Lena stage:
1 – through fluid-dynamic structures, 2 – fluid-dynamic structures localized in the halogen-carbonate floor;
b – fragments of time sections with volcanic apparatuses/explosion pipes from the Nepa dome, Nepa-Botuoba antecline, according to geological exploration data for oil and gas (predicted “through” fluid dynamic structures in the sedimentary cover are shown; subsidence troughs of the strata are formed in the junction area of normal sedimentary section)

Рис. 1. Флюидодинамические структуры на временном разрезе сейсморазведочных работ методом общей глубинной точки (интерпретация А.В. Левина):

- a* – фрагмент временного разреза с Ковыктинской площади, Ангара-Ленская ступень:
1 – сквозные флюидодинамические структуры,
2 – флюидодинамические структуры, локализованные в галогенно-карбонатном этаже;
b – фрагменты временных разрезов с вулканическими аппаратами/трубками взрыва с Непского свода, Непско-Ботуобинской антеклизы по данным геолого-разведочных работ на нефть и газ (показаны прогнозируемые «сквозные» флюидодинамические структуры в осадочном чехле; в зоне примыкания нормально-осадочного разреза сформированы мульды проседания толщи)

channels for migration of hypogene fluids, which led to the localization of hydrothermal discharge: vapor hydrotherms in the postmagmatic stages of continental magmatism.

Subsequently, the fluid-dynamic structures under consideration were preserved as relics of hydraulic fracturing: the breakthrough of the va-

por-gas front of boiled brines, “rapa sills” [13, 14], as well as transit routes for long-term discharge of hydrothermal fluids and triggered the formation of secondary high-capacity karst fractured reservoirs.

The authors consider the combination of linear fractures and small “gas pipes” to be diagnostic indicators that allow the observed structural and



compositional heterogeneities in the sedimentary cover to be attributed to fluid-dynamic structures. Due to their small size, these features are not always visible in the seismic wavefield. However, signs of fluid-dynamic structures are detected based on geological and field data from deep drilling, as well as on the results of electrical exploration, which indicate the presence or absence of anomalously hydrodynamic reservoirs.

Thus, Fig. 2 shows the zoning scheme of the northwestern wall of the Zhigalovsky swell, the megastructure closest to the Usolsky sill in the sedimentary cover [33]. The mosaic oval contours of the fluid-saturated void (capacitive and transit) space of the predicted subsidence troughs in intersalt carbonate fractured reservoir rocks of the Cambrian macro-reservoir are highlighted in blue. Two troughs have been opened by deep wells, and inflows of extremely saturated brines from the predicted “rapa sills” have been obtained.

The specific shape and internal structure of fluid-dynamic structures are determined by the thickness and other parameters of the forming fluid flow, as well as the strength properties of the rocks in which fluid-dynamic structures are formed, their

tectonic dislocation and fracturing. In fact, the fluid-dynamic interpretation of geophysical data consists in extracting information about the movement of underground fluids and the formation of their accumulations in the sedimentary cover².

The Angara-Lena stage and the artesian volcanogenic-sedimentary basin of the same name have developed an intrusive formation-like hypabyssal facies, represented by dolerites, Usolsky (Fig. 3) and other sills. Its structure is characterized by materials from more than 400 wells, as well as data from regional and detailed seismic surveys. The area occupied by it exceeds 300,000 km² and it is probably the most extensive formation trap body known on Earth. According to A.V. Migursky [34], “this is the most famous formation trap”. The distance of the Usolsky sill wedging boundary from the source area (the central part of the Sayan-Yenisei syncline) reaches 500 km or more. The amoeboid shape of the sill has large bay-shaped contours and step rises in hypsometry and stratigraphy as it moves away from the source of intrusion. Fig. 3 shows the main fields of trap sills, Usolsky sill, accumulations of hydrocarbons, known and predicted deposits of rare metal brines. The position of brine-producing wells

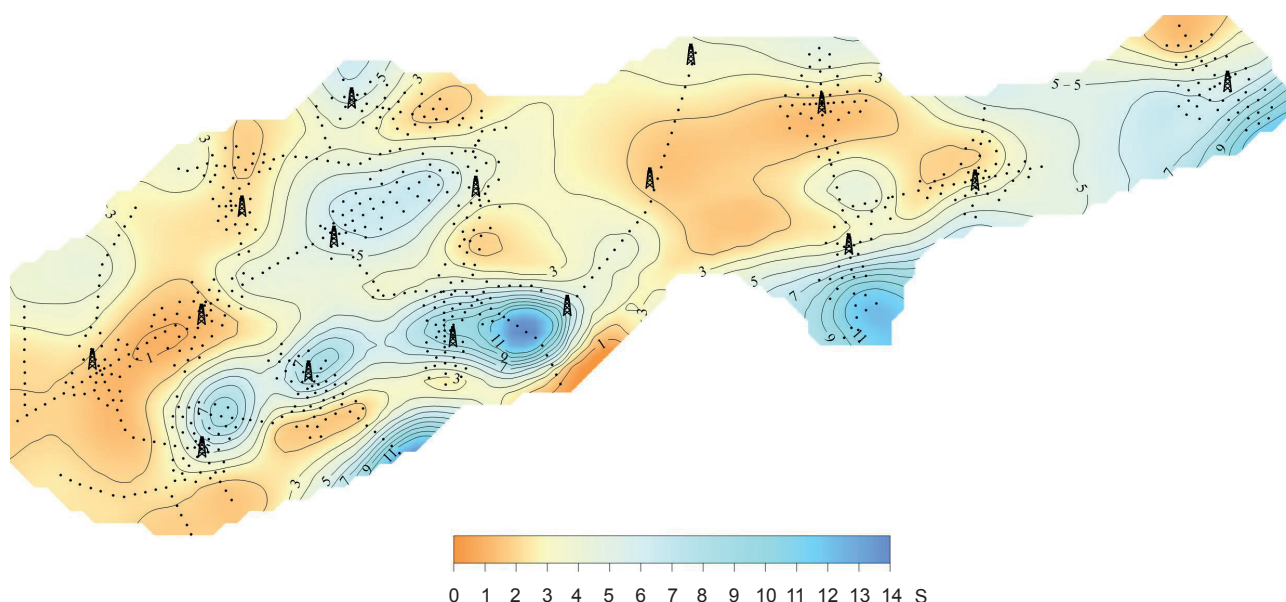


Fig. 2. Zoning scheme of the northeastern flank of the Zhigalovsky swell based on the presence/absence of anomalous hydraulic reservoirs (based on geological exploration data) [33]

Рис. 2. Схема районирования северо-восточного крыла Жигаловского вала по наличию/отсутствию anomalно-гидропроводных коллекторов (по данным геолого-разведочных работ) [33]

² Nezhdanov A.A., Smirnov A.S. *Fluid dynamic interpretation of seismic data: textbook*. Tyumen: Industrial University of Tyumen; 2021, 286 p.

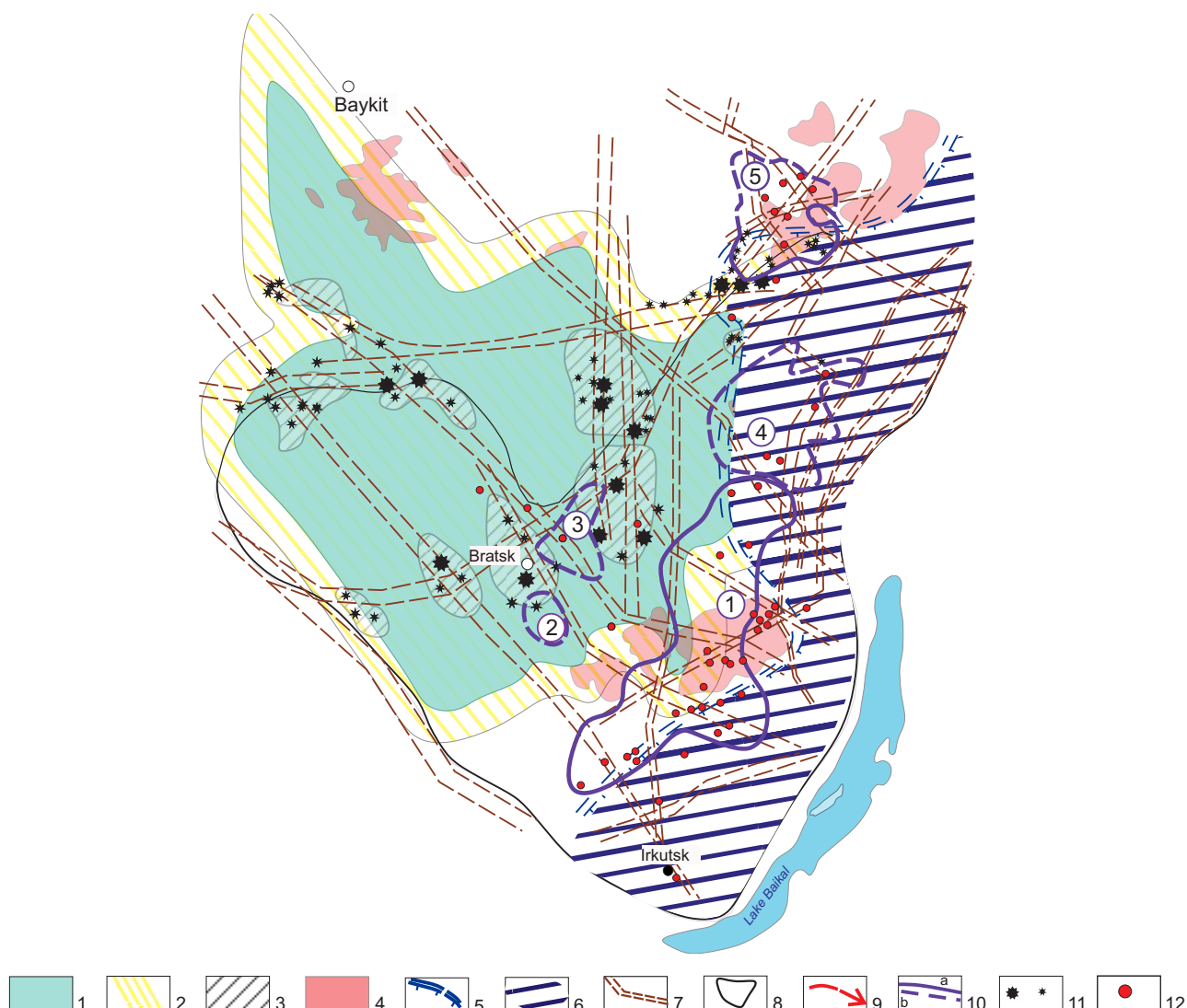


Fig. 3. Zonal igneous areas as metallogenetic basis to form ore clusters and deposits of rare metal industrial brines in the sedimentary cover of the hydromineral province of the Siberian Platform, Angara-Lena artesian basin

