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Generalizing the experience of forecasting dynamic events at the Upper Kama potassium salt deposit according to geological and geophysical data

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Abstract
Introduction. *Mineral deposits opencast and underground mining is accompanied by excavation and conveyance of enormous rock masses. As a result, geological medium natural stress state is disturbed. Its balance restoration is accompanied by dynamic events of various forms and intensity, often catastrophic. That is why the problem of deposits safe exploitation is relevant in scientific and practical terms. At the territory of the Ural region there are several regions where the level of technogenic load is estimated to be potentially dangerous. One such region is Solikamsk-Berezniki region; the largest in the world, the Upper Kama (Verkhnekamskoe) potassium salt deposit (VKMKS) has been mined there since 1932, along with hydrocarbon, underground waters, and other mineral deposits. There is also a large reservoir there. Geological medium within the deposit is in the state of unstable balance. Catastrophic dynamic events of 1995, 1999, and 2006 give evidences of this.*
Research aim *is to generalize the experience of studying dynamic events at VKMKS and substantiate the criteria of their forecasting.*
Research methodology. *Generalization and analysis of the results of geological and geophysical survey made at VKMKS.*
Research results. *Structural-tectonic models of the Upper Kama deposit and its separate parts have been built, within the limits of which hazardous dynamic events took place.*
Conclusions. *Features characterizing deposit sites within which dynamic events took place have been formulated. These features can be considered as criteria for potential dynamic events forecast.*

Key words: *Upper Kama (Verkhnekamskoe) potassium salt deposit; dynamic events; forecasting; criteria; geological and geophysical data.*

Object and aim of research. When studying geological medium, the problem of determining genesis and nature of this or that event or object is fundamental. This problem has got satisfactory solution if we know the mechanism or mechanisms through which the event took place or the object formed. Having answered this question, we can forecast the development of an event in time and space.

Time-space sequence of geological events, their interrelation and conditions they happen under, are complex and often difficult to study. That is why geological events are studies at the phenomenological level, i. e. without their nature determination. And, nevertheless, descriptive research of geological events often allows to describe the observable facts correctly and even forecast their space-time evolution.

Empirical facts generalization and systematization is finished by the construction of a model (or models) of the studied event. Models in the form of maps are the most widespread in geology: geological, tectonic, structural, petrophysical, geological-physical, etc.

Research methodology. As regards methodology, the problem of building a model of an event or an object is assigned to inverse problems; multiple solutions (theoretically infinite) are their main feature. This means that several models can be built as a result

