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Geological Model of the Mechanism of Formation of Gas-Dynamic Hazard Centers in the Rocks of the Sylvinite-Carnallite Zone at the Verkhnekamskoye Potassium-Magnesium Salt Deposit

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Геологическая модель механизма образования очагов газодинамической опасности в породах сильвинито-карналлитовой зоны на Верхнекамском месторождении калийно-магниевых солей

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In the course of the research, a geological model of the mechanism of formation of gas-dynamic hazard centers in the rocks of the sylvinite-carnallite zone at the Verkhnekamskoye potassium salt deposit was developed. During the formation of gas-dynamic hazard centers in the rocks of the sylvinite-carnallite zone, the sources of gas-saturated fluids were gas-bearing aqueous solutions, including fluids from oil-bearing deposits located in the thickness of rocks underlying the salt deposit. The paths of ascending migration of gas-saturated fluids could be: rupture tectonic faults, thrusts, through zones of increased fracturing and permeability zones above the slopes of reef structures. Migration of gas-saturated fluids into the salt thickness from the underlying rocks occurred in a subvertical direction (from the bottom up). In the rocks of the sylvinite-carnallite zone, the lateral direction of migration of gas-saturated aqueous solutions prevailed over the vertical one due to the pronounced anisotropy of filtration properties. Fluids moved laterally along numerous clay layers, interlayers and intergranular space. During the migration of gas-saturated fluids in the rocks of the sylvinite-carnallite zone, epigenetic transformations of salt rocks occurred: replacement of sylvinites with rock salt, sylvinization of carnallites, formation of rocks of mixed composition (sylvinite + carnallite). During sylvinization of carnallites, the migration of aggressive gas-saturated fluids occurred in the direction from the zones of replacement of sylvinites with rock salt and variegated sylvinites in the direction of development of carnallite rocks. Variegated sylvinite as a product of epigenetic processes in rocks of the sylvinite-carnallite zone near the contact with carnallite rock has increased porosity and decreased strength. The patterns of free gas distribution in the layers of the sylvinite-carnallite zone are determined by the work of the three-zone functional system of halogen metasomatism. The decomposition of carnallite was accompanied by the formation of a deficit of the solid phase, the value of which could vary in a wide range of values and reach almost 70%. In areas of complete decomposition of carnallite in rocks of the sylvinite-carnallite zone, voids were formed due to the deficit of the solid phase. These voids, by analogy, can be considered a process of natural "undermining" of the overlying layers and "overmining" of the underlying ones. The effect of natural "undermining" was accompanied by the formation of crack systems in the undermining part of the sylvinite-carnallite zone due to unloading from rock pressure and rock displacement, through which free gases migrated into the undermining layers. As a result, in the rocks of the sylvinite-carnallite zone, under the influence of natural "undermining", in the zone of unloading from vertical stresses due to destruction and stratification at the contacts of layers and layers, as well as along clay interlayers, favorable conditions are created for the filtration of free gases into it.

Ключевые слова:
геолого-разведочные скважины, нефтяные месторождения, нефтеперспективные структуры, газовыделения, газодинамические явления, зоны замещения, сильвинитизация карналлитов, природная подработка, расслоения, газонаполненные трещины, мульды сдвижения, краевая часть.

В процессе проведения исследований разработана геологическая модель механизма образования очагов газодинамической опасности в породах сильвинито-карналлитовой зоны на Верхнекамском месторождении калийных солей. При образовании в породах сильвинито-карналлитовой зоны очагов газодинамической опасности источниками газонасыщенных флюидов являлись газоносные водные растворы, в том числе и флюиды из нефтеносных месторождений, расположенных в толще пород, постилающих соляную залежь. Путями восходящей миграции газонасыщенных флюидов могли быть: разрывные тектонические нарушения, надвиги, сквозные зоны повышенной трещиноватости и зоны проницаемости над склонами рифогенных структур. Миграция газонасыщенных флюидов в соляную толщу из подстилающих пород происходила в субвертикальном направлении (снизу вверх). В породах сильвинито-карналлитовой зоны латеральное направление миграции газонасыщенных водных растворов преобладало над вертикальным вследствие ярко выраженной анизотропии фильтрационных свойств. Флюиды в латеральном направлении двигались по многочисленным глинистым слоям прослойкам и межзерновому пространству. В процессе миграции газонасыщенных флюидов в породах сильвинито-карналлитовой зоны происходили эпигенетические преобразования соляных пород: замещение сильвинитов каменной солью, сильвинитизация карналлитов, образование пород смешанного состава (сильвинит + карналлит). При сильвинизации карналлитов миграция агрессивных газонасыщенных флюидов происходила в направлении от зон замещения сильвинитов каменной солью и пестрых сильвинитов в направлении развития карналлитовых пород. Пестрый сильвинит как продукт эпигенетических процессов в породах сильвинито-карналлитовой зоны вблизи контакта с карналлитовой породой обладает повышенной пористостью и пониженной прочностью. Закономерности распределения свободных газов в пластах сильвинито-карналлитовой зоны обусловлены работой трехзонной функциональной системы галогенного метасоматоза. Разложение карналлита сопровождалось образованием дефицита твердой фазы, величина которого могла изменяться в широком диапазоне значений и достигать почти 70 %. На участках полного разложения карналлита в породах сильвинито-карналлитовой зоны из-за дефицита твердой фазы формировались пустоты. Эти пустоты по аналогии можно считать процессом природной «подработки» вышележащих пластов и «надработки» нижележащих. Эффект природной «подработки» сопровождался формированием в подработанной части сильвинито-карналлитовой зоны за счет разгрузки от горного давления и сдвижения пород систем трещин, через которые происходила миграция свободных газов в подработанные пласты. В результате в породах сильвинито-карналлитовой зоны под воздействием природной «подработки» в зоне разгрузки от вертикальных напряжений за счет разрушений и расслоений по контактам слоев и пластов, а также по глинистым прослоям создаются благоприятные условия для фильтрации в нее свободных газов.

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Introduction

The Verkhnekamskoye potassium salt deposit (VKPSD), located in Perm Krai, is the second largest potash salt reserves after the world's largest Saskatchewan potassium satt deposit. The thickness of salt rocks has the shape of a lens with an area of up to 8.2 thousand km^2. The area of the main multi-layered deposit of potassium-magnesium salts is 3.7 thousand km^2 [1]. The genesis and structure of the Verkhnekamskoe deposit have been studied by many famous scientists and reflected in a number of works [1–4]. The geological value of the field increases due to the presence of oil-bearing structures in the subsalt rocks.

The potash deposit of the Verkhnekamskoye field is represented by a series of productive layers separated by rock salt layers (Fig. 1). The deposit is divided into sylvinite and sylvinite-carnallite zones. The sylvinite zone with an average thickness of 20 metres is composed of alternating formations of red sylvinites (RedIII, RedII and RedI), of banded sylvinite (A) and separating rock salt formations (RedIII – RedII, RedII – RedI and RedI – A). The sylvinite-carnallite zone with an average thickness of 60 m is composed of alternating formations of potassium-magnesium salts (nine banks, which are indexed from the bottom to the top with letters from B to K and rock salt (eight formations – from B-V to I-K). Formation B lies at the base of the sylvinite-carnallite zone, directly on the banded sylvinite A bed.

Along with potassium salt reserves within the Verkhnekamskoye field territory 14 oil and gas fields and 17 potentially oil-bearing structures (Lower and Middle Carboniferous and Upper Devonian) have been discovered in pre-salt sediments at depths of 1,600–2,300 meters (see Fig. 1) [5].

It is known that the gas factor plays a major role in the initiation and process of gas emissions and gas dynamic phenomena in geological exploration. Free gases in salt rocks are under high pressure, sometimes reaching up to 8.0 MPa [6]. The first information about gas emissions at the Verkhnekamsk potassium salt deposit during well drilling dates back to 1925. At opening salts by wells gas emissions are manifested in different ways. Sometimes only foaming of the drilling fluid is observed and a faint noise is heard in the well. In other cases, gas emission is violent, accompanied by mud and cuttings ejections from wells to a height of several tens of metres, leading in some cases to flammable gas outbreaks and fires in the drilling room. Particularly violent gas emissions take place during penetration of sylvinite-carnallite formations from E to V and are most often observed in wells located in the rear parts and on the wings of anticlinal structures. The duration of gas emissions (taking into account pauses) can vary from a fraction of an hour to several days and even weeks.