(compiled by: M.A. Danilova, A.V. Levin, A.G. Vakhromeev, A.V. Oshchepkova, S.K. Kvachko):

1 – Usolsky sill; 2 – predicted discharge area of vapour-dominated hydrothermal fluid systems; 3 – iron ore areas as recharge zones of deep-seated geofluid systems; 4 – hydrocarbon deposits in the cover; 5 – frontal area (foreland) of Baikal-Patom fold-thrust belt; 6 – Baikal-Patom fold-thrust belt; 7 – ore-controlling crustal faults of the basement; 8 – contour of the Angara-Lena artesian basin; 9 – discharge directions of vapor-dominated hydrothermal systems; 10 – identified (a) and predicted (b) contours of rare metal brine deposits: 1 – Angara-Lena, 2 – Karakhunsky, 3 – Bratsko-Kovinsky, 4 – Yarakhtinsky, 5 – Danilovsko-Preobrazhensky; 11 – “explosion pipes – diatremes” as hydrogeological “windows” for subvertical fluid circulation; 12 – deep wells with inflows of industrial rare-metal brines (according to the sources [21, 22, 32] with authors’ additions)

Рис. 3. Зональные магматические ареалы как металлогеническая основа формирования рудных узлов и месторождений редкометалльных промышленных рассолов в осадочном чехле гидроминеральной провинции Сибирской платформы, Ангара-Ленский артезианский бассейн (составили: М.А. Данилова, А.В. Левин, А.Г. Вахромеев, А.В. Ощепкова, С.К. Квачко):

1 – Усольский силл; 2 – прогнозируемая область разгрузки пародоминирующих гидротермальных флюидных систем; 3 – железорудные районы как зоны питания глубинными флюидными системами; 4 – месторождения углеводородов в чехле; 5 – фронтальная область (форланд) Байкало-Патомского складчато-надвигового пояса; 6 – Байкало-Патомский складчато-надвиговый пояс; 7 – рудоконтролирующие коровые разломы фундамента; 8 – контур Ангара-Ленского артезианского бассейна; 9 – направления разгрузки пародоминирующих гидротермальных систем; 10 – установленные (а) и прогнозируемые (б) контуры месторождений редкометалльных рассолов: 1 – Ангара-Ленского, 2 – Карахунского, 3 – Братско-Ковинского, 4 – Ярактинского, 5 – Даниловско-Преображенского; 11 – «трубки взрыва – диатремы» как гидрогеологические «окна» субвертикальной циркуляции флюидов; 12 – глубокие скважины с притоками промышленных редкометалльных рассолов (согласно источникам [21, 22, 32] с дополнениями авторов)



and predicted ore clusters of localization of “liquid” rare metal ore and deposits relative to crustal fault zones that are fluid permeable during the stages of tectonomagmatic activation, and the expected directions of vapor hydrothermal paleofiltration relative to magmatic bodies of the Usolsky sill, volcanic apparatuses of the central type – “explosion tubes” is shown. The above scheme represents the most important stages of metallogeny of this type of lithium-bearing raw materials: rare metal industrial brines. The discharge of the pneumatolite-hydrothermal systems proceeded from the apical region of the sill along the subhorizontal filtration channels of the thrust sheets of the allochthon of the Markov-Ichersk sector (in Fig. 3 in the direction to the north and northeast).

Sills, fluid-dynamic structures, and volcanic explosion tubes within the Usolsky and Motsky sills are distinguished according to 2D and 3D seismic survey data in the south of the Siberian Platform: Fig. 4 shows a seismogeological section across the strike of an allochthonous anticline [27].

Considering the features of the geological structure of the Usolsky sill, a giant magmatic trap body in terms of area, its marginal region and the

area of the sedimentary cover above it in the halogen-carbonate stratum of the Early Cambrian (see Fig. 3). It should be noted that in the southern and southeastern parts of the Angara-Lena stage, the Usolsky sill is traced in the Pravoberezhnaya, Zhiagalovskaya, Gruznovskaya, Kovyktinskaya, Chikanskaya, Omoloyskaya and Ust-Kut areas [32]. In this territory, traps lie in the bottom of the Usolsky formation, under the Osinsky horizon, break through the Osinsky horizon along the bedding or are located on it. In the eastern part (on Pravoberezhnaya, Gruznovskaya, Zharkovskaya, Kovyktinskaya and Chikanskaya areas), they lie under the Osinsky horizon. Further to the east of Kovyktinskaya area, there is no trap body (see Fig. 3, a). The Angara-Lena industrial brine deposit [32, 35] is predicted here (see Fig. 3). It is currently being explored at the Znamenskoye, Verkholskoye, Kovyktinskoye and Omoloyskoye sites.

To the northwest, in Chorskaya area, in well 1, the traps lie under the Osinsky horizon, and in wells 2 and 115, they are located above the Osinsky horizon. To the west, in Karakhunskaya and Rodionovskaya areas, the basic sill “breaks” the Osinsky horizon. Here, in well 2 of Karakhunskaya

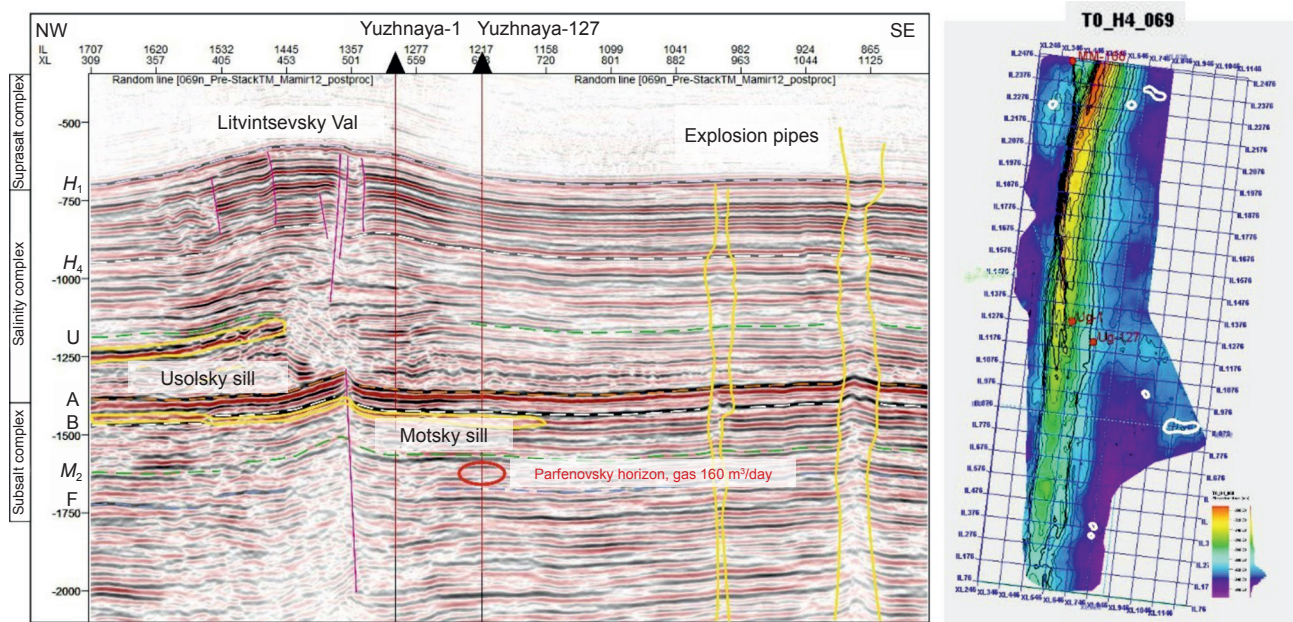


Fig. 4. Fluid-dynamic structures and volcanic eruption pipes within Usolsky sill distribution in the south of the Siberian platform (based on geological exploration data) [27]

a – wave pattern display at the Mamyrsky subsurface site (Mamyrsky-1, -2);

b – preliminary location of eruption pipes in a cube after prestack time migration

Рис. 4. Флюидодинамические структуры и вулканические трубки взрыва в пределах распространения Усольского сипла на юге Сибирской платформы (по данным геолого-разведочных работ) [27]:

a – отображение волновой картины на Мамырском участке недр (Мамырский-1, -2);

b – предварительное расположение трубок взрыва по кубу после временной миграции до суммирования



area, during drilling, a free flow of concentrated brine with hydrogen sulfide was obtained with a flow rate of about 2,000 m³/day. It is predicted (see Fig. 3) the industrial brine deposit of the same name.