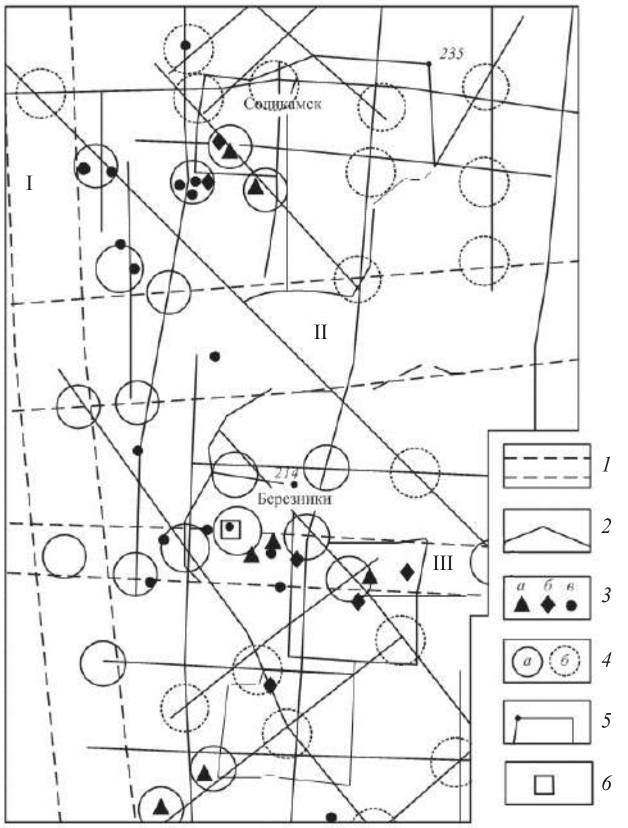

Fig. 1. Structural-tectonic scheme of VKMKS and the location of the forecasted sites of dynamic events:
1 – fracture zones: I – Krasnoufimskii, II – Durinskii, III – Zyrianskii; *2* – the axial lines of fracture zones; *3* – the epicentres of earthquakes – *a*, seismic events – *б*, caves-in and the sites of earth's surface increased subsidence – *в*; *4* – the sites of the forecasted dy-namic events: steadily marked out – *a*, less steadily marked out – *б*; *5* – the location of wells and contours of mine fields; *6* – the site of the accident, October 2006.

Рис. 1. Структурно-тектоническая схема ВКМКС и положение прогнозируемых участков динамических событий:
1 – зоны разломов: I – Красноуфимского, II – Дуринского, III – Зырянского; *2* – осевые линии разломных зон; 3 – эпицентры землетрясений – *а*, сейсмопроявления – *б*, провалы и участки ускоренного оседания дневной поверхности – *в*; *4* – участки прогнозируемых динамических событий: выделяемые уверенно – *а*, выделяемые менее уверенно – *б*; *5* – положение скважин и контуров шахтных полей; *6* – место аварии в октябре 2006 г.

of generalizing and interpreting one set of actual data. Which one of them is going to be the most probable? Unfortunately, the criterion, allowing to make an unambiguous choice, has not been formulated yet. The priority should be given to the model describing the major part of the observed facts. Apparently, this model will make it possible to forecast the development of this or that event sufficiently.

The mentioned criterion is particularly suited for the study of technogenic dynamic events taking place within relatively short periods of time, amounting to years or decades. They are common with the regions of intensive urbanization, regions, where deposits are mined, and geological medium loses its balance under significant technogenic load, and the restoration of balance is accompanied with such dynamic events as induced earthquakes, rock bursts, caves-in, and the earth's surface collapse.

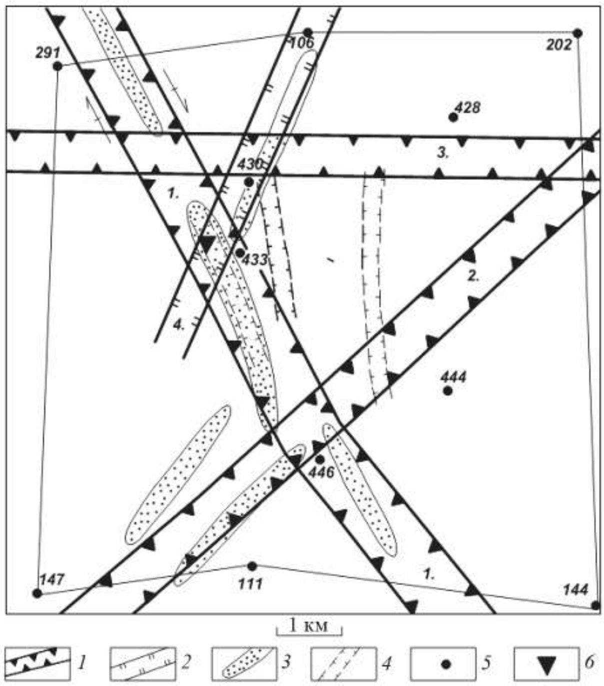

Fig. 2. The scheme of Balakhontsevskii (BKRU-3) site tectonics elements according to geophysical data:
1 – fracture zones of the 3rd order, marked out mainly by gravimetric data; *2* – the same, 4th order (according to L. D. Noiaksova and G. G. Kassin); *3* – zones of increased rock fracture at the suprasalt strata, marked out by gravimetric data; *4* – zones of increased electrical conductivity conditioned by suprasalt strata fractured rock (according V. P. Beliaev); *5* – the location of wells and their numbers; *6* – the point of brines outflow