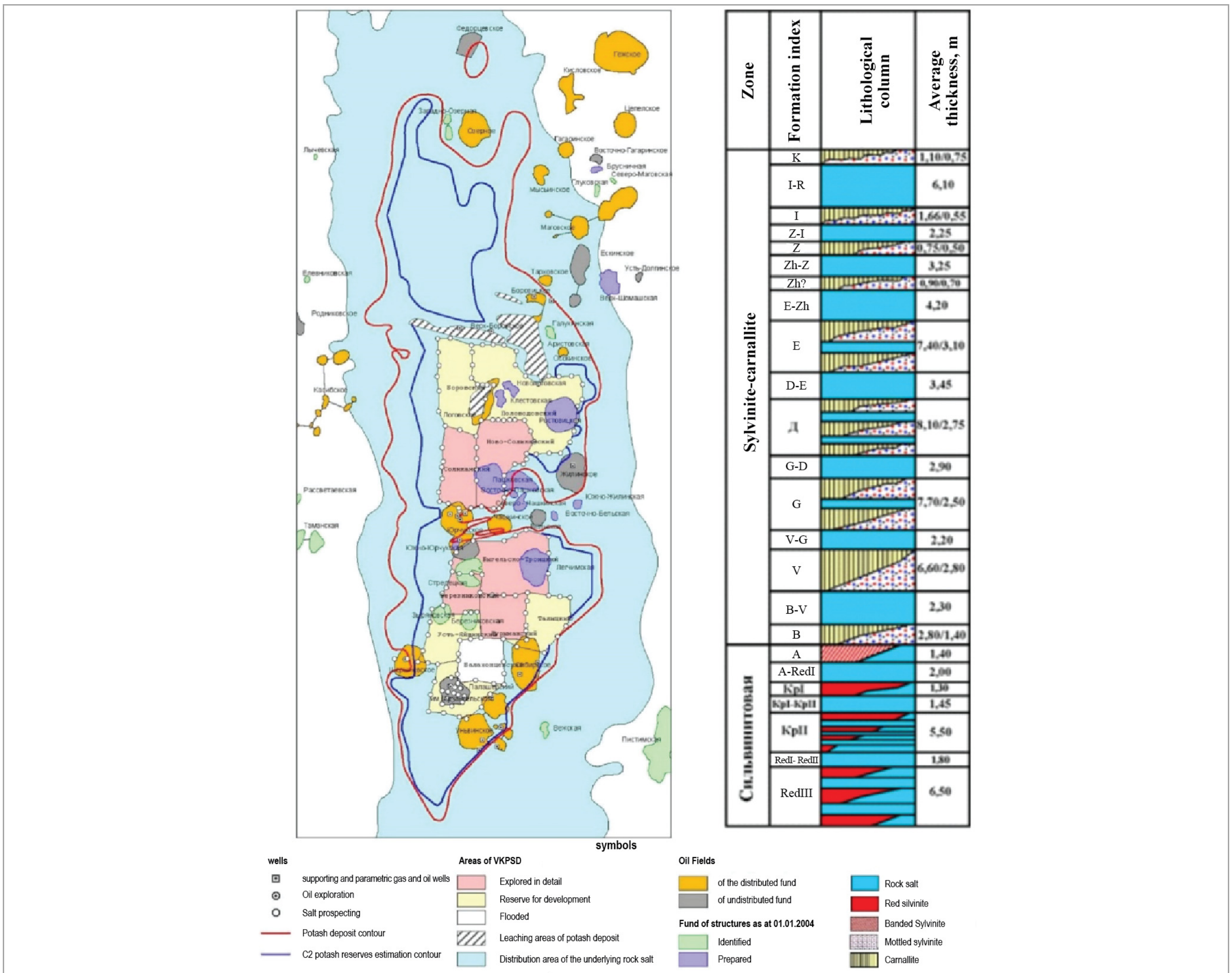

Fig. 1. Combined plan of the Verkhnekamskoe potassium deposit, oil fields and potentially oil-bearing structures

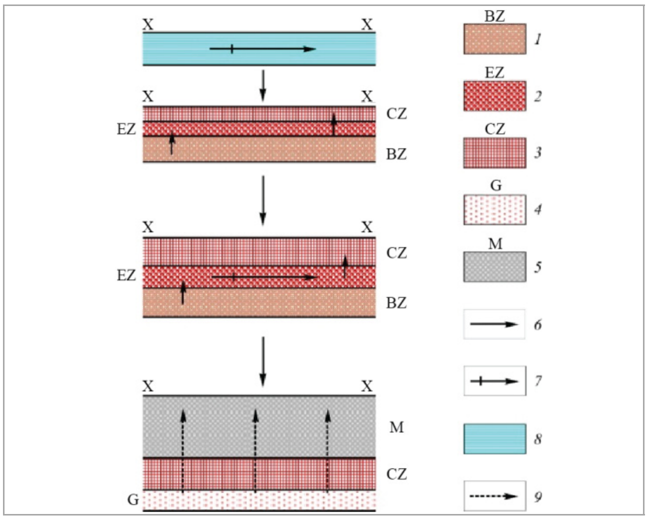

Fig. 2. Model elementary diagram of three-zone functional systems of metasomatosis in the formation of GDP source kitchens: P – conductor; T – crack; *1* – bottomhole zone; *2* – exchange zone; *3* – condensation zone; *4* – free gas; *5* – metasomatitis and intersomatitis; *6* – mass transfer between the bottomhole and condensation zones through the exchange; *7* – longitudinal mass transfer along the exchange zone; *8* – rock salt with a "cake" and halopelite layers and interlayers; *9* – direction of migration of free gases in the process of metasomatosis; TK – transit zone

Information on gas emissions recorded during drilling of wells at the Verkhnekamskoe potassium deposit, given in archive data and prospecting and evaluating reports, was compiled into a table and analysed. A total of 410 events were collected from more than 180 wells. The largest number of gas occurrences was recorded in the Polovodovsky, Ust-Yayvinsky, Borovsky and Palashersky sections of the VKPSD [7].

It should be noted that in order to increase the reliability of the forecast of gas-dynamic hazard and the effectiveness of preventive measures for its control, it is necessary consider the geological conditions for the accumulations of free gases formation and kitchen sources of gas-dynamic phenomena. including a possible genetic link with epigenetic processes in the potash deposit and oil and gas content of the underlying deposits, which is manifested in the workins of potassium mines in the form of traces of oil showings and the presence of free gases in salt rocks in certain areas of the deposit with an abnormally high total content of heavy hydrocarbon gases reaching 20% or more.

At present, there is no model of the geological mechanism of gas accumulation sources and gas dynamic phenomena in the sylvinite-carnallite zone rocks above the bed V in the process of epigenetic transformations of sylvinite and sylvinite-carnallite zone rocks of the Verkhnekamskoye potash deposit salt column and possible migration of gas-saturated fluids into the salt column from the underlying oil-and-gas-bearing deposits.

The methods of modelling and forecasting of gasdynamic hazard are described in detail in the works of both domestic and foreign authors [8-34]. For the first time, GDP kitchen sources were considered in the work of M.P. Fiveg [35]. Their consideration is based on the point of view based on the ideas of halokinesis and rejecting the existence of discontinuous dislocations. Kitchen sources of GDP in the bed V was attributed to crushing zones by Dr. Sci. N.M. Proskuryakov [36, 37]. The contours of the geological model of formation of gas-dynamic sources in salt rocks were formulated by Dr. A.I. Kudryashov and further developed by Dr. S.S. Andreiko [1]. However, in the construction of the geological model the authors considered only industrial formations RedII or AB. Geological mechanisms of formation of free gas accumulation sources and sources of gas dynamic phenomena in the rocks of the sylvinite-carnallite zone (with the exception of formation V) of the Verkhnekamsk potassium salt deposit have not been considered at all so far.

Therefore, the development of a geological model of the mechanism of formation of gas-dynamic hazard zones in the rocks of the sylvinite-carnallite zone of the Verkhnekamsk potassium salt deposit in the process of epigenetic transformations of rocks of the sylvinite and sylvinite-carnallite zones of the Verkhnekamskoe potassium salt deposit is an urgent task. On the basis of this model, it is planned to develop methods for predicting gas-dynamic hazard zones in the sylvinite-carnallite zone rocks of the Verkhnekamsk potash deposit, which will improve the safety of geological exploration from the surface and from mine workings in potash mines.

Methods of research

In order to develop a scientifically based geological model of the mechanism of formation of gas-dynamic hazard centers in the rocks of the sylvinite-carnallite zone, it is necessary to establish the sources of gas-saturated fluids, the ways of fluid migration into the salt stratum and the mechanism of formation of gas-saturated zones.

For the conditions of the Verkhnekamskoye potassium salt deposit the model scheme of the three-zone system of metasomatosis, presented in Fig. 2, corresponds to the mechanism of formation of gas-saturated zones in the process of epigenetic transformations of salt rocks, in particular, carnalitte sylvinitization, most completely. In this case, free gas will accumulate in microcavities and voids between the metasomatite and the outer wall of the conductor of aqueous solutions. Based on the work of the model scheme of the three-zone system of metasomatosis, a geological model of the mechanism of formation of gas-dynamic hazard centers in the rocks of the sylvinite-carnallite zone was constructed.

Geological model of the mechanism of gas saturated zones formation

In the conditions of the Verkhnekamskoye potassium salt deposit, the mechanism of formation of gas-saturated zones in the rocks of the sylvinite-carnallite zone of the salt stratum should be considered as a single process of tectogenesis, migration of gas-saturated fluids, epigenetic transformations of rocks of the sylvinite-carnallite zone, cracking and delamination in the process of natural "underworking" and accumulation of gases (formation of gas-saturated zones – zones of gas-dynamic hazard during geological exploration and mining) in areas of natural "undermining". In the proposed geological model of the mechanism of gas-saturated zones formation, as mentioned above, the sources of gas-saturated fluids could be packs of clay-anhydrite rocks (sources of gas-bearing aqueous solutions), as well as oil-bearing fields and promising oil-bearing structures in the underlying rock strata [38]. The formation of gas-saturated zones in the rocks of the sylvinite-carnallite zone of the field was followed by a very complex process of halogen metasomatosis, accompanied by epigenetic transformations of rocks and the release of dissolved gases into the free phase.