According to borehole data, core and geophysical well logging studies, trap sill was installed in the wells 1UKV, 2UKV, 22CHI, and 62KOV in the Kovytkinskaya and Chikanskaya areas. The thickness of magmatic bodies is 10 m in the Pravoberezhnaya-1 well, 19.3 m in the 23CHI well, 70.1 m in the 14CHI and 21CHI wells. The maximum thickness of the stripped deposits in the southwest is in the Gruznovskaya-1 well (123 m). Similar values of thickness were detected according to drilling data in the Gruznovskaya 134 (105 m) and Zharovskaya 133 (118 m) wells. The minimum is in the Pravoberezhnaya-1 (10 m) and Zhigalovskaya-1 (1 m) wells. According to the material composition, the intrusive body is mainly represented by dolerites, less often by gabbro-dolerites. Thus, in the Kov-62 well, according to the materials of geophysical studies, trap formations were uncovered in the range of 2,586.6–2,652.2 m. According to the description of the core and sludge, the interval is represented by dolerites, from dark gray to black, fine crystalline, strong with dolomite interbeds.

Thus, the unique Kovykta gas condensate field, the largest field in the eastern part, is characterized by a complex two-layer structure of the volcanogenic-sedimentary cover³ [32, 35] and is complicated by trap sill in the western, northwestern parts of the territory (Fig. 5). The authors of the work [30] suggested the following: "It is possible that a powerful continuous dolomite formation (the Osinsky horizon) was a hard-to-penetrate barrier for high-temperature (1,100–1,200°C) trap magma. In the zones of deconsolidation and increased fracturing of the Osinsky horizon, trap magma flowed through tectonic zones into the supra-Osinskaya part of the section".

At the same time, in this model, the processes of interaction of magma and natural brines of the Osinsky horizon, auto-hydraulic fracturing and the intrusion of a vapor-gas front are not considered, although they are characteristic of

the magmatic stage of the upper crust development. We emphasize that here, at the stage of the intrusion of dolerite magma, the Osinsky horizon was located in the area of the formation of a vapor-dominated reservoir. Such processes take place at objects-analogues, for example in Kamchatka [6, 24, 25].

According to A.V. Kiryukhin [6], under conditions of horizontal crustal compression, active volcanoes are injectors of water and magma into adjacent geofluidic reservoirs, forming high-temperature hydrothermal systems (for example, the Mutnovsky volcano). It is the geodynamic conditions of horizontal compression that are characteristic of the Caledonian stage in the range of the middle, Early Cambrian halogen-carbonate strata [3, 32, 34] of this territory.

The authors compared the well-known hypotheses of the formation of brines of the Siberian platform [15, 16, 36], ore bodies of the Angara-Ilim type, the Norilsk ore node [4, 19], mineragenic concepts [33], the plume hypothesis [37]. This comparison suggested a possible model of not only explosive [33], but also a probable powerful, long-term secondary paleo-hydrothermal formation of the considered fluid-dynamic structures: objects in the sedimentary cover. [13, 14, 32, 38, 39]. On the one hand, this model was based on a comparison of field-geological data of drilling (see Fig. 5) and seismic surveys on the territory of the Angara-Lena artesian basin, hydrochemical studies of concentrated brine samples [9, 40], experiments of the water-rock interaction process at temperatures above boiling point and up to postcritical temperatures [12]. On the other hand, correlation of detailed geodynamic models of thrust tectonics [32], as well as the results of studies of modern and paleo-hydrothermal systems [6, 8, 25, 39], detailed description of the structure of trap sills and volcanic apparatuses of the central type, their relationship to the primary sedimentary rocks of the cover according to seismic surveys and deep drilling in the study area [27, 30, 41, 42].

If a number of observed fluid-dynamic structures are indeed formed in the processes of active filtration of fluids in the sedimentary cover, then

³ Misyurkeeva N.V. Folds and thrust structures of the sedimentary cover of the southeastern margin of the Siberian Craton (Kovykta–Khanda zone): *dissertation for the degree of Ph.D. in Geology*: 25.00.03. Irkutsk; 2022, 140 p.

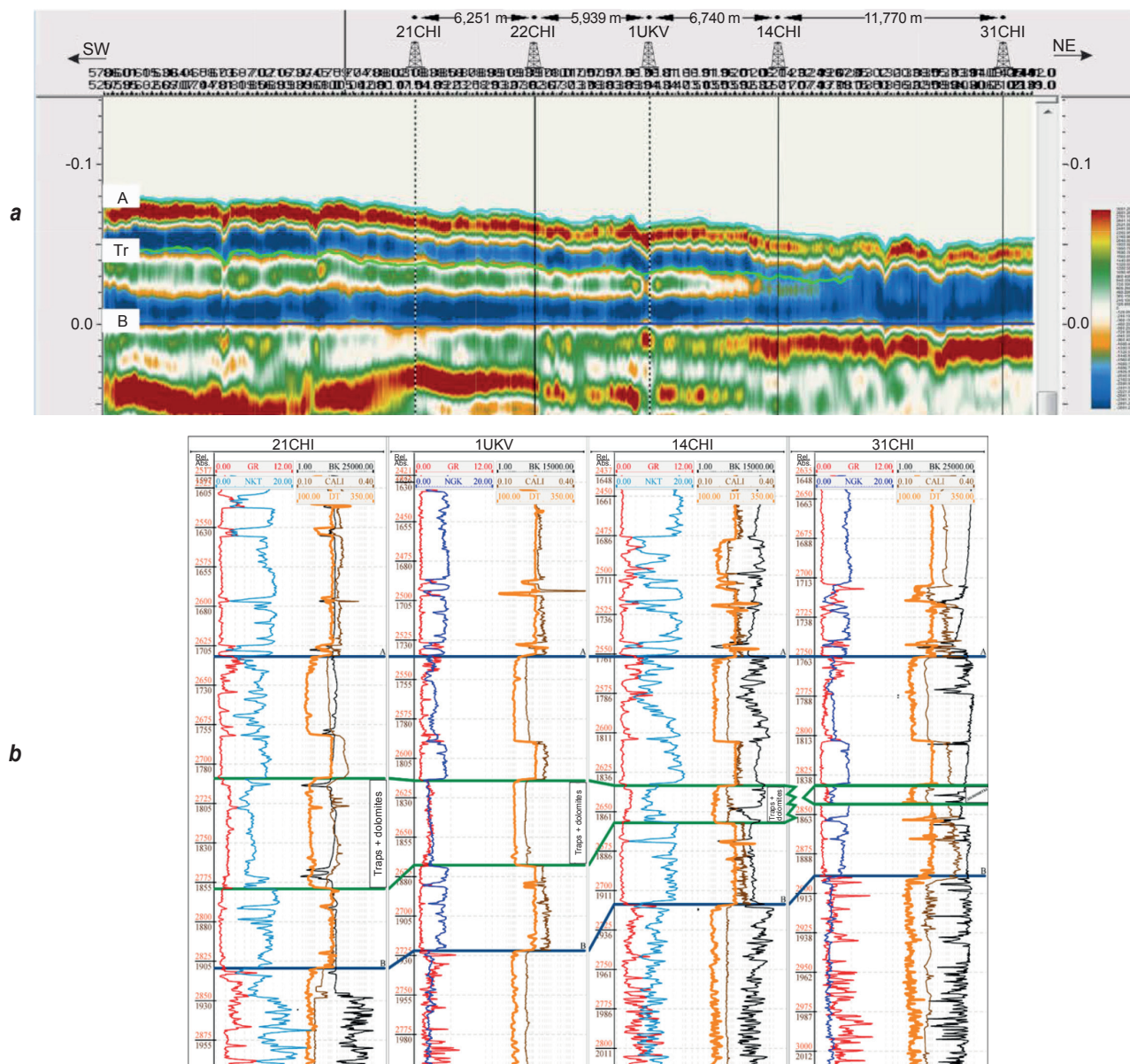


Fig. 5. Detailing of the geological model of the marginal apical region in the southeastern closure of the Usolsky Sill according to geological exploration data (drilling, geophysical surveys, time section of seismic surveys using the common depth point method) on Kovyktinskaya area [27, 30]:

a – in the plan (A – the roof of the Osinsky horizon, B – the roof of the Teter formation, Tr – trap sills);

b – fragment of geophysical research data correlation the line of wells 21CHI, 1UKV, 14CHI, 31CHI aligned with the roof of the Osinsky horizon (characteristics of the wave field in the wedging area of the Usolsky sill, seismic survey)

Рис. 5. Детализация геологической модели краевой апиальной области в юго-восточном замыкании Усольского силла по данным геолого-разведочных работ (бурение, геофизические исследования, временной разрез сейсморазведочных работ методом общей глубинной точки) на Ковыктинской площади [27, 30]:

а – в плане (А – кровля осинского горизонта, Б – кровля тэтэрской свиты, Тр – трапповое тело);

б – фрагмент корреляции данных геофизических исследований по линии скважин Чик-21, ЮК-1, Чик-14, Чик-31, выровненный на кровлю осинского горизонта (характеристика волнового поля в районе выклинивания усольского траппового тела, сейсморазведка)

there must be confirmation of these processes at the compositional level, in rock samples. According to A.Y. Ozerov, Doctor of Geological and Mineralogical Sciences, Corresponding member

of the Russian Academy of Sciences, an important argument for the formation of permeable sections of a trap body is the linearly permeable sections represented by “pore channel paths” on doler-



ite samples (Fig. 6, a). These areas reflect the process of “hydrovolcanism”, the breakthrough of an overheated steam-water mixture through liquid magma [43]. This phenomenon indicates a significant pressure of the vapor-gas jets of the vapor-dominated reservoir [24] below the contact area with magma, forming channels of vertical fluid filtration in the thickness of the melt area of the future trap sill. Fig. 6, b shows the phenomenon of intense karst in a core sample taken from the Osinsky horizon in one of the wells of the Nepa-Botuoba antecline, redeposition of the halite melt in caverns and karst cavities.