Рис. 2. Схема элементов тектоники Балахонцевского (БКРУ-3) участка по геофизическим данным:
1 – зоны разломов 3-го ранга, выделенные преимущественно по гравиметрическим данным; *2* – то же, 4-го ранга (по Л. Д. Нояксовой и Г. Г. Кассину); *3* – зоны повышенной трещиноватости пород надсоляной толщи, выделенные по гравиметрическим данным; *4* – зоны повышенной электропроводности, обусловленные трещиноватыми породами надсоляной толщи (по В. П. Беляеву); *5* – положение скважин и их номера; *6* – место истечения рассолов

The problem concerning dynamic zoning and spatial forecasting of the areas with the most probable dynamic events manifestation is an important problem of urban lands study. The basis for its solution is the model of structural-tectonic and dynamic structure and properties of geological medium at various scale levels, as soon as these are the exact factors which determine dynamic behaviour conditioned by natural and technogenic force fields [1–5].

Research results. This problem has been solved (to some extent) through the study of VKMKS. By means of generalizing various empirical data: geological, structural-tectonic, geomorphological, petrophysical, geophysical (the results of detailed high-precision gravimetric observation with a scale of 1 : 25 000, the results of gravimetric observation with a scale of 1 : 100 000, the results of high-precision detailed aeromagnetic survey with a scale of 1 : 10 000) and other [6–8], based on the principles of similarity and hierarchy, a structural-tectonic model of the deposit (fig. 1) has been built in the form of the system of ganged faults with their kinematic type characteristics at various development stages, activation time and penetration depth estimations, determination of their monitoring role under the modern dynamic behaviour, and the establishment of the main types of local structures, strongly influencing the formation of a technogenic stress field (force field).

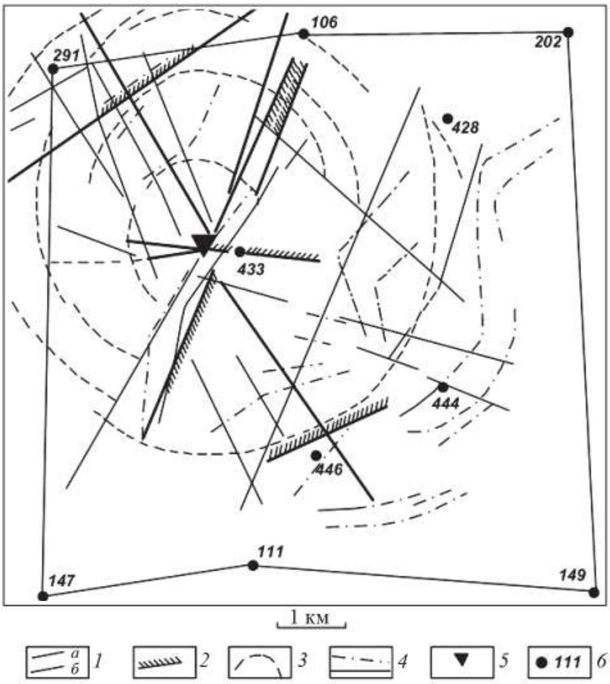

Fig. 3. The scheme of the elements fracture tectonics of Balakhontsevskii site (BKRU-3) by geomorphological data (according to S. Iu. Kvitkin):
1 – lineaments reflecting fracture zones in the sedimentary cover – *a*, with the increased fractures propagation – *б* (according to Iu. A. Iliinykh); *2* – the zones of the predicted increased infiltration of surface waters according to Iu. A. Iliinykh; *3* – the outlines of landscape anomaly according to Iu. A. Iliinykh; *4* – tectonic zones (according to Iu. A. Tretiakov); *5* – the point of brines outflow; *6* – the location of wells and their numbers

Рис. 3. Схема элементов разрывной тектоники Балахонцевского участка (БКРУ-3) по геоморфологическим данным (по С. Ю. Квиткину):
1 – линеаменты, отображающие трещинно-разрывные зоны в осадочном чехле – *а*, с повышенным раскрытием трещин – *б* (по Ю. А. Ильиных); *2* – зоны предполагаемой повышенной инфильтрации поверхностных вод (по Ю. А. Ильиных); *3* – контуры ландшафтной аномалии (по Ю. А. Ильиных); *4* – тектонические зоны (по Ю. А. Третьякову); *5* – место истечения рассолов; *6* – положение скважин и их номера

During the study of VKMKS tectonic structure and dynamic behaviour, it has been stated that the epicentres of dynamic events (induced earthquakes, rock bursts, etc.) are spatially and genetically connected with the following tectonic structures: fracture zones, active faults of various ranks and the intersection nodes of faults.