The chemical impact of groundwater is the most powerful factor in the epigenesis of the salt strata of the Verkhnekamsk potassium salt deposit. In the conditions of the deposit the groundwater include post-salt, intra-salt and sub-salt waters [1]. Post-salt waters are infiltrative, and their participation in the mechanism of formation of gas-saturated zones is unlikely. On the contrary, penetrating into the salt column, infiltration water played a destructive role, destroying gas-saturated zones within the large positive structures of the Verkhnekamskoye field. The amount of intra-salt waters in the modern deposit is small, and the waters themselves are in physical-chemical equilibrium with the composition of the host rocks. At the same time, there is a correlation between the intensity of salt deformation and their secondary transformations (clarification, recrystallisation, partial replacement), which is most logically explained by the interaction of salts with intra-salt aqueous solutions. The most probable source of aqueous solutions within the salt strata are clay-anhydrite rock packs. It is known that the pre-salt hydrogeological stage contains six aquifer systems: Lower Permian-Upper Carboniferous; Moscovian; Bashkirian-Upper Visean; Middle-Lower Visean terrigenous, Turnean-Upper Devonian carbonate and Upper-Middle Devonian terrigenous [1, p. 79]. According to a number of researchers, subsalt waters within the Solikamsk depression are gas-saturated and, in the presence of upward migration pathways, could also come into contact with salts.

The upward migration pathways could be: discontinuous tectonic disturbances that were formed as a result of differentiated movements of the subsalt bed; thrust faults formed as a result of unidirectional east-west tectonic pressure directed from bottom to top and from east to west; end-to-end zones of excessive fracturing formed in the course of tectonic development of the Solikamsk depression over the joints of crystalline basement blocks in the sedimentary cover, which could penetrate the salt deposit as well [1, 39, 40]. Without entering into discussions about the ways of upward migration of aggressive gas-saturated aqueous solutions with the authors of these scientific works, we accept that the ways of upward migration of gas-saturated fluids into the salt strata could be all the above-mentioned permeable zones.

It should be noted that the upward migration pathways of gas-saturated fluids from oil fields and potentially oil-bearing structures could be permeable zones above the reeffogenic structures. It is known that substitution zones in potassium reservoirs gravitate to the slopes of reeffogenic structures [41]. At present, the hypothesis of initiating fracture development above the reef slope has been put forward and geomechanical modelling by the boundary element method in the "discontinuous displacement" variant has been carried out [43, 44]. As a result of the studies, it was determined the area of fracture propagation above the reefogenic structures which is about 2000 m and reaches the rocks of the salt strata. Thus, it was proved that permeable zones are formed above the reeffogenic structures which can serve as pathways for migration of oil fluids into the salt strata.

The migration of gas-saturated fluids into the salt column occurred in the subvertical direction (from bottom to top) in the underlying rocks. Directly in the rocks of the salt stratum, due to the pronounced anisotropy of filtration properties of the saline stratum, the lateral direction of gas-saturated fluid migration prevailed over the vertical direction, and fluid movement occurred along the strata. In this case, the fluids moved through clay interlayers, including the marking clay layer and the intergranular space.

The important role of replacement zones (halitisation) of sylvinite and carnallite strata in the geological mechanism of gas-saturated zones formation in rocks of sylvinite-carnallite zone should be specially pointed out. Replacement of sylvinites and carnallites by rock salt, formation of mottled sylvinites, mixed salts (sylvinite + carnallite) and formation of gas saturated zones in rocks of sylvinite-carnallite zone should be considered as a single process occurring as a result of migration through the thickness and in the thickness ofpotassium-magnesium salts fluids represented by gas-saturated aqueous solutions or fluids of oil fields (potentially oil-bearing structures). In accordance with the accepted typology, replacement (halitisation) zones of sylvinite beds are subdivided into shielded, open and through [39, p.156-160]. Shielded replacement zones are characterised by the fact that directly above the replacement zone of industrial strata lies one or more beds of sylvinite-carnallite zone, composed of mottled sylvinites. This type includes small, medium and large replacement zones. The open type of replacement zones is characterised by the location of all sylvinite-carnallite zone strata above the industrial replacement zone, represented by mottled sylvinites. Through type of replacemet zones is characterized by replacement by rock salt of all layers of sylvinite and sylvinite-carnallite zones by rock salt at completeness of their section in which a layer of marking clay and covering rock salt is presented. The main difference of the internal structure of the through-type replacement zone of the previous two types is replacement of all sylvinite-carnallite zone strata by rock salt. As can be seen from the characteristics of the considered substitution zones, the external and internal structure of all substitution zones are not fundamentally different from each other, which indicates a single epigenetic process of such zones formation. The main difference will consist in the scales of epigenetic processes vertically and laterally in the rocks of the sylvinite-carnallite zone during the formation of gas-saturated zones.

Let us consider the geological mechanism of formation of gas-saturated zones in the rocks of sylvinite-carnallite zone at migration of gas-saturated water solutions in the direction from the replacement zone towards the development of carnallitic rocks.

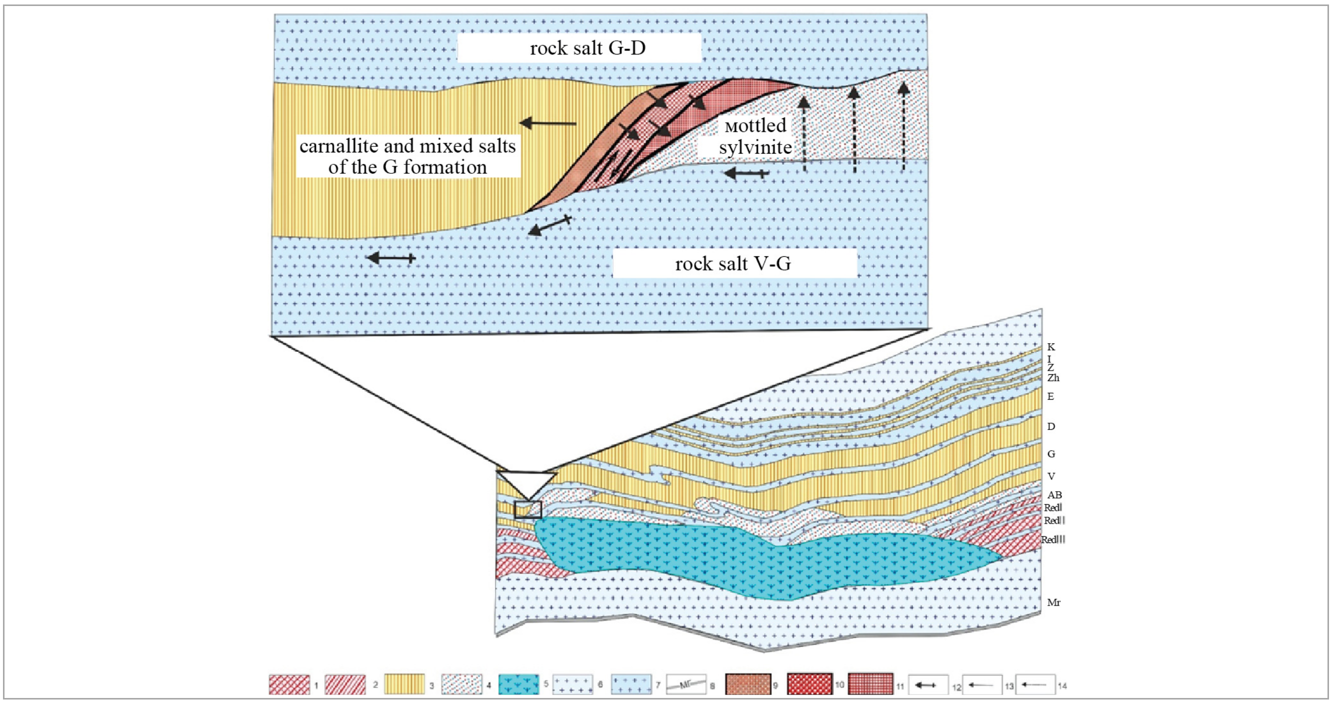

Fig. 3. Model scheme of the three-zone functional system of metasomatosis during lateral migration of gas-saturated fluids from the shielded replacement zone in the conditions of the G formation during generation of gas-saturated zones: *1* – red sylvinite; *2* – banded sylvinite; *3* – carnallite; *4* – mottled sylvinite; *5* – replacement rock salt; *6* – covering and underlying rock salt; *7* – interbed rock salt; *8* – marking horizon; *9* – condensation zone; *10* – exchange zone; *11* – bottom-hole zone; *12* – mass exchange between bottom-hole and condensation zone through exchange zone, of exchange zone with transit zone; *13* – longitudinal mass transfer; *14* – direction of free gas migration in the process of metasomatosis

