ГОРНОПРОМЫШЛЕННАЯ И НЕФТЕГАЗОВАЯ ГЕОЛОГИЯ, ГЕОФИЗИКА

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Generalizing the results of fracture zones study in the Upper Kama potassium salt deposit with the help of gravity study

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Abstract

Introduction. *The history of the Upper Kama potassium salt deposit (VKMKS) exploration and operation should be divided into two periods. The first period lasted from 1929, the start of exploitation, until 1986, when the water-protective barrier collapsed and the largest VKMKS mine, the 3rd Berezniki mine, was flooded. The second period began in 1986 and continues to the present day. The first period is characterized by a low level of technogenic load on the geological environment, significantly less than its long-term strength. After 60 years of VKMKS large-scale exploitation, the technogenic load on the geologic environment has increased significantly. As a result, its equilibrium state was upset, giving rise to destruction, accompanied by various dynamic events: caves-in, surface collapses, rockbursts, and tectonic rockbursts. VKMKS structural-tectonic profile study revealed that active faults, nodal structures, and fracture zones have a decisive effect on the geologic environment equilibrium state.*

Research methodology. *When structural and tectonic elements are formed in the supra-salt, salt, and subsalt strata of the deposit, the geologic environment density characteristic changes naturally leading to the development of local density inhomogeneities within. It is possible to locate these inhomogeneities and establish their relationship with structural and tectonic elements of the geological environment, particularly, fractured zones, only by studying the gravity field of the deposit. For this purpose, an area-wide, detailed, and high-precision gravimetric survey was performed at a scale of 1:25,000, the results of which were used to identify and study the fracture zones.*

Research results. *Based on the results of gravity field anomalies interpretation on the territory of VKMKS, the horizontal position and size of about 200 local negative linear anomalies of the near north-south, north-east, and north-west orientations were determined, the sources of which were confidently identified with the fracture zones.*

Conclusions. *The experience of studying the structural and tectonic structure of VKMKS has shown that currently for the deposit's physical and geological conditions, the detailed, high-precision aerial gravity study is the most effective geophysical method for fracture zones mapping.*

Keywords: *Upper Kama potassium salt deposit; fracture zones; gravity study.*

Research subject and aim. At first approximation, fracture zones represent tabular formations of tectonic nature fractured heavier than the surrounding rock (Geology Dictionary, 1978). In the Upper Kama potassium salt deposit (VKMKS), for the first time tectonic zones in various strata were first established by P. I. Preobrazhenskii, who pointed to "high probability of fracturing, which crosses all supra-salt rocks" and gets into the saline deposits. At the same time, he underlined that "the plasticity of salt which prevents from that phenomenon, must show up at great depths (more than 500 m), but for the upper strata of the salt mass the possible presence of such fractures...

is conceivable" (Preobrazhenskii P. I., 1928). Observations of P. I. Preobrazhenskii were at the time confirmed by A. A. Varov, a chemical hydrologist: "Water of "gypsum series" and "covering salt" have no direct independent outcrops [to the surface] ... but water penetration to salt strata is proved by the salinization of "flag" [marly limestone and marl] water" (Varov A. A., 1928).