Actually, the described fluid-dynamic structures (see Figs 1, 4) are fixed in two regions. The part of fluid-dynamic structures is observed above the sill in the field of its spread. The other part of them is shifted from the contour (sill) projection and is located in the band (see Fig. 3), enveloping the marginal, apical parts of the Usolsky sill in the plan. At the same time, it captures the frontal area of the thrust folding of the allochthon of the Baikal-Patom fold-thrust belt, located in the

area of the prospected front of the main thrust sectors [13, 14, 32]. The Usolsky sill, the active intrusion of which is established in the Permian–Triassic, is limited along its contour by a foreland, or its intrusion stopped at some distance from the foreland (see Fig. 3). The magma intruded along the Osinsky horizon from the northwest to the southeast, up the rise. It is worth noting that the duration of up to 60 million years [11] of hydrothermal activity, with hydrothermal fluids circulating through the decompressed near-contact zones from the base of the magmatic bodies. Hydrothermal fluids, vapor-gas jets, and high-temperature fumaroles with temperatures up to 400–650°C [4, 12, 44] contributed to the transformation and movement of dissolved substances in the cavernous fractured strata of the carbonate layers of the Early Cambrian. As a result, the formation of subvertical fluid decompression zones led to the decompression of the salt carbonate strata and the development of superimposed subsidence structures (Fig. 7) according to the model of deep salt karst [31, 32].

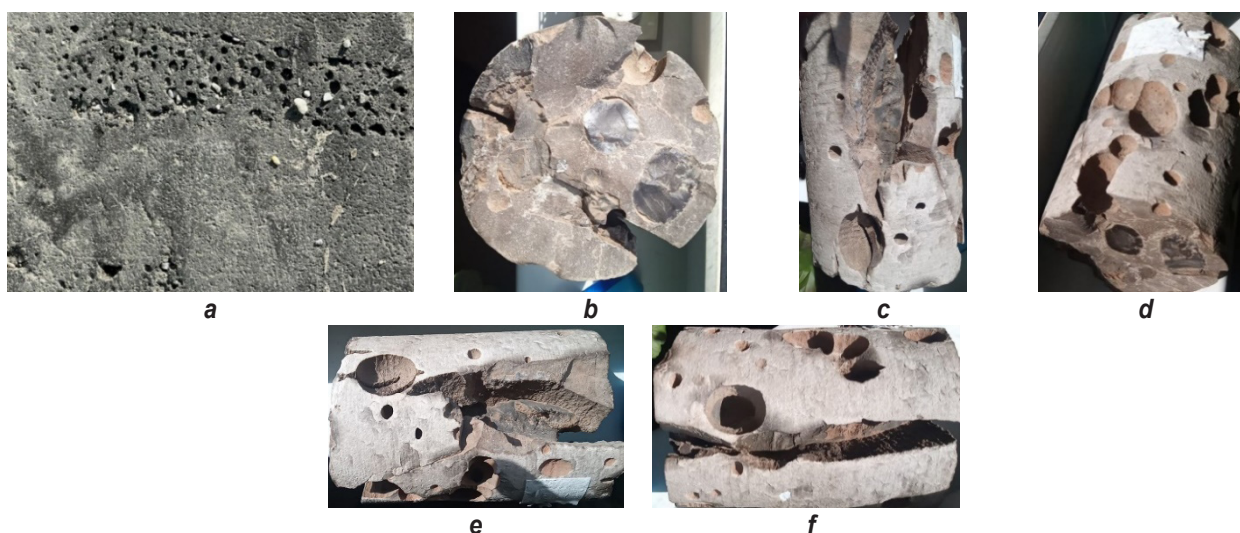


Fig. 6. Reflection of active paleofiltration of fluids in the sedimentary cover at the material level in rock samples:

- a – hydrovolcanism, linearly permeable areas represented by the “paths” of pore channels on the sawn dolerite samples (photo by A.Yu. Ozerov, 2024);
- b – manifestation of intense karst in a core sample taken from the Osinsky horizon;
- c–f – redeposition of black volcanic remolten salt in caverns and in the karst cavity (photo by A.G. Vakhromeev, 2025)

Рис. 6. Отражение активной палеофильтрации флюидов в осадочном чехле на вещественном уровне в образцах горных пород:

- a – гидровулканизм, линейно-проницаемые участки, представленные «дорожками» поровых каналов на распиленных образцах долеритов (фото А.Ю. Озерова, 2024 г.);
- b – проявление интенсивного карста в образце керна, отобранного из осинского горизонта;
- с–f – переотложение черной вулканической переплавленной соли в кавернах и карстовой полости (фото А.Г. Вахромеева, 2025 г.)

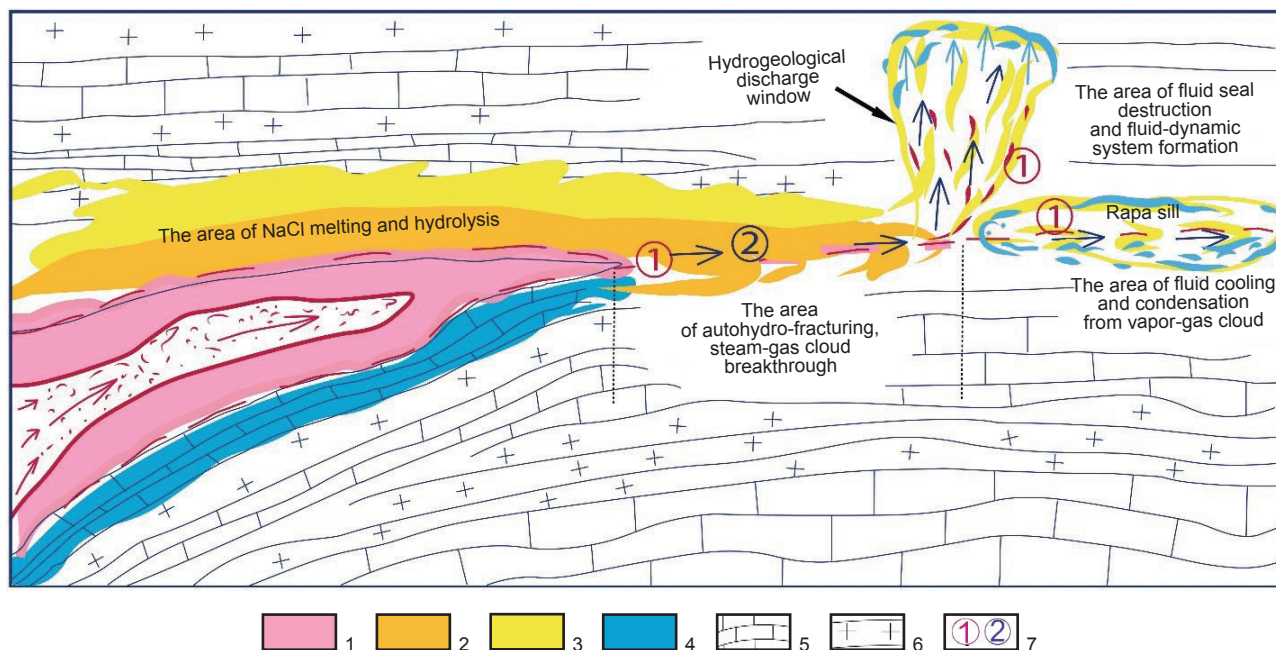


Fig. 7. Model and main development stages of the influence area of basic igneous melt on sedimentary rocks and fluid systems of sedimentary cover with area designation (according to A.G. Vakhromeev, M.A. Danilova, A.V. Levin, S.K. Kvachko, A.V. Sergeeva):
1 – magma area; 2 – area of salt melting and hydrolysis; 3 – area of vapor-dominated reservoir, hot (up to 100°C) liquid phase of brines; 4 – area of brine flow from lower levels of the cover section in the magmatic heating area, fluid-dynamic structure – area of subvertical decompression and discharge to the Earth's surface; 5 – carbonate intersalt reservoirs; 6 – halite layers; 7 – area of boiling and transition (1) to a supercritical state of the aqueous phase (2); rapa sill – area of the formed “rapa sill”

Рис. 7. Модель и основные этапы развития области воздействия базитового магматического расплава на осадочные породы и флюидные системы осадочного чехла с обозначением областей (по данным А.Г. Вахромеева, М.А. Даниловой, А.В. Левина, С.К. Квачко, А.В. Сергеевой):
1 – область магмы; 2 – область плавления и гидролиза солей; 3 – область пародоминирующего резервуара, горячей (до 100 °С) жидкой фазы рассолов; 4 – область перетока рассолов с нижних уровней разреза чехла в зону магматического прогрева, флюидодинамическая структура – область субвертикального разуплотнения и разгрузки на земную поверхность; 5 – карбонатные межсолевые резервуары; 6 – слои галита; 7 – зона вскипания и перехода (1) в сверхкритическое состояние водной фазы (2); рапа-силл – область сформированного «рапа-силла»

Within the framework of the magmatogenic-tectonic hydrothermal model of the transformation of the sedimentary cover in the apical region of the Usolsky sill, we consider the latter to be a gigantic magmatic body in terms of its area. The intrusion of its magma, which occurred about 250 million years ago, fundamentally influenced the reshaping of carbonate reservoirs and formed secondary, repeatedly reheated deposits of extremely saturated lithium-bearing brines in these reservoirs. In other words, it impulsively activated the processes of concentration of chloride brines, the accumulation of rare trace elements and mineral salts in them. The boiling of the brines led to the transition of water into the vapor phase [12, 45] and the removal of the solvent from the chloride system, resulting in the concentration of salts according to the eutectic system [46].