In this case, we will proceed from a special case when the replacement zone is represented by the shielded type as the most widespread in the deposit. As an example of epigenetic changes in carnallitic rocks of sylvinite-carnallite zone by the mechanism of halogen metasomatosis let us consider carnallitic formation G. It should be noted that when gas-saturated aqueous solutions affect other carnallitic formations (D, E, Zh, etc.) during their lateral migration from replacement zones towards carnallitic rocks, the mechanism of epigenetic change of rocks will be similar to the one considered for formation G. The model scheme of a three-zone functional system of halogen metasomatosis in conditions of carnallitic formation G is presented in Fig. 3. Due to the high permeability of clay-anhydrite interlayers, aggressive solutions penetrated, first of all, through saline clays and, consequently, sylvinitisation of carnallitic rocks of Formation G started mainly from above. In the presence of saline clay layers and interlayers in the soil of Formation G, sylvinitisation could also occur from below, as shown in Fig. 3. The strike zone of the three-zone functional system of metasomatosis moved both downward from the conductor and forward in the direction of water solution movement. The decomposition of carnallite was accompanied by the deficit of solid phase, since the aggressiveness of aqueous solution with respect to carnallite is equal to approximately unity element [1, p. 304–308; 41]. As a result, the newly formed rock – mottled sylvinite – has increased porosity near the contact with carnallite rock. In the areas of complete decomposition of carnallite of the G formation, structural bonds between mineral grains under the influence of lithostatic pressure and continuing migration of solutions were restored, and the rock became monolithic, practically devoid of large pores. Thus, a kind of "gas barrier" was created, preventing the migration of gases in the direction opposite to the movement of the sylvinitisation front of the carnallite of the G formation. As the sylvinitisation front (bottomhole, exchange and condensation zones of the halogen metasomatosis system) progressed, the areas with different porosity moved in the same direction as the migrating solutions – towards the carnallitic rocks of the G formation. As the practice of mining operations at the industrial AB formation shows, the greatest amount of gas emissions and gas-dynamic phenomena occurred in the areas of development of more porous rocks at "fading" of the sylvinitisation process, i.e. near the contact of mottled sylvinite with carnallitic rock [1, p. 318–321; 45, p. 110–118]. This explains the shift of the maximum frequency of gasdynamic phenomena towards carnallitic rocks.

It is necessary to mention one more very important nuance in the mechanism of formation of gas-saturated zones in the rocks of sylvinite-carnallite zone. As mentioned above, in the presence of layers and interlayers of saline clays in the soil of bed G, sylvinitisation could occur from below. In this case, the process of halogen metasomatosis could spread not over the entire thickness of the carnallitic formation, but only to the lower part of the formation. As a result, gas-saturated zones were formed vertically in the formation section at the boundary with the carnallitic rock. Similarly, gas-saturated zones could be formed in other thick carnallite beds of the sylvinite-carnallite zone. The illustration of the stated situation is the case of a gas dynamic phenomenon with an intensity of 180 tons, which occurred at the mine BKPRU-2 March 15, 1973, presented in Fig. 4.

As can be seen from Fig. 4, a powerful gas-dynamic phenomenon occurred from the roof of the workings with a width of 3.0 м. The V formation, from which the gas dynamic event occurred, is of mixed composition: the lower part of the formation is mottled sylvinites, the upper part is carnallitic rock. Similar cases of gas dynamic phenomena have repeatedly occurred in potash mines at the Verkhnekamskoe deposit.

Geomechanical is also very important aspect of formation of gas-saturated zones in rocks of sylvinite-carnallite zone during halogen metasomatosis at sylvinite formation of carnallite formations. The bottomhole zone of the three-zone functional metasomatosis system moved both upward from the conductor and forward in the direction of the aqueous solution movement The decomposition of carnallite was accompanied by a shortage of solid phase since the aggressiveness of aqueous fluids relative to carnallite is approximately one. Let us consider the geomechanical processes which accompanied the sylvinitization of carnallite formations by the example of carnallite formation G. Voids were formed in the areas of complete decomposition of carnallite of formation G due to a shortage of solid phase, i.e. the thickness of formation G during sylvinitization decreased significantly, by about 3 times with average values of thickness from 7.70 to 2.50 m. The formation of such natural voids created the mining effect of additional processing of the formation suite above formation G, which underwent sylvinitization. Due to the fact that only natural processes are involved in the process of sylvinitization of carnallite beds, in this case we will understand the change in the thickness of carnallite beds during sylvinitization as natural undermining.

There are two main areas of research on the impact of mining on potash reservoirs. The first direction is related to the study of rock shear and the nature of rock pressure redistribution around the mine workings of the potash reservoir. The second direction is related to the study of processes associated with changes in the gas-dynamic characteristics of potash beds under development. Up to the present in the conditions of the Verkhnekamsk potash deposit no studies of the regularities of changes in the gas-dynamic properties of potash strata during their natural mining have been carried out. Consequently, the participation of geomechanical processes in the mechanism of formation of gas saturated zones in sylvinite-carnallite zone rocks has not been investigated so far.

It is known, that by analogy with technogenic mining, the process of sylvinitisation of carnallitic strata will be accompanied by redistribution of rock pressure, so carnallitic strata of the sylvinite-carnallite zone were exposed to different force fields. Let us consider these processes on the example of sylvinitisation of carnallitic formation G. In the area of influence of the moving front of sylvinitisation of formation G, depending on the nature of deformation and redistribution of rock pressure, the following characteristic zones were formed: not affected by mining operations (zone I); increased rock pressure (zone II); unloading (zone III); restored geostatic pressure (zone IV) (Fig. 5).

Each section of carnallitic strata located in the geological section above the G formation, when the sylvinitisation front was moving along the G formation, consistently appeared in each zone, which was accompanied by multiple changes in the type of their stress state: the state of hydrostatic compression in the zone not affected by the natural reworking; the transition

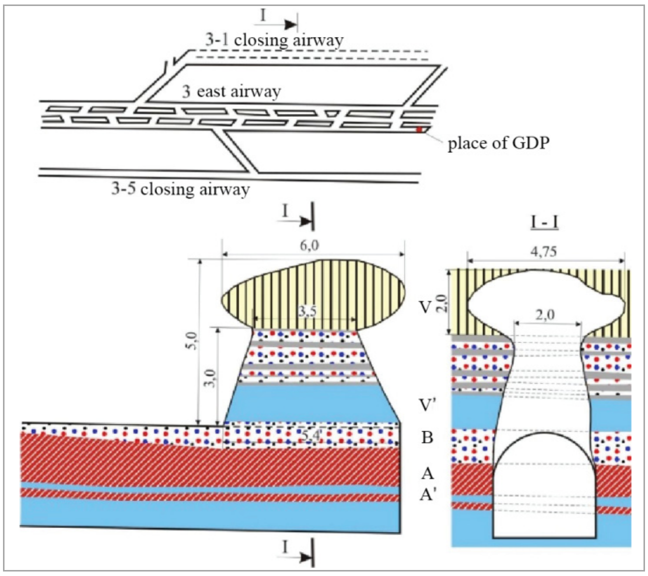

Fig. 4. Gas-dynamic phenomenon in the AB formation (mine BKPRU-2, 3rd East Panel, 3-1 East gate)

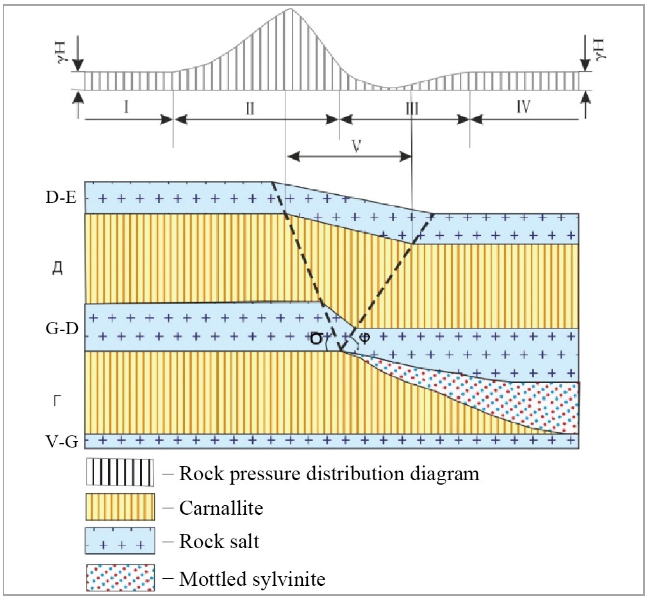

Fig. 5. Zones formed as a result of sylvinitisation (natural mining) of carnallitic formation G: I – unaffected by mining operations; II – of increased mining pressure; III – of unloading; IV – restored geostatic pressure; V – bending; σ, φ – respectively external and internal boundary angles of full shear at sylvinitisation of the G carnallite formation

to the state of unequal compression associated with the growth of stresses normal to the stratum in the zone of support pressure; reduction of lateral spreading at the boundary of the zone of supporting event and unloading; bending and associated tensile stresses; unloading from rock pressure; recovery of rock pressure and transition to a state of hydrostatic compression.