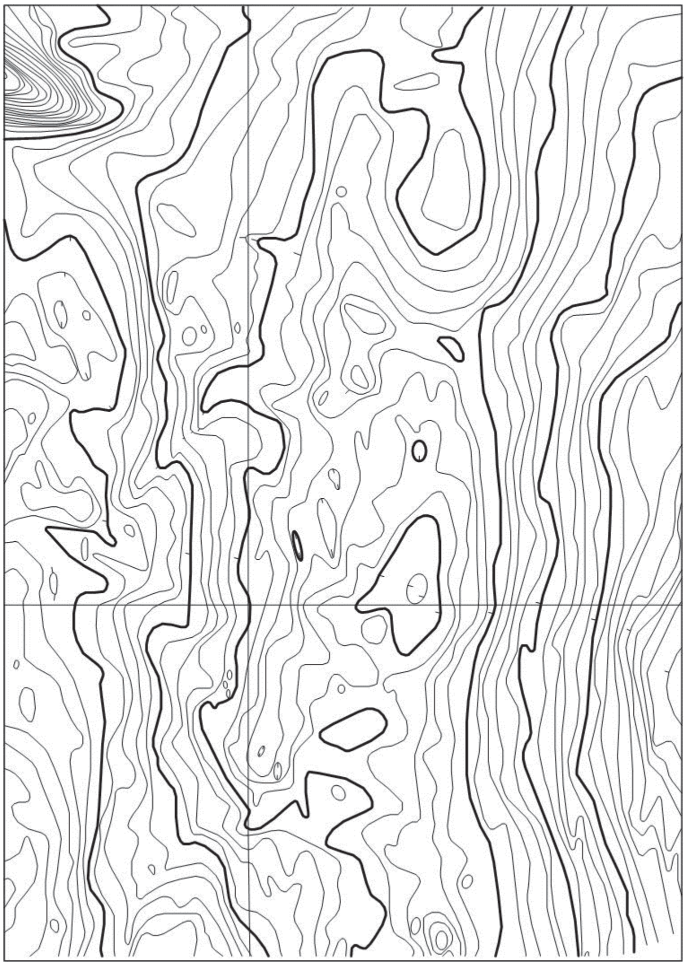

Fig. 1. Schematic map of isoanomalies of a part of the Upper Kama potassium salt deposit
Рис. 1. Схематический план изоаномал части территории Верхне-камского месторождения калийных солей

It unambiguously followed from the brief characteristic of fracture zones that such zones of increased permeability for the supra-salt and subsalt waters, could be of great importance for deposit accident-free operation. Unfortunately, this point was not taken into account, and there was no systematic study of fracture zones in VKMKS. The consequence of such mine-geological policy was the flooding of the 3rd Berezniki mine in 1986. Describing the reasons for the catastrophe, A. A. Bariakh explicitly stated that it happened due to mine tunneling in one of the fracture zones [1]. Thus, the subject of the present work is the fracture zones study, which is essential in order to estimate the state of the geologic environment to prevent catastrophic dynamic events.

Research methodology includes generalizing the results of fracture zones study in mine workings to estimate their spatial position, geometry, and kinematic characteristics, and, on this basis, establishing their horizontal position in the section as density inhomogeneities through interpreting the local anomalies of the gravity field created by them.

Research results. Fractures and fracture zones in VKMKS were occasionally studied by various researchers mainly in mine workings (Vakhromeeva V. A., 1959; Filippov S. A., Naimushina R. P., 1988; Filippov S. A., Korochkina O. F., 1990; Dzhinoridze N. M. et al., 1988; Beliaev V. P. et al., 1985; Valeev R. N. et al., 1974; Kopnin V. I., 1999).