As the blocks of geological medium move along the fracture zones, elastic energy accumulates and discharges in the form of various dynamic events. It is generally accepted that earthquakes (as a type of dynamic events), especially minor, are generated by crust fractures. This conclusion is considered to be one of the most significant achievements of modern seismology [3].

In this regard, let us refer to the study of dynamic events at the territory of VKMKS:

– 24 epicentres of dynamic events out of 25 are located within the fracture zones;

– more than half of epicentres of dynamic events are in the intersection nodes of two or more fracture zones;

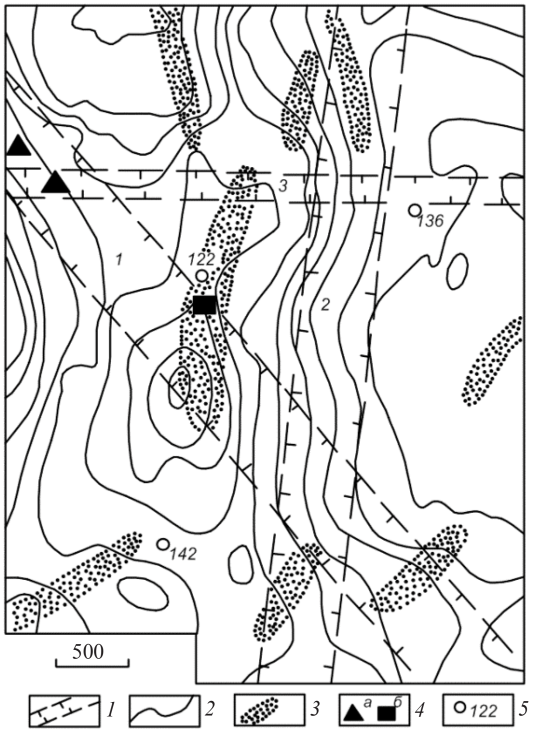

Fig. 4. The scheme of Solikamsk node structure (SKRU-2): *1* – fracture zones established by geophysical data (*1* – Timan-Kokshetau fault); *2* – isoanomalies of the gravity field; *3* – local negative anomalies in the gravity field; *4* – the location of earthquake's epicentre – *a* and other dynamic events – *б*; *5* – the location of wells and their numbers

Рис. 4. Схема Соликамской узловой структуры (СКРУ-2): *1* – зоны разломов, установленные по геофизическим данным (*1* – Тимано-Кокчетавский разлом); *2* – изоаномалы поля силы тяжести; *3* – локальные отрицательные аномалии в поле силы тяжести; *4* – положение эпицентра землетрясения – *а* и других динамических событий – *б*; *5* – положение скважин и их номера

– the major part of dynamic events took place in the east part of VKMKS, the activity of which is conditioned by three factors: the influence of the Upper Kama Reservoir, Krasnoufimsky deep fault, active at the modern stage of tectogenesis, and high speed of the earth's surface motion (up to 6 mm per year) [1].

The nodes, the elements of which are faults and fracture zones, have got the most complex structure; node structures strongly influence the formation of natural and technogenic force fields (stress fields).

The analysis of these structures properties has shown that the probability of forecasting dynamic events within their epicentres is very high and depends on a great number of factors [4]:

– the number and the type of dynamic events which occurred within the area of the node;
– the presence of active faults in the node structure;
– the number of faults forming the structure;
– the presence of the sites of increased fracturing at the area of node structure;
– the distance to the nearest dynamic event epicentre;
– the presence of negative anomaly in the gravity field at the area of node structure;
– the presence of helium anomaly at the area of node structure;
– the presence of structural complications in the relief of crust deep horizons within the area of node structure;
– the distance between the node structure and the edge part of a growing salt dome;
– the distance between the node structure and the nearest large reservoir;
– the presence of a mine within the area of node structure;
– kinematic type and azimuth of strike of faults, forming the node structure;
– variation of the earth's surface relief height at the area of node structure;
– the distance to the nearest node structure;
– the character of lineaments at the area of node structure according to the results of space and aero images interpretation;
– the character of river system at the area of node structure;
– the presence of troubles in shearing kinematics among the faults forming the tectonic node [9].