Thus, the process of impulse reshaping of cavernous fractured systems of intersalt carbonate reservoirs (reservoirs of highly concentrated brines) can be schematically described by the following stages (see Fig. 7):

1. During the magma intrusion and the formation of a magmatic focus in the frontal part of the future sill, a vapor-gas cloud of supercritical fluid with a temperature exceeding 374°C formed in the sub- and supra-Osinskaya parts of the Usolskaya formation. Above it (400–650°C) there were supercritical geothermal reservoirs (supercritical fluid with a temperature above 375°C) [6, 25, 43]. The formation of supercritical hydrothermal reservoirs led to a sharp increase in reservoir pressure, which initiated natural hydraulic fracturing processes in the sedimentary rock layers.



2. In the initial stage of water and vapor-gas exchange, the brines “boiled” with the evaporation of water as a solvent in the formations and horizons closest to the sill and directly above the sill. The concept of free water as a solvent for natural salts is discussed in the works of E.V. Zelinskaya [45], S. Yuan, et al. [12]. It is permitted [14, 38] to repeatedly pulsating mix of deep fresh thermal waters with ore (lithium, rubidium, cesium, strontium, boron, lead, tantalum, niobium, zirconium, yttrium, ytterbium, europium [32]) mineralization and primary sedimentary, metamorphosed brines of the sedimentary cover.

3. Supercritical pneumatolytic and vapor-gas jets and boiling brines, superheated above 400–600°C, “arrived” via circulation in the boundary area of the sill. Here, a zone of anomalous pressure and pulsatory [32] active fluid exchange formed, in which circulating heterophase hydrotherms and buried heated rare-metal brines from the contact zones of subvertical magmatic dikes and necks, and explosion pipes were involved. These deposits of industrial metal-bearing brines are discovered by deep wells during oil and gas exploration drilling (see Fig. 3).

4. The condensation of vapor and the aggressiveness of diluted hot brines towards carbonates, which are to varying degrees enriched with deep magmatic fluids, accelerated the rate of deep karst processes and likely formed fluid-dynamic structures of various scales. Such structures are recorded both in the basin above the sill and in the area of the band along the apical boundary of the sill and adjacent tectonic structures (swells and disjunctive zones of decompaction, faults with displacement (see Figs 5–7). The process of deep salt and carbonate paleokarst in the the sedimentary cover, disturbed by explosion, has activated the formation of superimposed structural forms within the allochthon.

Conclusions

Using the southeastern part of the Siberian Platform as an example, the hypothesis of magmatogenic-hydrothermal formation of fluid-dynamic structures and the transformation of rare-metal industrial brines in a volcanogenic-sedimentary basin under thick strata of Cambrian salts are

examined. The hypothesis is based on the most powerful stage of platform magmatism in the Permian-Triassic [2, 3, 4, 37]. Permeable “fluid-dynamic” paleostructures are identified based on the results of detailed seismic exploration work, including volume seismic exploration within the sedimentary cover. They are considered to be channels of concentrated paleodischarge of fluid pneumatolytic-hydrothermal systems.

The authors attribute the following structures to the formed fluid-dynamic structures observed in time sections:

- subsidence (compensation) troughs both in the area of subvertical “explosion pipes” of the Angara-Ilimsk type [10] and at some distance from the sill (see Figs 5, 7);

- subsidence troughs on the eastern, thrust faults, allochthonous limbs of linear anticlines in the Early Cambrian strata [32].

- injective deposits of multicomponent metal-bearing brines, “rapa sills”, distributed in inter-salt fractured carbonate reservoirs of the Usolkaya formation of the Early Cambrian, which are hypostatically close to the Osinsky horizon [13, 14].

During the stage of trap magmatism, along deep crustal faults, through tectonic structures in the frontal part of the Baikal-Patom thrust system, and along the formed channels of interstratal sole thrusts, a breakthrough of the vapor-gas front occurred, and a basaltic melt with a temperature of about 1200°C was injected. Subsequently, heating occurred, and boiling of fluid systems was observed, with partial melting of salts and the evacuation of vapor through fluid-dynamic structures. The final stage of the process involved prolonged development, leaching, and karstification of carbonate fractured reservoirs by hot hydrothermal fluids [7]. The process proceeded both through through subvertical zones of decompaction, fluid-dynamic structures, and laterally into auto-hydraulic fracturing zones, which are located closest to the magmatic focus zone in the sedimentary cover. Hydrothermal fluids also intruded into the zones of the interstratal sole thrusts in the detachment areas, and subsidence basins formed in the intersalt carbonate fractured reservoir rocks of the Cambrian macro-reservoir.



The authors believe that the volcanic and post-volcanic stages of the impact of magmatic and postmagmatic pneumatolithic–hydrothermal solutions on the areas of the sedimentary cover closest to the sills are the main stages in the formation of the observed fluid-dynamic structures as subvertical “hydrogeological windows” and subhorizontal closed isometric “rapa sills” [13, 14], which are visible on geological and geophysical materials of modern 3D volume seismic survey (see Figs 1, 3, 6). In support of this model, a number of sinkholes in the Ordovician carbonate strata in the studied area, hydrogen sulfide contamination of hydrocarbon formations, and sudden emissions of non-hydrocarbon gases: carbon monoxide, carbon dioxide, and hydrogen sulfide. These phenomena were observed by geologists during the drilling of deep wells 1 Pravoberezhnaya, 133, 3 Zharkovskaya, 134 Gruznovskaya, 176 Rudovskaya, as well as a number of core drilling exploratory wells for potash salts in the Tuturskaya area in the Ilginskaya paleodepression, and in many exploration areas of the Nepa dome.

From the moment the magma intruded until the end of its movement beneath and above the Osinsky horizon, and through the processes of solidification and heat transfer during cooling, the salt-bearing primary sedimentary artesian basin was divided by the sill into two sub-basins – the supra-magmatic and sub-magmatic ones. The first (upper, supra-magmatic) includes sedimentary rocks located above the magmatic melt chamber, and later, the solidified sill (see Figs 2–4, 7). The second (lower, sub-magmatic) unites the strata and natural reservoirs of the Riphean, terrigenous and carbonate Vendian, and Vendian–Cambrian. The development of circulation two-phase (liquid and vapor) hydrogeological systems in this basin, which is divided by a gigantic magmatic body, followed the thermolift model along subvertical permeable zones from the lower sub-basin to the upper one. Pneumatolytic fluid systems (mantle-derived diluted metal-bearing supercritical gases and vapor-hydrothermal fluids, superheated vapor, boiling metamorphosed strong and super-strong brines) circulated through the hydrogeological windows of volcanic explosion pipes and dikes (fluid-dynamic structures) that penetrated the cover in areas

where the sill “jumped” from lower to higher levels of the cover, as well as through local filtration channels (see Figs 5, 7).

The formation of the observed fluid-dynamic structures in the sedimentary cover, the phenomenon of deep salt and carbonate paleokarst, the paleoprocesses responsible for the formation of complex cavernous fractured intersalt reservoirs, and the patterns governing the localization of injective deposits of multicomponent metal-bearing brines, “rapa sills” [14] in natural intersalt fractured carbonate reservoirs of the Lower Cambrian, are interpreted by the authors as the cumulative result of two levels of hydrogeological evolution:

- long-term, by geological standards, equilibrium–nonequilibrium transformation of brines according to the “water–rock” model [47–49];
- impulsed geochemical and geodynamic evolution of fluid systems of the volcanogenic-sedimentary cover of the craton at magmatogenic and post-volcanic stages in the processes of localized hydrothermal discharge [12–16, 33, 38].

Thus, fluid-dynamic structures were formed during the intrusion of liquid, high-temperature (up to 1,100–1,200°C) trap magma into the halogen-carbonate-volcanogenic stratum of the salt-bearing basin cover. Today, the authors consider intersalt karst-fractured natural reservoirs of the Early Cambrian in the area influenced by the giant Usolsky sill in the south of the Siberian Platform as relics of the breach of the vapor-gas front of boiling rare-metal brines, “rapa-sills”, and also as transit routes for the prolonged paleodischarge of hydrothermal ore-bearing fluids. Natural circulation pneumatolytic-hydrothermal systems during the stages of platform magmatism fundamentally transformed the hydrogeochemistry of natural rare-metal multicomponent industrial chloride brines in the Angara-Lena artesian basin. This is a crucial [13, 14, 38] metallogenic cycle for the “liquid lithium ore”.

Thus, the stages of platform magmatism of the Siberian craton and postmagmatic processes played an important ore-forming and ore-localizing role in metallogeny, minerageny of industrial metalliferous brines, caused the secondary concentration of the richest “liquid” ore of rare, dispersed elements and mineral salts, including



bromine, alkali metals: lithium, rubidium, caesium, potassium, compounds with alkaline earth calcium and strontium, the formation of natural reservoirs with high filtration and capacitive

properties, the localization of brine deposits and their subsequent self-isolation with a decrease in temperatures of extremely saturated chloride systems.