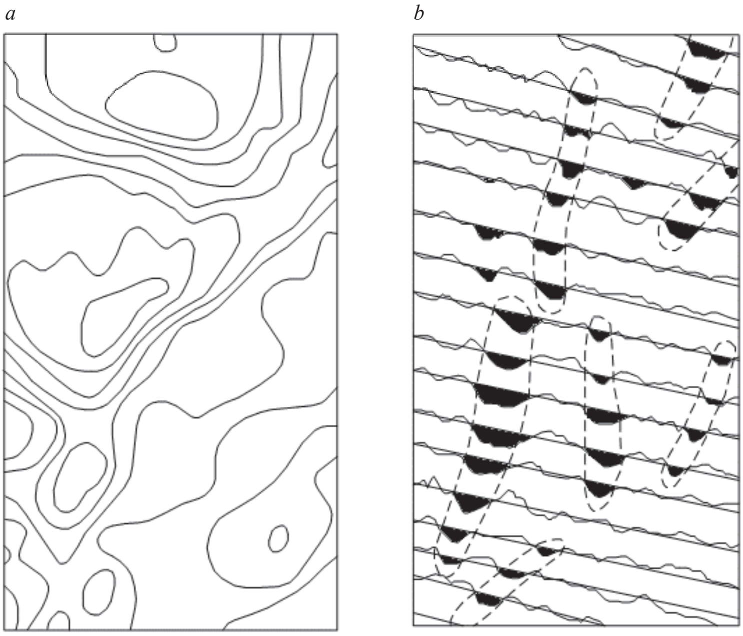

Fig. 2. Graphical representation of gravity survey results:
a – a fragment of isoanomalies map; *b* – a fragment of graphs map; a dashed line shows the contours of negative local anomalies conditioned by geologic environment deconsolidation (fracture zones)

Рис. 2. Графические формы представления результатов гравиметрической съемки:
а – фрагмент плана изоаномал; *b* – фрагмент плана графиков; пунктиром показаны контуры отрицательных локальных аномалий, обусловленных разуплотнением геологической среды (трещинными зонами)

In kinematic terms, fractures in productive series are divided into tension joints and shear fractures. Shear fractures develop as a result of folding since the systems of such fractures are symmetrical about the folding axes. Fracture width does not exceed 10–15 cm. In the cavities of the fractures, there are sylvine and halite, that indicates that they developed at the final stage of Hercynian orogeny.

Tension joints systems are also conditioned by folding. At the initial stage of the process, tension joints are formed along the folding axes as a result of break-up in the bed roof when it bends. The tension joints width changes from the first centimeters to 1.0–1.5 m. At the final stage of folding, the salt stratum breaks up completely; a span from 20–30 to 100–150 m wide appears between the edges of the joint fissure under the strike length of a few tens of meters.

The connection between structure formation and fracture formation was studied in detail in the productive series of Tveritinsky trough, where two zones of tension joints and two zones of shear fractures were mapped 200–400 m wide under the strike length of more than 1 km. The distance between the separate shear fractures reaches 800 m, they dip at high angle, observed 13 m vertically, their opening does not exceed 1 cm, and units displacement makes up from 0.5 to 1.5 cm. Tension joints are up to 15–20 m long with 0.5 to 50 m distance between them; they dip at high angle too, range in vertical direction makes up from 10 cm to 1.5 m under the opening from 1 dm to 1.5 m.