The deformation of carnallitic strata located above the G formation in the zone of supporting pressure can be considered from the standpoint of the Griffiths theory, which in its qualitative part is reduced to the fact that any body contains within itself a multitude of chaotically located defects. In this case, numerous contacts between lithological differences of rocks, layers and interlayers of clays in carnallitic strata can be considered as inclusions. In conditions of unequal compression, tensile stresses arise on the contour of these defects, which cause the destruction of the body. Under triaxial unequal-component compression there are observed large plastic deformations of the body caused by the development of internal fracturing and delaminations, which are accompanied by an increase in volume and gas permeability. In this case, the intensity of the process will be the higher, the greater the difference between the normal components of the stress tensor, i.e. reduction of lateral spreading at the boundary of the support pressure zone and the unloading zone will contribute to disruption of the original structure of carnallitic strata as a result of microdefects development.

The deformation of carnallitic strata in the bending zone, which includes part of the zones of increased rock pressure and unloading is of particular interest from the point of view of rock structure disturbance (Fig. 5, zone IV). Within this zone there are active stages of shearing processes, deformation of the massif and redistribution of rock pressure. At the same time, various combinations of main stresses can be generated, up to the appearance of tensile forces. In addition, this zone is characterised by the growth of tangential stresses. In the bending zone, there are created conditions for the increase of fracturing and formation of delaminations, which are undermined during sylvinitisation of the G formation in carnallitic strata as a result of shearing and stretching along the planes of natural heterogeneities and newly formed fracturing.

Changes in the structure of carnallitic strata during their natural reworking will also be promoted by their gas saturation, which leads to the deformations growth in both elastic and plastic regions, as well as to a reduction of strength, yield strength and fracture work.

In accordance with the abovementioned provisions natural reworking of carnallitic strata located above the G formation during its sylvinitisation can be represented as a sequential change of stress state types, each of which corresponds to a certain form of deformation:

– fracturing during the transition of rocks from the state of hydrostatic compression to the state of unequal volumetric compression as a result of loading in the reference pressure zone;

– shear along natural planes of weakening and newly formed fracturing under the action of tangential stresses during the transition from the zone of supporting pressure to the zone of unloading;

– cracking, crack opening and delamination at layer contacts, clay layers and interlayers under the influence of tensile bending stresses.

The peculiarity of deformation of carnallitic strata during natural undermining in the process of sylvinitisation in the zones of increased mining pressure at the border of the sylvinitisation front is that it proceeds under prolonged action of loads. At that, the entire period of deformation can be divided into two stages:

– at direct movement of the sylvinitisation front along the carnallite bed;

– as a result of prolonged stay of carnallitic strata in the zone of increased mining pressure during natural mining.

The nature of the structure of carnallite formations formed after natural reworking is determined by the combination of deformations that took place at these stages. At the first stage, when carnallitic strata are located in the zone of influence of the moving wave of support pressure, plastic deformations of rocks are caused by the growth of stresses normal to the strata. The main form of plastic deformations in this case will be the formation of new systems of micro- and macrocracks due to the development of internal defects. At the second stage, as a result of prolonged action of elevated stresses, plasticity and creep deformations develop and stress relaxation occurs. In the unloading zones, areas of stratification of carnallitic strata are formed along the contacts of lithological rock differences, clay interlayers and layers.

Thus, in the process of natural underworking of carnallitic strata during sylvinitisation, prerequisites for changing the original rock structure are created, consisting in the appearance of new systems of micro- and macrocracks, as well as segregation along layer contacts, clay interlayers and layers. When several carnallitic strata are sylvinitised, e.g. B, V and G, these effects are intensified. This process can be defined as geomechanical destruction of carnallitic strata of the sylvinite-carnallitic zone under the influence of natural underworking during sylvinitisation of carnallitic formations. As a result of natural underworking within the area of influence of sylvinitisation fronts, areas with different structures and, consequently, with different gas-dynamic characteristics of rocks are formed in carnallitic formations.

Since the deformation of carnallitic strata under the influence of natural underworking lasts for a long geological time, any stop of the sylvinitisation front boundary is a source of the edge part of the shift trough. In the marginal parts of shift troughs carnallitic strata will undergo maximum deformation with the development of fracturing and stratification at layer contacts, clay layers and interlayers, therefore, filtration and reservoir properties of carnallitic strata in these zones will play a very important role in terms of the possibility of formation of gas saturated zones. In these areas, gas-dynamic anomalies are most likely to appear in carnallitic formations, i.e. areas characterised by the degree of rock disturbance, gas content and gas-dynamic characteristics.

In carnallitic strata, mined during sylvinitisation, in the zone of unloading from vertical stresses caused by fractures and stratification along layer contacts, clay layers and interlayers, favourable conditions for free gas filtration into it are created. Thus, during natural underworking in the area of low stresses, quasi-isolated gas-filled areas are formed as a result of rock stratification at layer contacts, clay layers and interlayers. As a result, free gas accumulates in the low-stress zone in quantities exceeding its content in the tight rock. At the same time, additional compressive stresses acting on the other side of the boundary play the role of a kind of barrier preventing further filtration of the gas and its more uniform distribution along the undermined rock. Due to the unstable equilibrium of the system of gas-filled cracks, gas pressure growth in them can occur impulsively, so that to reach very significant values. A similar mechanism could be used to form gas-saturated zones in the layers of the sylvinite-carnallite zone in the process of sylvinitization of other carnallite formations, one or more simultaneously.

Conclusion

The geological model of the mechanism of formation of gas-dynamic hazard centers in the rocks of the sylvinite-carnallite zone at the Verkhnekamsk potassium-magnesium salt deposit can be presented as follows:

1. The sources of gas-saturated fluids were gas-bearing aqueous solutions from the underlying salt strata, including oil fields and potentially oil-bearing structures. The upward migration pathways of gas-saturated fluids into the salt column could be tectonic discontinuities, thrusts, through zones of increased fracturing and permeability zones above the reef slopes.

2. Migration of gas-saturated fluids into the salt strata through the underlying rocks was predominantly in the subvertical direction (from bottom to top). Directly in the rocks of the sylvinite-carnallite zone, the lateral direction of gas-saturated fluid migration prevailed over the vertical direction. In the rocks of the sylvinite-carnallite zone, gas-saturated fluids moved through clay layers and interlayers, as well as through the intergranular space.

3. Replacement of sylvinites and carnallites by rock salt, formation of mottled sylvinites, mixed salts (sylvinite + carnallite) and formation of gas-saturated zones in rocks of sylvinite-carnallite zone should be considered as a single process occurring as a result of the migration of through and in the thickness of potassium-magnesium salts of gas-saturated fluids represented by gas-saturated aqueous solutions or fluids of oil fields (oil prospective structures).

4. Gas-saturated fluids penetrated into the sylvinite-carnallite zone along the upward migration paths and moved laterally from the replacement zones towards the carnallitic rocks. Lateral migration of gas-saturated fluids through clay layers and interlayers, as well as intergranular space of carnallitic rocks was accompanied by epigenetic changes – sylvinitisation of carnallitic formations by the mechanism of halogen metasomatosis, which is the work of a three-zone functional system consisting of bottomhole, exchange and condensation zones.

5. The rock formed during sylvinitisation of carnallites – mottled sylvinite near the contact with carnallitic rock both laterally and vertically – had increased porosity.

In such rocks there was an accumulation of free gases released from gas-saturated fluids under changing thermobaric conditions and the effect of "salinisation" of gases under increasing mineralisation of aqueous solutions. In addition, bound gases, which were transferred to the free phase during the decomposition of carnallites, could also accumulate here.

6. Further, the structural bonds between mineral grains under the influence of lithostatic pressure and continuing migration of solutions were restored, and the rock became monolithic, practically devoid of large pores. At some distance from the "carnallite – mottled sylvinite" contact, a kind of "gas barrier" was created, preventing gas migration in the direction opposite to the movement of the sylvinitisation front of carnallitic strata. As the sylvinitisation front (bottomole, exchange and condensation zones of the halogen metasomatosis system) progressed, the areas with different porosity moved in the same direction as the migrating solutions – towards the carnallitic rocks. The process of sylvinitisation of carnallites subsided as aggressive solutions saturated with magnesium chloride.

7. In areas of complete decomposition of carnallites in the process of sylvinitisation, voids were formed due to the deficit of solid phase, i.e. the thickness of formations during sylvinitisation decreased significantly, approximately by 2-3 times. The formation of such natural voids created the well-known mining effect of undermining the formation of layers above the layer that had undergone sylvinitization. In the process of natural underworking of carnallitic formations during sylvinitisation, there are created prerequisites for changing the original rock structure, consisting in the appearance of new systems of micro- and macro-cracks, as well as stratification at layer contacts, clay interlayers and layers. As a result of natural underworking within the area of influence of sylvinitisation fronts, areas with different structures and, consequently, with different gas dynamic characteristics of rocks are formed in carnallitic strata.

8. The deformation of carnallite formations under the influence of natural undermining lasts for a long geological time, and any stop of the border of the sylvinitization front turns out to be the source of the marginal part of the shift trough. In the marginal parts of the shift troughs, carnallite beds will undergo maximum deformations with the development of fracturing and stratification along the contacts of layers, clay layers and interlayers. The filtration and reservoir properties of carnallite formations in these zones will play a very important role in terms of the possibility of forming gas-saturated zones. In these areas, gas-dynamic anomalies are most likely to appear in carnallite formations, i.e. areas that differ in the degree of rock disturbance, their gas content and gas-dynamic characteristics, which are zones of gas-dynamic hazard during mining operations. The boundaries of such zones of gas-dynamic hazard within specific carnallite formations of the sylvinite-carnallite zone will be determined by the angular characteristics of the marginal parts of the shift troughs formed on the border of the sylvinitization front of carnallites.