The set of the enumerated features (criteria) with the account of the results of seismic monitoring [10, 11] is not random. It reflects the state of geological medium under the action of two force fields, natural and technogenic. It is impossible to estimate the weight and the role of each feature as well as the informative completeness of the whole set of the features and what should be done for this set to grow into a new quality, i. e. into the system of forecasting features. Nevertheless, structural-tectonic scheme of VKMKS (fig. 1), which has got the features described earlier at bottom, should be considered as adequately substantiated and used to forecast dynamic events.

Up to 1986 technogenic loads never led to geological medium disturbances at VKMKS. The first catastrophic event happened in autumn, 1986. That event resulted in mine BKRU-3 flooding (fig. 2, 3). In 1995 there was an induced earthquake in SKRU-2 mine with collapse of significant rock mass into the goaf (fig. 4). In 1999 in the vicinity of Novaia Zyrianka village within the limits of BKRU-1 mine, a chain of caves-in appeared at the earth's surface (fig. 5). In October 2006 there was a catastrophic flooding of BKRU-1 mine (fig. 6). These events testify to the presence of systematic disturbances of geological medium happened under the action of technogenic load conditioned by the deposit exploitation.

In the course of studying these events, structural-tectonic conditions they occur under, have been analysed.

The region of flooded mine BKRU-3 (Balakhontsevskii site) is characterized by hierarchical node structure and represents three blocks put one into another and limited by the faults of various ranks of north-south, north-west, and north-east strike (fig. 2). The flooded region epicentre, the point of brine outflow, is the intersection node of faults of east-west north-west, and north-east strike, and fracture zone which is steadily mapped in gravity and electric fields. Faults in the plan coincide with the lineaments. It testifies to the fact that motions along the faults occurred in the contemporary history. The faults are strike-slip faults. At the earth's surface relief, the node structure is connected with the landscape anomaly – the upheaval with the radius of 6–7 km, complicated by the ring-type tectonic troubles conforming to relief isohypses. In the plan, the centre of landscape anomaly coincides with the point of brines outflow. The dynamic influence area radius of faults forming the node structure has been ranked at 3–4 km. According to [2], within the mine field of BKRU-3, polygene dislocations are developed which are formed during underground water migration in the suprasalt and salt parts of the salt-marl strata in the points of ancient discharge channels. These locations should be considered as one feature of node structure tectonic activity, while brines could inflow through the channels.

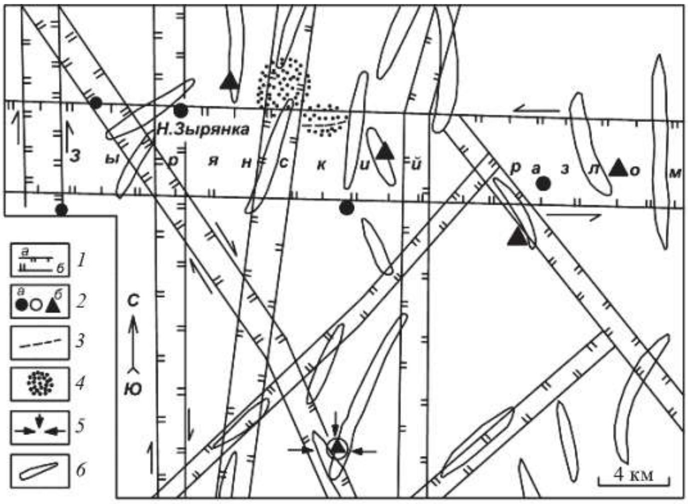

Fig. 5. The fragment of the Upper Kama deposit tectonic scheme in the area of Zyrianskii fault:
1 – fracture zones and the time of their activation by geophysical data: *a* – Paleozoic and earlier, *б* – contemporary (arrows indicate the direction of shift along the fracture zone); *2* – the location of dynamic events epicentres (according to V. M. Nezhdanov): *a* – earthquakes and seismic events, *б* – earth's surface subsidence; *3* – linear zone of caves-in of the earth's surface in 1999; *4* – the points of rock and gas pressure manifestation; *5* – the location of the cave-in at the place of BKRU-3 mine flooding; *6* – the sites of increased fracturing of geological medium