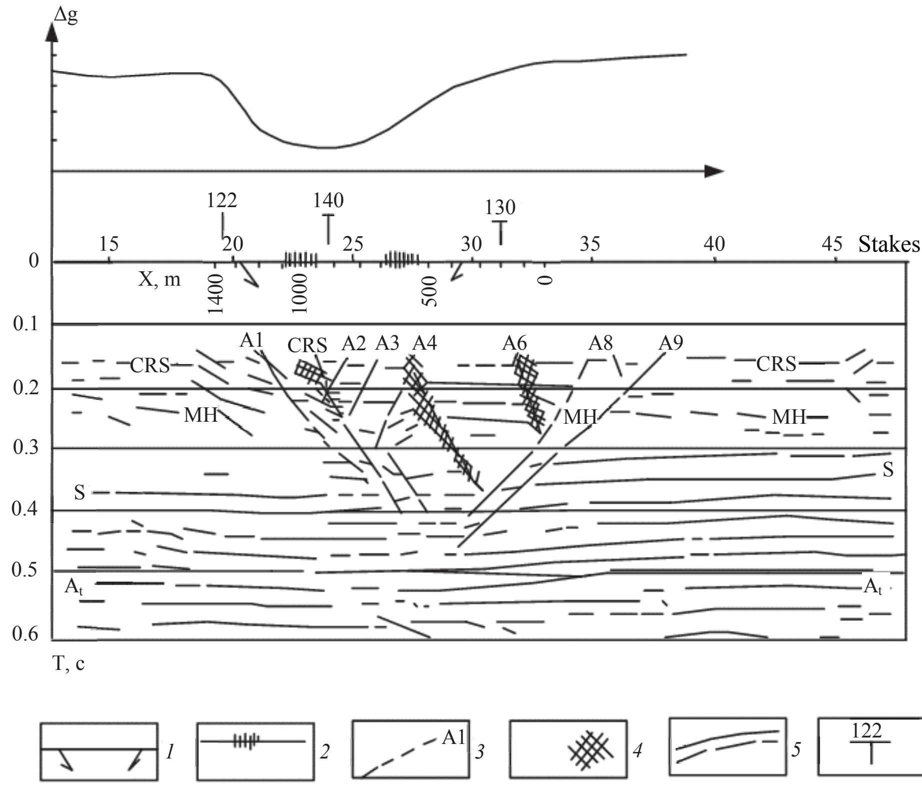

Fig. 3. Mapping the fracture zone using seismic (Dzhinoridze N. M. et al., 1988) and gravity methods in the area of the SKRU-2 mine:

1 – the boundaries of the surface subsidence site; *2* – the areas with fractured rock on the surface; *3* – the joint fissures on the seismic cross-section; *4* – the zones of no seismic waves reflection; *5* – the reflecting segments and horizons on the seismic cross-section; *6* – wells and their numbers; seismic markers: CRS – covering rock salt, MH – marker horizon in a salt stratum, S – the superface of the sub-salt formations or the base surface of the salt stratum, A_t – the superface of the terrigenous stratum of the Artinskian stratum

Рис. 3. Картирование трещинной зоны сейсмическим (Джиноридзе Н. М. и др., 1988) и гравитационным методами в районе рудника СКРУ-2:

1 – границы участка проседания дневной поверхности; *2* – положение участков развития трещиноватых пород на дневной поверхности; *3* – положение разрывов на временном разрезе; *4* – зоны отсутствия отражений сейсмических волн; *5* – положение на временном разрезе отражающих площадок и горизонтов; *6* – положение скважин и их номера; опорные сейсмические горизонты: CRS – покровная каменная соль, MH – маркирующий горизонт в соляной толще, S – кровля подсолевых отложений или подошва соляной толщи, A_t – кровля терригенной толщи артинского яруса

In terms of groundwater migration, the most hazardous tension joints are those crossing several productive series. As a rule, they are younger and sub-vertical with the strike length reaching 90 m. Sub-vertical fracture zones and mylonitized sections in the supra-salt terrigenous-carbonate stratum are also hazardous.

The orientation of the fracture zones of both geneses agrees with the general orientation of VKMKS tectonic structures [2]: north-east at angles of 25º–60º and 10º–40º and north-west at angles of 280º–310º.

A considerable number of separate fractures and fracture zones connected with anticlinal and synclinal folds were mapped along the flexural troughs and in the crests of anticlines (Popovsky and Pashkovsky uplifts) of the near north-south and rarely north-west and east-west strike.

The tectonics of the pre-Riphean basement at a depth of 5 km in the Solikamsk depression is a crucial factor affecting fractures formation. The connection between the basement tectonics and fracture formation tectonics was studied revealing not only plastic but also brittle deformations occurring in the halogenic stratum during tectonic stress unloading in fault and fracture zones. The study has also shown that along the permeable zones of fracturing, sub-salt and day water intrudes promoting the development of catagenetic and supergene leaching, recrystallization, and substituting secondary salt for primary salt. All these processes weaken the geologic environment potentially promoting the depositTs water-protective barrier collapse.

In addition to the described fractures and fracture zones, fractures of unknown genesis were detected in VKMKS. They are rare, possess north-south strike, the length reaching tens of meters; they have no direct connection with the structures, and are younger than tension joints and shear fractures. In our opinion, these fractures developed in the areas of dynamic impact from north-south deep faults enclosing the Solikamsk depression from east and west.