References

1. Krasnov N.I., Lurie M.L., Masaitis V.L. *Geology of the Siberian Platform*. Moscow: Nedra; 1966, 447 p. (In Russ.).
2. Odintsov M.M., Domyshv V.G., Strakhov L.G., Zuev P.P., Khramov A.G., Shemes P.I., et al. *Angara-Vilyui ore belt of the Siberian platform*. Novosibirsk: Nauka; 1980, 113 p. (In Russ.).
3. Strakhov L.G. *Ore-bearing volcanic edifices of the south of the Siberian platform*. Novosibirsk: Nauka; 1978, 117 p. (In Russ.).
4. Feoktistov G.D. *Trap sill petrology and formation conditions*. Novosibirsk: Nauka; 1978, 168 p. (In Russ.).
5. Gladkochub D.P., Donskaya T.V., Ivanov A.V., Mazukabzov A.M., Ukhova N.A., Ernst R., et al. Phanerozoic mafic magmatism in the southern Siberian craton: geodynamic implications. *Russian Geology and Geophysics*. 2010;51(9):952-961. 10.1016/j.rgg.2010.08.005.
6. Kiryukhin A.V., Solomatin A.V. Geomechanical conditions of seismic, volcanic, and hydrothermal activity in Kamchatka. *Journal of Volcanology and Seismology*. 2026;20(2):67-80. 10.1134/S0742046326700120.
7. Nikulin V.I., Fon-der Flaas G.S., Baryshev A.S. Explosive volcanic basaltoid ore-forming system (Angara iron ore province). *Geologiya rudnykh mestorozhdenii*. 1991;3:26-40. (In Russ.).
8. Fedotov S.A. *Magmatic feeding systems and mechanism of volcano eruptions*. Moscow: Nauka; 2006, 454 p. (In Russ.).
9. Pinneker E.V. *Brines of the Angara Lena artesian basin: patterns of distribution, composition, dynamics, formation and use*. Moscow: Nauka; 1966, 332 p. (In Russ.).
10. Letnikov F.A., Medvedev V.Ya., Ivanova L.A. *Interaction of granite melt with carbonates and silicates: monograph*. Novosibirsk: Nauka; 1978, 151 p. (In Russ.).
11. Von-der-Flaas G.S. Magmatic stage in evolution of the ore-forming system of the Angara-Ilim type. *Russian Geology and Geophysics*. 1992;33(2):77-84. (In Russ.).
12. Yuan X., Hu Y., Zhao Y., Li Q., Liu C. Contribution of hydrothermal processes to the enrichment of lithium in brines: evidence from water – rock interacting experiments. *Aquatic Geochemistry*. 2021;27(3):221-239. 10.1007/s10498-021-09395-1.
13. Vakhromeev A.G., Kiryukhin A.V., Litvinova I.V., Danilova M.A., Surmaazhav D. Volcanogenic-tectonic model of the formation of ore-localizing structures and enrichment of deposits of industrial lithium-bearing brines of the halogen-carbonate hydrogeological formation of the Angara-Lena artesian basin, Siberian platform. In: *Volcanism and Related Processes: Proceedings of the 27th annual scientific conference dedicated to the Volcanologist Day*. 27–29 March 2024, Petropavlovsk-Kamchatsky. Petropavlovsk-Kamchatsky: Institute of Volcanology and Seismology, Far East Branch of the Russian Academy of Sciences; 2024, p. 199-202. (In Russ.).
14. Vakhromeev A.G., Kiryukhin A.V., Sergeeva A.V., Litvinova I.V. Modeling formation conditions of brine sills and operation of maximally saturated lithium-bearing brines in the south of the Siberian platform. In: *Underground Hydrosphere: Proceedings of the All-Russian meeting on groundwater in the east of Russia (24th Meeting on groundwater in Siberia and the Far East with international participation)*. 21–28 June 2024, Ekaterinburg. Ekaterinburg: Institute of Mining, Ural Branch of the Russian Academy of Sciences; 2024, p. 14-19. (In Russ.).
15. Vozhov V.I. *Groundwater and hydromineral raw materials of the Lena-Tunguska oil and gas province*. Novosibirsk: Siberian Research Institute of Geology, Geophysics and Mineral Raw Materials; 2006, 209 p. (In Russ.).
16. Dzyuba A.A. *Siberian platform brines discharge*. Novosibirsk: Nauka; 1984, 155 p. (In Russ.).
17. Belenitskaya G.A. On the participation of natural salts in alkaline magmatism. Article 3. Genetic aspects of the model of salt-alkaline interactions. *Lithosphere (Russia)*. 2021;21(2):172-197. (In Russ.). 10.24930/1681-9004-2021-21-2-172-197.
18. Al'mukhamedov A.I., Medvedev A.Ya. On the geochemistry of the initial stages of basaltic volcanism. In: Kuz'min M.I., Tauson L.V. (eds). *Geochemistry of volcanic rocks in various geodynamic settings*. Novosibirsk: Nauka; 1986, p. 49-69. (In Russ.).
19. Al'mukhamedov A.I., Nesterenko G.V. *Geochemistry of differentiated traps (Siberian Platform)*. Moscow: Nauka; 1973, 298 p. (In Russ.).
20. Nezhdanov A.A., Ogibenin V.V., Smirnov A.S., Spodobaev A.A. Fluid dynamic interpretation seismic survey data MRV CDP for oil and gas prospecting and exploration. *Burenie i nef't'*. 2023;2:12-19. (In Russ.).
21. Seminsky Zh.V. On Baikal region tectonic zoning and metallogeny. *Proceedings of the Siberian Department of the Section of Earth Sciences of the Russian Academy of Natural Sciences. Geology, Exploration and Development of Mineral Deposits*. 2017;40(4):112-117. (In Russian). 10.21285/2541-9455-2017-40-4-112-117.
22. Baryshev A.S., Egorov K.N., Koshkarev D.A. Mineragenic zones of the south of Siberian platform. *Proceedings of the Siberian Department of the Section of Earth Sciences of the Russian Academy of Natural Sciences. Geology, Prospecting and Exploration of Ore Deposits*. 2009;1:5-17. (In Russ.).



23. Romanyuk T.V., Tkachev A.V. *Geodynamic scenario of generation of the largest in the world boron-lithium provinces in the Miocene-quaternary*. Moscow: Svetoch Plyus; 2010, 304 p. (In Russian).
24. Kiryukhin A.V., Kiryukhin V.A., Manukhin Yu.F. *Hydrogeology of volcanogenic rocks*. Saint Petersburg: Nauka; 2010, 394 p. (In Russ.).
25. Kiryukhin A.V., Chernykh E., Polyakov A., Solomatin A. Magma fracking beneath active volcanoes based on seismic data and hydrothermal activity observations. *Geosciences*. 2020;10(2):52. 10.3390/geosciences10020052.
26. Mel'nikov N.V. *Vendian-Cambrian salt-bearing basin of the Siberian platform (stratigraphy, history of development): the monograph*. Novosibirsk: Siberian Research Institute of Geology, Geophysics and Mineral Raw Materials; 2009, 177 p. (In Russ.).
27. Tatyana N.V., Kozionov A.E., Smirnov A.S. Trap bodies tracing in seismic field at different stratigraphic levels in halogenic-carbonate section of Angaro-Kovyktinsky oil and gas accumulation zone. *Russian Oil and Gas Geology*. 2025;1:37-45. (In Russ.). 10.47148/0016-7894-2025-1-37-45.
28. Seminsky K.Zh., Gladkov A.S., Vakchromeev A.G., Cheremnykh A.V., Bobrov A.A., Kogut E.I. Faults and seismicity of the south of Siberian Platform: features of display at different scale levels. *Lithosphere (Russia)*. 2008;4:3-21. (In Russ.).
29. Seminsky K.Zh., Sankov V.A., Ogibenin V.V., Burzunova Yu.P., Miroshnichenko A.I., Gorbunova E.A., et al. Tectonophysical approach to the analysis of geological and geophysical data on gas-condensate deposits with the complex platform cover. *Geodynamics & Tectonophysics*. 2018;9(3):587-627. (In Russ.). 10.5800/GT-2018-9-3-0364.
30. Smirnov O.A., Borodkin V.N., Plavnik A.G., Lukashov A.V., Faryshova I.A., Vasiliev Yu.V. Characteristics of trapping magmatism within the fields of the Angara-Lena oil and gas-bearing region according to drilling and 3D seismic exploration data. *Geology, Geophysics and Development of Oil and Gas Fields*. 2022;6:5-10. (In Russ.). 10.33285/2413-5011-2022-6(366)-5-10.
31. Aleksandrov A.A., Levit A.N., Semakin B.V. *Local heterogeneities of salt strata in seismic exploration*. Moscow: Nauka; 1989, 77 p. (In Russ.).
32. Vakchromeev A.G. *Patterns of industrial brine deposits formation and localization in Cambrian carbonated vuggy-fractured rocks reservoir of south Siberian plate (based on deep drilling, well testing, and field geophysics data)*. Irkutsk: Irkutsk National Research Technical University; 2015, 247 p. (In Russ.).
33. Ilin A.I., Kompaniets S.V., Vakchromeev A.G. Features of the forecast of geological conditions of drilling of deep wells according to electromagnetic sounding. In: *Saint Petersburg 2012 – 5th Saint Petersburg International Conference & Exhibition 2012. Making the Most of the Earth's Resources.*, 2–5 April 2012, Saint Petersburg. Houten: European Association of Geoscientists & Engineers; 2012.
34. Migurskii A.V. Fluid dynamics on the Siberian platform during Permo-Triassic trap magmatism. In: *Degassing of the Earth: Geofluids, Oil and Gas, Paragenesis in the Fossil Fuel System: abstracts of the International Conference*. 30–31 May – 1 June 2006, Moscow. Moscow: GEOS; 2006, p. 153-155. (In Russ.).
35. Vakchromeev A.G., Gorlov I.V., Misiurkeeva N.V., Sverkunov S.A., Lankin Yu.K., Smirnov A.S. Hydrogeological fundamentals of local forecast of fluid pressure systems with AHRP in carbonate natural Cambrian reservoirs of the Kovyktinskoye gas condensate field. *Geology and Mineral Resources of Siberia*. 2018;4:49-59. (In Russ.). 10.20403/2078-0575-2018-4-49-59.
36. Antsiferov A.S. Resources of unique calcium chloride brines of the Siberian Platform and problems of their industrial development. *Prospect and Protection of Mineral Resources*. 2004;8-9:30-32. (In Russ.).
37. Abramovich G.Ya., Kuz'min M.I., Yarmolyuk V.V. Plume magmatogenic ore systems of the Southern Eastern Siberia. In: *Geology and minerals of the South of Eastern Siberia: collected scientific papers of the East Siberian Scientific Research Institute of Geology, Geophysics and Mineral Resources*. Irkutsk: Irkutsk State University; 2014, iss. 3, p. 18-24. (In Russ.).
38. Vakchromeev A.G., Zelinskaya E.V., Litvinova I.V., Pogrebnaya D.A. Model of secondary concentration of lithium-bearing brines in boiling fluid systems of magmatogenic-sedimentary basins of the hydromineral province of the Siberian Platform. In: *Geothermal Volcanology, Hydrogeology, Oil and Gas Geology: Proceedings of All-Russian scientific conference with international participation*. 4–10 September 2023, Petropavlovsk-Kamchatsky. Petropavlovsk-Kamchatsky: Institute of Volcanology and Seismology, Far East Branch of the Russian Academy of Sciences; 2023, p. 15-20. (In Russ.).
39. Surnin A.I., Litvinova I.V., Ivanova N.A. Hydrothermal stage in the formation of the hydrodynamic system of the sedimentary cover of the Siberian Platform. In: *Geothermal Volcanology, Hydrogeology, Oil and Gas Geology: Proceedings of All-Russian scientific conference with international participation*. 3–8 September 2020, Petropavlovsk-Kamchatsky. Petropavlovsk-Kamchatsky: Institute of Volcanology and Seismology, Far East Branch of the Russian Academy of Sciences; 2020, p. 151-154. (In Russ.).
40. Alekseev S.V., Vakchromeev A.G., Kotsupalo N.P., Ryabtsev A.D. *Industrial brines of the Siberian Platform: hydrogeology, drilling and production, processing, utilization*. Irkutsk: ООО "Географ"; 2014, 162 p. (In Russ.).
41. Gazhula S.V. Peculiarities of a trap mechanism in connection with the petroleum potential conditions of the Siberian Platform. *Petroleum Geology – Theoretical and Applied Studies*. 2008;3(1):5. (In Russ.).
42. Tonkikh M.E., Baryshev A.S., Egorov K.N., Koshkarev D.A. Structural position of traps in the south of Siberian Platform. *Proceedings of Irkutsk State Technical University*. 2011;12:65-73. (In Russ.).