References

1. Kudriashov A.I. Verkhnekamskoe mestorozhdenie solei [Verkhnekamskoye salt deposit]. Perm': Gornyi institut Ural'skogo otdeleniia Rossiiskoi akademii nauk, 2013, 429 p.
2. Raevskii V.I. et al. Mestorozhdeniia kaliinykh solei SSSR. Metody ikh poiskov i razvedki [Potassium salt deposits of the USSR. Methods of their search and exploration]. Leningrad: Nedra, 1973, 344 p.
3. Ivanov A.A., Voronova M.L. Verkhnekamskoe mestorozhdenie kaliinykh solei [Verkhnekamskoye deposit of potassium salts]. Leningrad: Nedra, 1975, 219 p.
4. Belolikov A.I., Sapegin B.I. Verkhnekamskoe kaliinoe mestorozhdenie [Verkhnekamskoye potash deposit]. *Problemy prognoza, poiskov i razvedki gorno-khimicheskogo syr'ia SSSR*. Moscow: Nedra, 1971, pp. 193-209.
5. Galkin V.I. et al. Analiz geologicheskogo stroeniia i otsenka vozmozhnosti razrabotki neftianykh mestorozhdenii, raspolozhennykh pod tolshchei kaliino-magnievykh solei Verkhnekamskogo mestorozhdeniia Permskoi oblasti [Analysis of the geological structure and assessment of the possibility of developing oil fields located under the layer of potassium-magnesium salts of the Verkhnekamskoye deposit in the Perm region]. Perm': Permskii gosudarstvennyi tekhnicheskii universitet, 2005, pp. 41-52.
6. Andreiko S.S., Ivanov O.V., Lialina T.A., Nesterov E.A. Gazonosnost' po svobodnym gazam porod sil'vinitovoi i sil'vinito-karnallitovoi zon Verkhnekamskogo mestorozhdeniia [Free gas content of the rocks of the silvinite and silvinite-carnallite zones at the Upper Kama districts]. *Gornaia promyshlennost'*, 2021, no. 4, pp. 125-133. DOI: 10.30686/1609-9192-2021-4-125-133

7. Andreiko S.S., Lialina T.A. Issledovanie gazovydelenii iz geologorazvedochnykh skvazhin na Verkhnekamskom mestorozhdenii kaliinykh solei [The analysis of gas emission out of geologic prospecting wells at Verkhnekamskoye deposit of potassium salts]. *Izvestiia vysshikh uchebnykh zavedenii. Gornyi zhurnal*, 2017, no. 2, pp. 33-38.
8. Andreyko S.S., Lyalina T. Rockburst From Floors. *Soils and Rocks, São Paulo*, 2019, vol. 42 (1), pp. 77-82. DOI: 10.28927/SR.421077
9. Andreyko S.S., Litvinovskaya N., Papulov A., Lyalina T. The Static Analysis of the Gas Content and the Gas-Dynamic Characteristics at the Second Potash Bed in the Starobinsk Potassium Salts Deposit. *Fluids*, 2022, vol. 7, iss. 8, Art. 278, 14 p., available at: www.mdpi.com/2311-5521/7/8/278 (accessed 26 October 2022). DOI: 10.3390/fluids7080278
10. Galkin V.I., Andreiko S.S., Litvinovskaia N.A., Galkin S.V., Lialina T.A. Issledovanie soderzhaniia galopelitov v plaste kamennoi soli B-V Verkhnekamskogo mestorozhdeniia kaliino-magnievykh solei [Studies of halopelite content in the B-V rock salt layer of the Verkhnekamsk potassium-magnesium salt deposit]. *Gornaia promyshlennost'*, 2022, no. 4, pp. 103-108. DOI: 10.30686/1609-9192-2022-4-103-108
11. He M. et al. A review of rockburst: Experiments, theories, and simulations. *Journal of Rock Mechanics and Geotechnical Engineering*, 2022, vol. 15(E1), pp. 1312-1353. DOI: 10.1016/j.jrmge.2022.07.014
12. He M., Ren F., Liu D. Rockburst mechanism research and its control. *Int J Min Sci Technol.*, 2018, vol. 28, no. 5, pp. 829-837. DOI: 10.1016/j.ijmst.2018.09.002
13. Fanjie Y. et al. Numerical simulation method for the process of rockburst. *Eng Geol.*, 2022, vol. 306. DOI: 10.1016/j.enggeo.2022.106760
14. Askaripour M. et al. Rockburst in underground excavations: A review of mechanism, classification, and prediction methods. *Underground Space (China)*, 2022, vol. 7, no. 4, pp. 577-607. DOI: 10.1016/j.undsp.2021.11.008
15. Li D. et al. Novel Ensemble Tree Solution for Rockburst Prediction Using Deep Forest. *Mathematics*, 2022, vol. 10, no. 5, p. 787. DOI: 10.3390/math10050787
16. Pu Y. et al. Machine learning methods for rockburst prediction-state-of-the-art review. *Int J Min Sci Technol.*, 2019, vol. 29, no. 4, pp. 565-570. DOI: 10.1016/j.ijmst.2019.06.009
17. Farhadian H. A new empirical chart for rockburst analysis in tunnelling: Tunnel rockburst classification (TRC). *Int J Min Sci Technol.*, 2021, vol. 31, no. 4, pp. 603-610. DOI: 10.1016/j.ijmst.2021.03.010
18. hui Ma T. et al. Microseismic monitoring, analysis and early warning of rockburst. *Geomatics, Natural Hazards and Risk*, 2021, vol. 12, no. 1. DOI: 10.1080/19475705.2021.1968961
19. Ribeiro e Sousa L. et al. The Use of Data Mining Techniques in Rockburst Risk Assessment. *Engineering*, 2017, vol. 3, no. 4, pp. 552-558. DOI: 10.1016/J.ENG.2017.04.002
20. Feng X.T. et al. Monitoring, Warning, and Control of Rockburst in Deep Metal Mines. *Engineering*, 2017, vol. 3, no. 4, pp. 538-545. DOI: 10.1016/J.ENG.2017.04.013
21. Li D. et al. Intelligent rockburst prediction model with sample category balance using feedforward neural network and Bayesian optimization. *Underground Space (China)*, 2022, vol. 7, no. 5, pp. 833-846. DOI: 10.1016/j.undsp.2021.12.009
22. Li C.C. Principles and methods of rock support for rockburst control. *Journal of Rock Mechanics and Geotechnical Engineering. Chinese Academy of Sciences*, 2021, vol. 13, no. 1, pp. 46-59. DOI: 10.1016/j.jrmge.2020.11.001
23. Małkowski P., Niedbalski Z. A comprehensive geomechanical method for the assessment of rockburst hazards in underground mining. *International Journal of Mining Science and Technology*, 2020, vol. 4. DOI: 10.1016/j.ijmst.2020.04.009
24. Zhou J., Li X., Mitri H.S. Evaluation method of rockburst: State-of-the-art literature review. *Tunnelling and Underground Space Technology*, 2018, vol. 8. DOI: 10.1016/j.tust.2018.08.029
25. Fanjie Y., Hui Z., Fudong C. et al. Numerical simulation method for the process of rockburst. *Engineering Geology*, 2022. DOI: 10.1016/j.enggeo.2022.106760
26. Strelkova S.V., Ivanov O.V. Rezul'taty issledovanii gazonosnosti porod po svobodnym gazam na 1-5 severo-zapadnykh paneliakh shakhtnogo polia rudnika BKPRU-4 PAO "Uralkalii" [Results of studies of the gas content of rocks on free gases on 1-5 North-Western panels of the mine field of the BKRU-4 mine of PJSC Uralkali]. *Izvestiia Tul'skogo gosudarstvennogo universiteta. Nauki o Zemle*, 2023, iss. 1, pp. 490-495.
27. Nesterov E.A., Bobrov D.A., Papulov A.S., Liadov V.O. Obosnovanie parametrov profilakticheskogo degazatsionnogo bureniia dlia uslovii iugo-vostochnoi chasti shakhtnogo polia rudnika UK [Substantiation of preventive degassing drilling parameters in the South East of the mine field of Eurochem Usolsky potash plant]. *Gornyi zhurnal*, 2023, no. 11, pp. 94-96. DOI: 10.17580/gzh.2023.11.16
28. Litvinovskaia N.A., Papulov A.S., Petrovskii A.B., Podlesnyi I.A. Otsenka gazodinamicheskoi opasnosti porod krovli podgotovitel'nykh gornykh vyrabotok pri prokhodke v vyrabotannom prostranstve kamernoi sistemy razrabotki na Tret'em kaliinom plaste v usloviiakh Starobinskogo mestorozhdeniia kaliinykh solei [Risk of gas dynamic phenomena in roof rocks in entry heading in potassium stratum III]. *Gornyi zhurnal*, 2023, no. 8, pp. 24-28. DOI: 10.17580/gzh.2023.08.03
29. Chaikovskii I.I., Ivanov O.V., Papulov A.S. Sostav i priroda sviazannykh i svobodnykh gazov Verkhnekamskogo mestorozhdeniia solei [Composition and nature of bound and free gases at the Upper Kama salt deposit]. *Gornyi zhurnal*, 2023, no. 11, pp. 108-112. DOI: 10.17580/gzh.2023.11.19
30. Ivanov O.V., Nesterova S.Iu., Liadov V.O., Luk'ianets E.V. Regional'noe prognozirovanie opasnykh po gazodinamicheskim iavleniiam zon v usloviiakh shakhtnogo polia rudnika Talitskogo goka [Regional prediction of hazardous zones of gas-dynamic phenomena in mine field of Talitsa GOK]. *Gornyi zhurnal*, 2023, no. 11, pp. 84-88. DOI: 10.17580/gzh.2023.11.14
31. Chaikovskii I.I., Ivanov O.V., Bubnova M.V., Fedorov T.V. O prirode, sostave i gazonosnosti epigeneticheskoi mineralizatsii v solianoi tolshche Verkhnekamskogo mestorozhdeniia (na primere Usol'skogo rudnika) [On the nature, composition and gas content of epigenetic mineralization in the salt column of the Verkhnekamskoe deposit (on the example of the Usolsky mine)]. *LITOSFERA*, 2023, vol. 23, no. 1, pp. 117-132. DOI: 10.24930/1681-9004-2023-23-1-117-132
32. Ivanov O.V. Prognozirovanie gazodinamicheskikh iavlenii pri razvedke i razrabotke sil'vinitovykh plastov (na primere Verkhnekamskogo mestorozhdeniia kaliinykh solei) [Forecasting gas-dynamic phenomena during exploration and development of sylvinite formations (using the example of the Verkhnekamskoye potassium salt deposit)]. Abstract of Ph. D. thesis. Perm', 2005, 18 p.
33. Nesterov E.A., Bobrov D.A., Barbikov D.V., Petrovskii Iu.B. Gazonosnost' i gazodinamicheskie kharakteristiki porod sil'vinitovogo plasta IV-p Petrikovskogo mestorozhdeniia kaliinykh solei [Gas content and gas-dynamic characteristics of sylvinite stratum IV-p at Petrikov potash deposit]. *Gornyi zhurnal*, 2023, no. 8, pp. 29-33. DOI: 10.17580/gzh.2023.08.04
34. Liadov V.O., Papulov A.S. [Rezul'taty issledovanii polnoi gazonosnosti porod produktivnogo plasta Gremiachinskogo mestorozhdeniia kaliinykh solei [Results of studies on the full gas content in rocks of the productive formation of the Gremyachinskoye potash salt deposit]. *Problemy nedropol'zovaniia*, 2023, no, 2 (37), pp. 99-111. DOI: 10.25635/2313-1586.2023.02.099
35. Fiveg M.P. Stratigrafiia i vnutrenniaia tektonika produktivnoi tolshchi Verkhnekamskogo mestorozhdeniia kaliinykh i magnievykh solei [Stratigraphy and internal tectonics of the productive strata of the Verkhnekamskoye deposit of potassium and magnesium salts]. *Trudy VNIIG*. Leningrad, 1948, iss. XIX.
36. Proskuriakov N.M., Kovalev O.V., Meshcheriakov V.V. Upravlenie gazodinamicheskimi protsessami v plastakh kaliinykh rud [Control of gas-dynamic processes in potash ore formations]. Moscow: Nedra, 1988, 239 p.
37. Proskuriakov N.M. Vnezapnye vybrosy porody i gaza v kaliinykh rudnikakh [Rock and gas outbursts in potash mines]. Moscow: Nedra, 1980, 264 p.
38. Dzhinoridze N.M., Aristarov M.G., Polikarpov A.I. et al. Petrotektonicheskie osnovy bezopasnoi ekspluatatsii Verkhnekamskogo mestorozhdeniia kaliino-magnievykh solei [Petrotectonic foundations of safe exploitation of the Verkhnekamskoye deposit of potassium-magnesium salts]. Sankt-Peterburg; Solikamsk, 2000, 400 p.
39. Vishniakov A.K. Vtorichnye (epigeneticheskie) izmeneniia galogennoi tolshchi Solikamskoi vpadiny [Secondary (epigenetic) changes in the halogen layer of the Solikamsk depression]. *Stroenie i usloviia obrazovaniia solenosnykh formatsii*. Novosibirsk: Nauka, 1981.
40. Chaikovskii I.I., Galinova O.I., Morozov V.Iu. Tektonicheskoe stroenie Verkhnekamskogo mestorozhdeniia: stanovlenie novoi paradigmy [Tectonic structure of the Verkhnekamskoye deposit: the formation of a new paradigm]. *Gornoe Ekho: Vestnik gornogo instituta Ural'skogo otdeleniia Rossiiskoi akademii nauk*, 2006, no. 1, pp. 21-24.
41. Fon-der-Flaas, Kudriashov A.I. Osobennosti metasomaticheskogo protsessa solianykh porod [Features of the metasomatic process of salt rocks]. *Problemy kompleksnogo monitoringa na mestorozhdeniiakh poleznykh iskopaemykh. Sbornik dokladov*. Perm': Gornyi institut Ural'skogo otdeleniia Rossiiskoi akademii nauk, 2002, pp. 6-9.
42. Nikiforova A.I. Prognoz stroeniia i svoistv kaliinoi zalezhi na osnove seismostratigraficheskogo analiza razreza Verkhnekamskogo mestorozhdeniia [Forecast of the structure and properties of the potash deposit based on seismic stratigraphic analysis of the Verkhnekamskoye deposit section]. Ph D. thesis, Perm', 2013.
43. Bariakh A.A., Fedoseev A.K. Geomekhanicheskii prognoz raspredeleniia zon treshchinovatosti v solianoi tolshche Verkhnekamskogo mestorozhdeniia kaliinykh solei [Geomechanical forecast of distribution of fracture zones in the salt layer of the Verkhnekamskoye potassium salt deposit]. *Fiziko-tekhnicheskie problemy razrabotki poleznykh iskopaemykh*, 2007, no. 5, pp. 11-21.
44. Krauch S., Starfild A. Metody granichnykh elementov v mekhanike tverdogo tela [Boundary element methods in solid mechanics]. Moscow: Mir, 1987, 328 p.
45. Andreiko S.S. Mekhanizm obrazovaniia ochagov gazodinamicheskikh iavlenii v solianom porodnom massive [The mechanism of formation of foci of gas-dynamic phenomena in a salt rock massif]. Perm': Permskii gosudarstvennyi tekhnicheskii universitet, 2008.