Since the supra-salt formations represent rigid laminated complex, exogenetic and endogenetic fracturing develops inside. Endogenetic halokinesis fracturing develops as a result of layers tension during doming or opening of older fractures during rock sliding down the flanks of the salt domes. Exogenetic fractures are the weathering and release joints. They are relatively shallow (up to 100–150 m), inheritedly developed and, just like endogenetic fractures, are of little significance for the water-protective barrier collapse.

Valuable as that is, the results of the fractures and fracture zones study didn't make it possible to establish their horizontal distribution over the entire territory of the deposit, and consequently, answer a crucial question of where exactly the water-protective barrier may collapse. Only with the help of the gravity survey, the problem was solved. Physical-geological background was as follows. Under the formation of fractures in rocks of various genesis, including sedimentary, geologic environment density reduces. Research showed that due to fracture formation, rock density may reduce by 10–15% in sedimentary rock, and by 20–30% in igneous and metamorphic rock (Filatov V. V., Bolotnova L. A., 2015). Fractures develop in local areas of tabular form, the strike length of which may exceed 1 km, under the lateral dimensions and vertical extent from first tens to first hundreds of meters. Calculations suggest that such density inhomogeneities, under the deficit of 10% density, may create linearly elongated negative gravity anomalies with the intensity of first tenths of one milliGal reliably mapped by gravity survey at a scale of 1:25,000 carried out by Bazhenov Geophysical Expedition, Ural Regional Geological Committee Uralgeologia (Noiaksova L. D., 1990). A schematic map of isoanomalies with Bouguer correction constructed according to the results of that survey is presented in fig. 1.

When interpreting the gravity field, three particular problems were considered concerning fracture zones mapping; their solution established the horizontal position and characteristics of fracture zones:

– detecting negative linear local anomalies conditioned by geologic environment deconsolidated areas;

– defining the geological nature of negative local anomalies sources, i.e. justifying the conclusions that geologically the fracture zones are the sources of the anomalies;

– defining the fracture zones parameters: the value of rock deconsolidation within the limits of fracture zones and their lower edge depths.

Gravity survey graphic results are presented as a map of isoanomalies and a map of graphs by profiles, where gravity was measured. It has been concluded from isoanomalies map and graphs map that it is reasonable to map the low-intensity anomalies conditioned by the fracture zones not by the isoanomalies map but by the map of residuals obtained by the method of averaging. The method of averaging causes minor distortions to the detected anomalies form and intensity being extremely easy to implement, as far as computation is concerned. In this case, the number of anomaly manifestation profiles determines the reliability of anomalies detection, i.e. mapping problem is solved best by gravity anomalies interprofile correlation (fig. 2).

To establish the nature of negative local gravity anomalies, the results of terrain aeromagnetic survey at a scale of 1:10,000 were used (survey at a height of 50 m), as well as individual profile researches using the methods of vertical electrical sounding (VES) and seismic tomography, geomorphology data at a scale of 1:100,000, and other data [3–8].

Fig. 3 presents the results of fracture zone mapping using the methods of gravity study and seismic tomography at the territory of the SKRU-2 mine, which experienced a severe tectonic rockburst in 1995 [9]. In the gravity field, the area of geologic environment deconsolidation is mapped through the negative anomaly with the intensity of 0.25 mGal that corresponds to a 10% reduction in the density of the environment. According to the seismic data, as it follows from the seismic cross-section, the geologic environment is highly faulted by a system of near-vertical joint fissures, which penetrate both the supra-salt stratum and productive salt stratum. Here, fracturing promoted rock deconsolidation, their permeability increase, geological environment density reduction, and as a consequence, surface subsidence.