43. Rychagov S.N. Giant gas-rich hydrothermal systems and their role in the generation of vapor-dominated geothermal fields and ore mineralization. *Journal of Volcanology and Seismology*. 2014;8(2):69-92. 10.1134/S0742046314020067.
44. Novikov D.A., Gordeeva A.O., Chernykh A.V., Dultsev F.F., Zhitova L.M. The influence of trap magmatism on the geochemical composition of brines of petroliferous deposits in the western areas of the Kureika syncline (Siberian Platform). *Russian Geology and Geophysics*. 2021;62(6):701-719. 10.2113/RGG20194079.
45. Zelinskaya E.V. *Theoretical foundations of the study and rational use of underground brines*. Irkutsk: Irkutsk State Technical University; 2002, 98 p. (In Russ.).
46. Sonnenfeld P. *Brines and evaporates*. Orlando; 1984, 613 p. (Russ. ed.: *Rassoly i ehvapority*. Moscow: Mir; 1988, 480 p.).
47. Alekseev S.V., Alekseeva L.P., Vakhromeev A.G., Vladimirov A.G., Volkova N.I. Lithium-bearing ground waters of the Irkutsk region and West Yakutia. *Chemistry for Sustainable Development*. 2012;20(1):27-33. (In Russ.).
48. Shvartsev S.L., Pinneker E.V., Perel'man A.I., Kononov V.I., Nazarov A.D., Rasskazov N.M., et al. *Fundamentals of hydrogeology. Hydrogeochemistry*. Novosibirsk: Nauka; 1982, 286 p. (In Russ.).
49. Shvartsev S.L. On the formation of strong and extremely saturated underground brines. In: Zharkov M.A., Yan-shin A.L. (eds). *Problems of salt accumulation*. Novosibirsk: Nauka; 1977, vol. 1, p. 192-195. (In Russ.).

Список источников

1. Геология Сибирской платформы / под ред. Н.И. Краснова, М.Л. Лурье, В.Л. Масайтиса. М.: Недра, 1966. 447 с.
2. Одинцов М.М., Домышев В.Г., Страхов Л.Г., Зуев П.П., Храмов А.Г., Шемес П.И. [и др.]. Ангаро-Виллюйский рудный пояс Сибирской платформы / отв. ред. Ф.А. Летников. Новосибирск: Наука, 1980. 113 с.
3. Страхов Л.Г. Рудоносные вулканические аппараты юга Сибирской платформы / отв. ред. М.М. Одинцов. Новосибирск: Наука, 1978. 117 с.
4. Феоктистов Г.Д. Петрология и условия формирования трапповых силлов / отв. ред. В.В. Золотухин. Новосибирск: Наука, 1978. 168 с.
5. Gladkochub D.P., Donskaya T.V., Ivanov A.V., Mazukabzov A.M., Ukhova N.A., Ernst R., et al. Phanerozoic mafic magmatism in the southern Siberian craton: geodynamic implications // *Russian Geology and Geophysics*. 2010. Vol. 51. Iss. 9. P. 952–961. 10.1016/j.rgg.2010.08.005.
6. Kiryukhin A.V., Solomatin A.V. Geomechanical conditions of seismic, volcanic, and hydrothermal activity in Kamchatka // *Journal of Volcanology and Seismology*. 2026. Vol. 20. Iss. 2. P. 67–80. 10.1134/S0742046326700120.
7. Никулин В.И., Фон-дер Флаас Г.С., Барышев А.С. Эксплозивно-вулканическая базальтоидная рудообразующая система (Ангарская железорудная провинция) // *Геология рудных месторождений*. 1991. № 3. С. 26–40.
8. Федотов С.А. Магматические и питающие системы и механизм извержений вулканов. М.: Наука, 2006. 454 с.
9. Пиннекер Е.В. Рассолы Ангаро-Ленского артезианского бассейна: закономерности размещения, состав, динамика, формирование и использование. М.: Наука, 1966. 332 с.
10. Летников Ф.А., Медведев В.Я., Иванова Л.А. Взаимодействие гранитного расплава с карбонатами и силикатами: монография / отв. ред. Ю.В. Комаров. Новосибирск: Наука, 1978. 151 с.
11. Фон-дер Флаас Г.С. Магматический этап в эволюции рудообразующей системы ангаро-илимского типа // *Геология и геофизика*. 1992. Т. 33. № 2. С. 77–84.
12. Yuan X., Hu Y., Zhao Y., Li Q., Liu C. Contribution of hydrothermal processes to the enrichment of lithium in brines: evidence from water – rock interacting experiments // *Aquatic Geochemistry*. 2021. Vol. 27. Iss. 3. P. 221–239. 10.1007/s10498-021-09395-1.
13. Вахромеев А.Г., Кирюхин А.В., Литвинова И.В., Данилова М.А., Сурмаажав Д. Вулканогенно-тектоническая модель формирования рудолокализирующих структур и обогащения межсолевых залежей промышленных литиеносных рассолов Ангаро-Ленского артезианского бассейна, Сибирская платформа // *Вулканизм и связанные с ним процессы: материалы XXVII ежегод. науч. конф., посвящ. Дню вулканолога (г. Петропавловск-Камчатский, 27–29 марта 2024 г.)*. Петропавловск-Камчатский: Изд-во ИВиС ДВО РАН, 2024. С. 199–202.
14. Вахромеев А.Г., Кирюхин А.В., Сергеева А.В., Литвинова И.В. Моделирование условий формирования рап-силлов и эксплуатации предельно насыщенных литиеносных рассолов на юге Сибирской платформы // *Подземная гидросфера: материалы Всерос. совещания по подземным водам Востока России (XXIV Совещание по подземным водам Сибири и Дальнего Востока с междунар. участием. (г. Екатеринбург, 21–28 июня 2024 г.)*. Екатеринбург: Изд-во ИГД УрО РАН, 2024. С. 14–19.
15. Вожов В.И. Подземные воды и гидроминеральное сырье Лено-Тунгусской нефтегазоносной провинции: монография. Новосибирск: Изд-во СНИИГГиМС, 2006. 209 с.
16. Дзюба А.А. Разгрузка рассолов Сибирской платформы: монография / отв. ред. Е.В. Пиннекер. Новосибирск: Наука, 1984. 155 с.
17. Беленицкая Г.А. Об участии природных солей в щелочном магматизме. Статья 3. Генетические аспекты модели соляно-щелочных взаимодействий // *Литосфера*. 2021. Т. 21. № 2. С. 172–197. 10.24930/1681-9004-2021-21-2-172-197.