Библиографический список

1. Кудряшов, А.И. Верхнекамское месторождение солей / А.И. Кудряшов. – Пермь: ГИ УрО РАН, 2013. – 429с.
2. Месторождения калийных солей СССР. Методы их поисков и разведки / В.И. Раевский [и др.] – Л.: Недра, 1973. – 344 с.
3. Иванов, А.А. Верхнекамское месторождение калийных солей / А.А. Иванов, М.Л. Воронова. – Л.: Недра, 1975. – 219 с.
4. Белоликов, А.И. Верхнекамское калийное месторождение / А.И. Белоликов, Б.И. Сапегин // Проблемы прогноза, поисков и разведки горно-химического сырья СССР. – М.: Недра, 1971. – С. 193–209.
5. Анализ геологического строения и оценка возможности разработки нефтяных месторождений, расположенных под толщей калийно-магниевых солей Верхнекамского месторождения Пермской области / В.И. Галкин [и др.] – Пермь: Изд-во Перм. гос. техн. ун-та, 2005. – С. 41–52.
6. Газоносность по свободным газам пород сильвинитовой и сильвинито-карналлитовой зон Верхнекамского месторождения / С.С. Андрейко, О.В. Иванов, Т.А. Лялина, Е.А. Нестеров // Горная промышленность. – 2021. – № 4. – С. 125–133. DOI: 10.30686/1609-9192-2021-4-125-133
7. Андрейко, С.С. Исследование газовыделений из геологоразведочных скважин на Верхнекамском месторождении калийных солей / С.С. Андрейко, Т.А. Лялина // Известия высших учебных заведений. Горный журнал. – 2017. – № 2. – С. 33–38.