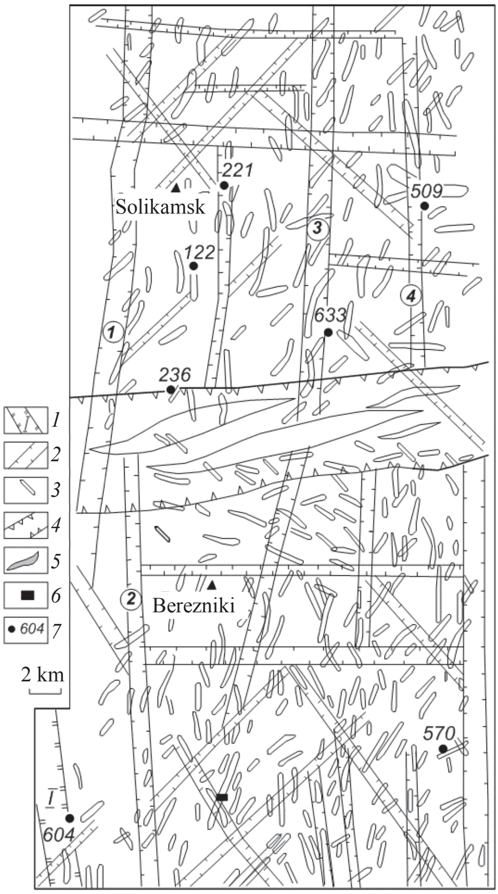

Fig. 4. Tectonic map of the Upper Kama potassium salt deposit:
1 – the zone of the Krasnoufimskii deep fault; *2* – the zones of intermediate tectonic dislocations of different ranges; *3* – the sites with increased fracturing of the geologic environment according to the gravity survey data; *4* – the boundaries of the Durinskii trough by the top of salt and the zones of the Durinskii deep fault; *5* – the contours of intensive gravity anomalies conditioned by local troughs in the top of salt in the Durinskii trough; *6* – BKRU-3 cave-in site; *7* –wells and their numbers

Рис. 4. Тектоническая схема Верхнекамского месторождения калийных солей:
1 – зона Красноуфимского глубинного разлома; *2* – зоны внутриблоковых разломов различных рангов; *3* – положение участков повышенной трещиноватости геологической среды по гравиметрическим данным; *4* – границы Дуринского прогиба по кровле солей и зоны одноименного глубинного разлома; *5* – контуры интенсивных аномалий силы тяжести, обусловленные локальными прогибами в кровле солей в Дуринском прогибе; *6* – место провала на территории БКРУ-3; *7* – положение скважин и их номера

The regions with the vast majority of linear gravity anomalies were not studied. The nature of such anomalies sources was defined as tectonic with some degree of certainty, based on their interpretation results and structural-tectonic position. In this way, for example, one negative gravity anomaly was mapped in the axial part of the Solikamsk ridge-like uplift by the top of salt. To the south of the anomalous area, there are the river Popovka and narrow, shallow glen. According to the drilling data, salt is diluted in the axial part of the uplift; here, its thickness is 30% (20 m) lesser than in the flanks. To the east of the anomalous area, aeromagnetic survey and electrical prospecting detected an intermediate tectonic dislocation of north-northeast strike. The width of the anomalous area is about 500 m, north-northeast strike length is over 4 km; maximum intensity of the anomaly is 0.41 mGal, which corresponds to the deficit of density of about 0.10–0.15 g/cm^3; the bottom boundary of the anomaly source, according to interpretation results, is in the salt stratum at a depth of about 200 m. For these reasons, the fracture zone is to be considered the source of the anomaly. Lithofacial variations of rocks promoting density reduction, in this case, are excluded because they were not detected in the wells around the anomalous area (wells 122, 134, 216, 130).

Geological nature of density inhomogeneities and their characteristics for other linear negative gravity anomalies were defined according to the described method.

Analysis and discussion. Based on the results of gravity field anomalies interpretation on the territory of VKMKS, the horizontal position and size of about 200 linear negative linear anomalies were mapped (fig. 4) with the intensity of first tenths of one milliGal, first hundreds of meters wide in a plan and more than 2–4 km long; the anomalies sources are mainly at a depth of 100–200 m, rarely at a depth of about 400 m. The anomalies orientation is near north-south, north-east, north-west, and rarely latitudinal, i.e. complying with VKMKS general tectonic map [2]. Most probable geologic nature of the anomalies lies in fracture zones. In some instances, this was proved by seismic tomography data (Dzhinoridze N. M. et al., 1989), aeromagnetic survey, and electrical prospecting by VES (Beliaev V. P. et al., 1989) in the form of zones with increased electrical conductance, together with geomorphology, structural-geologic and other data [3–8].