18. Альмухамедов А.И., Медведев А.Я. К геохимии инициальных стадий базальтового вулканизма // Геохимия вулканитов различных геодинамических обстановок / ред. М.И. Кузьмин, Л.В. Таусон. Новосибирск: Наука, 1986. С. 49–69.
19. Альмухамедов А.И. Нестеренко Г.В. Геохимия дифференцированных траппов (Сибирская платформа): монография. М.: Наука, 1973. 298 с.
20. Нежданов А.А., Огибенин В.В., Смирнов А.С., Сподобаев А.А. Флюидодинамическая интерпретация сейсморазведочных данных МОВ ОГТ для поисков и разведки нефти и газа // Бурение и нефть. 2023. № 2. С. 12–19.
21. Семинский Ж.В. О тектоническом районировании и металлогении Прибайкалья // Известия Сибирского отделения Секции наук о Земле Российской академии естественных наук. Геология, разведка и разработка месторождений полезных ископаемых. 2017. Т. 40. № 4. С. 112–117. 10.21285/2541-9455-2017-40-4-112-117.
22. Барышев А.С., Егоров К.Н., Кошкарёв Д.А. Минерагенические зоны юга Сибирской платформы // Известия Сибирского отделения секции наук о Земле Российской академии естественных наук. Геология, поиски и разведка рудных месторождений. 2009. № 1. С. 5–17.
23. Романюк Т.В., Ткачев А.В. Геодинамический сценарий формирования крупнейших мировых неоген-четвертичных бор-литиеносных провинций: монография. М.: Светоч Плюс, 2010. 304 с.
24. Кирюхин А.В., Кирюхин В.А., Манухин Ю.Ф. Гидрогеология вулканогенов. СПб.: Наука, 2010. 394 с.
25. Kiryukhin A.V., Chernykh E., Polyakov A., Solomatin A. Magma fracking beneath active volcanoes based on seismic data and hydrothermal activity observations // Geosciences. 2020. Vol. 10. Iss. 2. P. 52. 10.3390/geosciences10020052.
26. Мельников Н.В. Венд-кембрийский соленосный бассейн Сибирской платформы (стратиграфия, история развития): монография. Новосибирск: Изд-во СНИИГГИМС, 2009. 177 с.
27. Татьяна Н.В., Козионов А.Е., Смирнов А.С. Прослеживание трапповых тел в сейсмическом поле на разных стратиграфических уровнях в условиях карбонатно-галогенного разреза Ангара-Ковыктинской зоны нефтегазоаккумуляции // Геология нефти и газа. 2025. № 1. С. 37–45. 10.47148/0016-7894-2025-1-37-45.
28. Семинский К.Ж., Гладков А.С., Вахромеев А.Г. Черемных А.В., Бобров А.А., Когут Е.И. Разломы и сейсмичность юга Сибирской платформы: особенности проявления на разных масштабных уровнях // Литосфера. 2008. № 4. С. 3–21.
29. Семинский К.Ж., Саньков В.А., Огибенин В.В., Бурзунова Ю.П., Мирошников А.И., Горбунова Е.А. [и др.]. Тектонофизический подход к анализу геолого-геофизических данных на газоконденсатных месторождениях со сложным строением платформенного чехла // Геодинамика и тектонофизика. 2018. Т. 9. № 3. С. 587–627. 10.5800/GT-2018-9-3-0364.
30. Смирнов О.А., Бородин В.Н., Плавник А.Г., Лукашов А.В., Фарышова И.А., Васильев Ю.В. Характеристика траппового магматизма в пределах месторождений Ангара-Ленской нефтегазоносной области по данным бурения и сейсморазведки 3D // Геология, геофизика и разработка нефтяных и газовых месторождений. 2022. № 6. С. 5–10. 10.33285/2413-5011-2022-6(366)-5-10.
31. Александров А.А., Левит А.Н., Семакин Б.В. Локальные неоднородности соляных толщ в сейсморазведке / отв. ред. В.В. Корягин, В.М. Свищев. М.: Наука, 1989. 77 с.
32. Вахромеев А.Г. Закономерности формирования и локализации месторождений промышленных рассолов в карбонатных каверново-трещинных резервуарах кембрия юга Сибирской платформы (по данным глубокого бурения, испытания скважин и полевой геофизики): монография. Иркутск: Изд-во ИРНТУ, 2015. 247 с.
33. Ilin A.I., Kompaniets S.V., Vakhromeev A.G. Features of the forecast of geological conditions of drilling of deep wells according to electromagnetic sounding // Saint Petersburg 2012 – 5th Saint Petersburg International Conference & Exhibition 2012. Making the Most of the Earth's Resources (Saint Petersburg, 2–5 April 2012). Houten: European Association of Geoscientists & Engineers, 2012.
34. Мигурский А.В. Флюидодинамика на Сибирской платформе во время пермо-триасового траппового магматизма // Дегазация Земли: геофлюиды, нефть и газ, парагенезы в системе горючих ископаемых: тезисы Междунар. конф. (г. Москва, 30–31 мая – 1 июня 2006 г.). М.: ГЕОС, 2006. С. 153–155.
35. Вахромеев А.Г., Горлов И.В., Мисюркеева Н.В., Сверкунов С.А., Ланкин Ю.К., Смирнов А.С. Гидрогеологические основы локального прогноза флюидонапорных систем с аномально высоким пластовым давлением в карбонатных природных резервуарах кембрия Ковыктинского газоконденсатного месторождения // Геология и минерально-сырьевые ресурсы Сибири. 2018. № 4. С. 49–59. 10.20403/2078-0575-2018-4-49-59.
36. Анциферов А.С. Ресурсы уникальных хлоридных кальциевых рассолов Сибирской платформы и проблемы их промышленного освоения // Разведка и охрана недр. 2004. № 8–9. С. 30–32.
37. Абрамович Г.Я., Кузьмин М.И., Ярмолюк В.В. Плюмовые магматогенно-рудные системы юга Восточной Сибири // Геология и полезные ископаемые юга Восточной Сибири: сборник науч. трудов ВостСибНИИГГИМС. Иркутск: Изд-во ИГУ, 2014. Вып. 3. С. 18–24.
38. Вахромеев А.Г. Зелинская Е.В., Литвинова И.В., Погребная Д.А. Модель вторичного концентрирования литиеносных рассолов в кипящих флюидных системах магматогенно-осадочных бассейнов гидроминеральной провинции Сибирской платформы // Геотермальная вулканология, гидрогеология, геология нефти и газа: материалы Всерос. науч. конф. с междунар. участием. (г. Петропавловск-Камчатский, 4–10 сентября 2023 г.). Петропавловск-Камчатский: Изд-во ИВиС ДВО РАН, 2023. С. 15–20.



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40. Алексеев С.В., Вахромеев А.Г., Коцупало Н.П., Рябцев А.Д. Промышленные рассолы Сибирской платформы: гидрогеология, бурение и добыча, переработка, утилизация: монография / отв. ред. Е.В. Складов. Иркутск: Изд-во ООО «Географ», 2014. 162 с.
41. Гажула С.В. Особенности траппового магматизма в связи с условиями нефтегазоносности Сибирской платформы // Нефтегазовая геология. Теория и практика. 2008. Т. 3. № 1. С. 5.
42. Тонких М.Е., Барышев А.С., Егоров К.Н., Кошкарёв Д.А. Структурная позиция траппов юга Сибирской платформы // Вестник Иркутского государственного технического университета. 2011. № 12. С. 65–73.
43. Rychagov S.N. Giant gas-rich hydrothermal systems and their role in the generation of vapor-dominated geothermal fields and ore mineralization // Journal of Volcanology and Seismology. 2014. Vol. 8. Iss. 2. P. 69–92. 10.1134/S0742046314020067.
44. Novikov D.A., Gordeeva A.O., Chernykh A.V., Dultsev F.F., Zhitova L.M. The influence of trap magmatism on the geochemical composition of brines of petroliferous deposits in the western areas of the Kureika syncline (Siberian Platform) // Russian Geology and Geophysics. 2021. Vol. 62. Iss. 6. P. 701–719. 10.2113/RGG20194079.
45. Зелинская Е.В. Теоретические основы изучения и рационального использования подземных рассолов. Иркутск: Изд-во ИРГТУ, 2002. 98 с.
46. Сонненфельд П. Рассолы и эвапориты / пер. с англ. М.: Мир, 1988. 480 с.
47. Алексеев С.В., Алексеева Л.П., Вахромеев А.Г., Владимиров А.Г., Волкова Н.И. Литиевые подземные воды Иркутской области и Западной Якутии // Химия в интересах устойчивого развития. 2012. Т. 20. № 1. С. 27–33.
48. Шварцев С.Л., Пиннекер Е.В., Перельман А.И., Кононов В.И., Назаров А.Д., Рассказов Н.М. [и др.]. Основы гидрогеологии: монография. Гидрогеохимия. Новосибирск: Наука, 1982. 286 с.
49. Шварцев С.Л. О формировании крепких и предельно насыщенных подземных рассолов // Проблемы соленаккумуляции: сборник докладов / отв. ред. М.А. Жарков, А.Л. Яншин. Новосибирск: Наука, 1977. Т. 1. С. 192–195.

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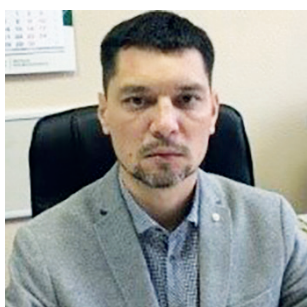
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