8. Andreyko, S.S. Rockburst From Floors / S.S. Andreyko, T. Lyalina // Soils and Rocks, São Paulo. – 2019. – Vol. 42(1). – P. 77–82. DOI: 10.28927/SR.421077
9. The Static Analysis of the Gas Content and the Gas-Dynamic Characteristics at the Second Potash Bed in the Starobinsk Potassium Salts Deposit [Электронный ресурс] / S.S. Andreyko, N. Litvinovskaya, A. Papulov, T. Lyalina // Fluids. – 2022. – Vol. 7, iss. 8. – Art. 278. – 14 p. – URL: www.mdpi.com/2311-5521/7/8/278 (дата обращения: 26.10.2022). DOI: 10.3390/fluids7080278
10. Исследование содержания галопелитов в пласте каменной соли Б-В Верхнекамского месторождения калийно-магниевых солей / В.И. Галкин, С.С. Андрейко, Н.А. Литвиновская, С.В. Галкин, Т.А. Лялина // Горная промышленность. – 2022. – № 4. – С. 103–108. DOI: 10.30686/1609-9192-2022-4-103-108
11. A review of rockburst: Experiments, theories, and simulations / M. He [et al.] // Journal of Rock Mechanics and Geotechnical Engineering. – 2022. – Vol. 15(E1). – P. 1312–1353. DOI: 10.1016/j.jrmge.2022.07.014
12. He, M. Rockburst mechanism research and its control / M. He, F. Ren, D. Liu // Int J Min Sci Technol. – 2018. – Vol. 28, № 5. – P. 829–837. DOI: 10.1016/j.ijmst.2018.09.002
13. Numerical simulation method for the process of rockburst / Y. Fanjie [et al.] // Eng Geol. – 2022. – Vol. 306. DOI: 10.1016/j.enggeo.2022.106760
14. Rockburst in underground excavations: A review of mechanism, classification, and prediction methods / M. Askaripour [et al.] // Underground Space (China). – 2022. – Vol. 7, № 4. – P. 577–607. DOI: 10.1016/j.undsp.2021.11.008
15. Novel Ensemble Tree Solution for Rockburst Prediction Using Deep Forest / D. Li [et al.] // Mathematics. – 2022. – Vol. 10, № 5. – P. 787. DOI: 10.3390/math10050787
16. Machine learning methods for rockburst prediction-state-of-the-art review / Y. Pu [et al.] // Int J Min Sci Technol. – 2019. – Vol. 29, № 4. – P. 565–570. DOI: 10.1016/j.ijmst.2019.06.009
17. Farhadian, H. A new empirical chart for rockburst analysis in tunnelling: Tunnel rockburst classification (TRC) / H. Farhadian // Int J Min Sci Technol. – 2021. – Vol. 31, № 4. – P. 603–610. DOI: 10.1016/j.ijmst.2021.03.010
18. Microseismic monitoring, analysis and early warning of rockburst / T. hui Ma [et al.] // Geomatics, Natural Hazards and Risk. – 2021. – Vol. 12, № 1. DOI: 10.1080/19475705.2021.1968961
19. The Use of Data Mining Techniques in Rockburst Risk Assessment / L. Ribeiro e Sousa [et al.] // Engineering. – 2017. – Vol. 3, № 4. DOI: 10.1016/J.ENG.2017.04.002
20. Monitoring, Warning, and Control of Rockburst in Deep Metal Mines / X.T. Feng [et al.] // Engineering. – 2017. – Vol. 3, № 4. DOI: 10.1016/J.ENG.2017.04.013
21. Intelligent rockburst prediction model with sample category balance using feedforward neural network and Bayesian optimization / D. Li [et al.] // Underground Space (China). – 2022. – Vol. 7, № 5.
22. Li, C.C. Principles and methods of rock support for rockburst control / C.C. Li // Journal of Rock Mechanics and Geotechnical Engineering. Chinese Academy of Sciences. – 2021. – Vol. 13, № 1. – P. 46–59. DOI: 10.1016/j.jrmge.2020.11.001
23. Małkowski, P. A comprehensive geomechanical method for the assessment of rockburst hazards in underground mining / P. Małkowski, Z. Niedbalski / International Journal of Mining Science and Technology. – 2020. – Vol. 4. DOI: 10.1016/j.ijmst.2020.04.009
24. Zhou, J. Evaluation method of rockburst: State-of-the-art literature review / J. Zhou, X. Li, H.S. Mitri / Tunnelling and Underground Space Technology. – 2018. – Vol. 8. DOI: 10.1016/j.tust.2018.08.029
25. Numerical simulation method for the process of rockburst / Y. Fanjie, Z. Hui, C. Fudong [et al.] / Engineering Geology. – 2022. DOI: 10.1016/j.enggeo.2022.106760
26. Стрелкова, С.В. Результаты исследований газоносности пород по свободным газам на 1–5 северо–западных панелях шахтного поля рудника БКПРУ–4 ПАО «Уралкалий» / С.В. Стрелкова, О.В. Иванов // Известия ТулГУ. Науки о Земле. – 2023. – Вып. 1. – С. 490–495.
27. Обоснование параметров профилактического дегазационного бурения для условий юго-восточной части шахтного поля рудника УКК / Е.А. Нестеров, Д.А. Бобров, А.С. Папулов, В.О. Лядов // Горный журнал. – 2023. – № 11. – С. 94–96. DOI: 10.17580/gzh.2023.11.16
28. Оценка газодинамической опасности пород кровли подготовительных горных выработок при проходке в выработанном пространстве камерной системы разработки на Третьем калийном пласте в условиях Старобинского месторождения калийных солей / Н.А. Литвиновская, А.С. Папулов, А.Б. Петровский, И.А. Подлесный // Горный журнал. – 2023. – № 8. – С. 24–28.
29. Чайковский, И.И. Состав и природа связанных и свободных газов Верхнекамского месторождения солей / И.И. Чайковский, О.В. Иванов, А.С. Папулов / Горный журнал. – 2023. – № 11. – С. 108–112. DOI: 10.17580/gzh.2023.08.03
30. Региональное прогнозирование опасных по газодинамическим явлениям зон в условиях шахтного поля рудника Талицкого гока / О.В. Иванов, С.Ю. Нестерова, В.О. Лядов, Е.В. Лукьянец // Горный журнал. – 2023. – № 11. – С. 84–88.
31. О природе, составе и газоносности эпигенетической минерализации в соляной толще Верхнекамского месторождения (на примере Усольского рудника) / И.И. Чайковский, О.В. Иванов, М.В. Бубнова, Т.В. Федоров // ЛИТОСФЕРА. – 2023. – Т. 23, № 1. – С. 117–132. DOI: 10.24930/1681-9004-2023-23-1-117-132
32. Иванов О.В. Прогнозирование газодинамических явлений при разведке и разработке сильвинитовых пластов (на примере Верхнекамского месторождения калийных солей): автореф. дис. … канд. тех. наук / Иванов О.В. – Пермь, 2005. – 18 с.
33. Газоносность и газодинамические характеристики пород сильвинитового пласта IV-п Петриковского месторождения калийных солей / Е.А. Нестеров, Д.А. Бобров, Д.В. Барбиков, Ю.Б. Петровский // Горный журнал. – № 8. – 2023. – С. 29–33. DOI: 10.17580/gzh.2023.08.04
34. Лядов, В.О. Результаты исследований полной газоносности пород продуктивного пласта Гремячинского месторождения калийных солей / В.О. Лядов, А.С. Папулов // Проблемы недропользования. – 2023. – № 2 (37). – С. 99–111. DOI: 10.25635/2313-1586.2023.02.099
35. Фивег, М.П. Стратиграфия и внутренняя тектоника продуктивной толщи Верхнекамского месторождения калийных и магниевых солей / М.П. Фивег // Труды ВНИИГ. – Л., 1948. – Вып. XIX.
36. Проскуряков, Н.М. Управление газодинамическими процессами в пластах калийных руд / Н.М. Проскуряков, О.В. Ковалев, В.В. Мещеряков. – М.: Недра, 1988. – 239 с.
37. Проскуряков, Н.М. Внезапные выбросы породы и газа в калийных рудниках / Н.М. Проскуряков. – М.: Недра, 1980. – 264 с.
38. Петротектонические основы безопасной эксплуатации Верхнекамского месторождения калийно-магниевых солей / Н.М. Джиноридзе, М.Г. Аристаров, А.И. Поликарпов [и др.]. – СПб.; Соликамск, 2000. – 400 с.
39. Вишняков, А.К. Вторичные (эпигенетические) изменения галогенной толщи Соликамской впадины / А.К. Вишняков // Строение и условия образования соленосных формаций. – Новосибирск: Наука, 1981.
40. Чайковский, И.И. Тектоническое строение Верхнекамского месторождения: становление новой парадигмы / И.И. Чайковский, О.И. Галинова, В.Ю. Морозов // Горное Эхо: Вестник ГИ УрО РАН. – 2006. – № 1. – С. 21–24.
41. Фон-дер–Флаас, Г.С. Особенности метасоматического процесса соляных пород / Г.С. Фон-дер–Флаас, А.И. Кудряшов // Проблемы комплексного мониторинга на месторождениях полезных ископаемых: сборник докладов. – Пермь: ГИ УрО РАН. – 2002. – С. 6–9.
42. Никифорова, А.И. Прогноз строения и свойств калийной залежи на основе сейсмостратиграфического анализа разреза Верхнекамского месторождения: дис. … канд. техн. наук / Никифорова А.И. – 2013
43. Барях, А.А. Геомеханический прогноз распределения зон трещиноватости в соляной толще Верхнекамского месторождения калийных солей / А.А. Барях, А.К. Федосеев // Физико-технические проблемы разработки полезных ископаемых. – 2007. – № 5. – С. 11–21.
44. Крауч, С. Методы граничных элементов в механике твердого тела / С. Крауч, А. Старфилд. – М.: Мир, 1987. – 328 с.
45. Андрейко, С.С. Механизм образования очагов газодинамических явлений в соляном породном массиве / С.С. Андрейко. – Пермь: Изд-во Перм. гос. техн. ун-та. – Пермь, 2008.

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