Summary and scope of results. Prediction of dynamic events resulting in the water-protective barrier collapse in VKMKS has become possible only based on a single physical-geologic reference model of the deposit, the properties of which prominently display the main elements of geologic environment tectonics. Such elements are fracture zones first of all. Currently, of all variety of geological-geophysical methods, only terrain, detailed, and high-precision gravity study could map local gravity anomalies, the sources of which, with a high degree of probability, are fracture zones. It is impossible to solve the problem using other geophysical methods for technical-methodical and economic reasons.

The revealed regularities in gravity local anomalies (fracture zones) horizontal position made it possible to formulate a range of criteria for dynamic events prediction. VKMKS zoning by dynamic hazard was carried out based on these criteria [10]. The system of prediction criteria described in [10] is the only one for the time being, i.e. having no alternative, despite detailed geological-mineralogical and structural-tectonic study of VKMKS [11, 12]. The objective of further VKMKS tectonic structure studies is to carry out a more detailed geophysical study, gravimetric first of all (at scales larger than 1:25,000), in local areas potentially hazardous in terms of dynamic events and develop alternative physical and geological basis of VKMKS.

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Обобщение результатов изучения трещинных зон на Верхнекамском месторождении калийных солей с помощью гравиразведки

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Реферат
Введение. *Историю разведки и эксплуатации Верхнекамского месторождения калийных солей (ВКМКС) следует разделить на два периода: первый период продолжался с 1929 г., т. е. с момента начала эксплуатации месторождения, и до 1986 г., когда произошло локальное разрушение его водозащитной толщи и был затоплен крупнейший на ВКМКС рудник БКРУ-3; второй период начался в 1986 г. и продолжается по настоящее время. Первый период характеризуется невысоким уровнем техногенной нагрузки на геологическую среду, существенно меньшей ее длительной прочности. Через 60 лет благодаря гигантским масштабам эксплуатации ВКМКС техногенная нагрузка на геологическую среду значительно возросла, и, как следствие, произошло нарушение ее равновесного состояния, реакцией на которое стало ее разрушение, сопровождаемое различными динамическими событиями: обрушениями породы в горных выработках, провалами дневной поверхности, горными и горно-тектоническими ударами. Изучение структурно-тектонического строения ВКМКС выявило, что определяющее воздействие на равновесное состояние геологической среды оказывают активные разломы, узловые структуры и трещинные зоны.*
Методика исследований. *При формировании структурно-тектонических элементов в надсолевой, солевой и подсолевой толщах месторождения происходит закономерное изменение плотностной характеристики геологической среды с образованием в ней локальных плотностных неоднородностей. Установить положение этих неоднородностей и выявить их связь со*

структурно-тектоническими элементами геологической среды, особенно с такими, как трещинные зоны, возможно только путем изучения поля силы тяжести месторождения. Для этого на всей территории ВКМКС была выполнена площадная, детальная и высокоточная гравиметрическая съемка в масштабе 1 : 25 000, результаты которой были использованы для выявления и изучения трещинных зон.

Результаты исследований. *На основании результатов интерпретации аномалий поля силы тяжести на территории ВКМКС было установлено плановое положение и размеры около 200 локальных отрицательных линейных аномалий субмеридиональной, северо-восточной и северо-западной ориентировок, источники которых были уверенно отождествлены с трещинными зонами.*

Выводы. *Опыт изучения структурно-тектонического строения ВКМКС показал, что для физико-геологических условий месторождения наиболее эффективным из всех геофизических методов картирования трещинных зон в настоящее время является детальная, высокоточная гравиразведка в площадном варианте.*

Ключевые слова: *Верхнекамское месторождение калийных солей; трещинные зоны; гравиразведка.*

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