Рис. 5. Фрагмент тектонической схемы Верхнекамского месторождения в районе Зырянского разлома:
1 – зоны разломов и время их активизации по геофизическим данным: *а* – палеозойское и более позднее, *б* – новейшее (стрелками показано направление сдвигания вдоль разломной зоны); *2* – положение эпицентров динамических событий (по В. М. Нежданову): *а* – землетрясения и сейсмопроявления, *б* – оседания дневной поверхности; *3* – линейная зона провалов дневной поверхности в 1999 г.; *4* – места проявления горного и газового давления; *5* – положение провала на месте затопления рудника БКРУ-3; *6* – участки повышенной трещиноватости геологической среды

The epicentre of the induced earthquake of 1995 was also located in the node structure limited by three faults: ancient deep Timan-Kokshetau fault of north-west strike, submeridional fault of Paleozoic age, and latitudinal fault of post-Paleozoic age; gravity field of a node structure is characterized by isometric, negative in the plan, anomaly (fig. 4). Geological structure of a node is complex both at suprasalt horizons (disjunctive and fracture zones), salt (halitization of sylvinite), and undersalt (tectonic troubles, Pashkovsky reefogenic upheaval). Seismic works in the node stated the increased fragmentation of cover rocks and tectonic troubles permeating the undersalt and suprasalt strata. The results of gravity force anomaly interpretation testify to the fact that the anomaly is conditioned by rock weakening and that the weakening process spreads to both productive and suprasalt rock. Weakening is not of lithological, but of tectonic nature pointing to the deposit's waterproof strata trouble.

At the course of VKMKS territory geodynamic zoning according to the set of geological and geophysical data, a sublatitudinal Novo-Zyrianskii fault with shear kinematics (fig. 5) has been mapped and assigned to the category of active faults.

The fault lies in the south part of the mine field of BKRU-1 mine. The conclusion about the fault's activity was proved in May, 1999 when within several days along the whole axis at the earth's surface, an echelon chain of caves-in occurred 2–4 m deep and about 1 m wide. Caves-in formed two sublatitudinal zones in the plan. The most pronounced of them was the southern one, about 2 km long. The planimetric position of some caves-in coincided with the earth's surface projections of das-dynamic manifestation sites in mine workings, which pointed at their possible interconnection. Caves-in were of tectonic nature and, apparently, formed as a result of a horizontal shear along the axial part of the Novo-Zyrianskii fault.

Fig. 6. Cave-in in Berezniki city at BKRU-1, October, 2006.
Рис. 6. Провал в г. Березники на БКРУ-1, октябрь 2006 г.

Another catastrophe occurred in October, 2006 within the limits of BKRU-1 mine field [12]. As the results of underground water inburst, the mine was flooded. The epicentre of the accident was situated within the dynamic influence of Novo-Zyrianskii active fault (fig. 5). In structural-tectonic terms the area of the accident represents a node structure formed by the sublatitudinal fracture zone and Novo-Zyrianskii fault. Tectonic node structure is situated at the west slope of the growing Bereznikovskii salt dome. Fracture zone (FZ) – is the fault of the fourth or fifth order, being the fragment of the system of deformational structures of Krasnoufimskii deep fault; according to gravimetrical data, FZ troubles the continuity of VKMKS sedimentary strata increasing its permeability for hundreds of meters vertically [12].

Results analysis and discussion. Thus, all dynamic events which occurred within the past thirty years at the territory of VKMKS, in structural-tectonic terms, are genetically and spatially connected to the fracture zones, active faults, and tectonic node structures, which are characterized by a large number of factors and features.

Conclusions and scope of results. The experience of studying forecasting features has shown that they are stable and they repeat within the limits of all investigated sites of the deposit where hazardous dynamic events occurred. That is why they should be used to forecast dynamic events.

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Обобщение опыта прогнозирования динамических явлений на Верхнекамском месторождении калийных солей по геолого-геофизическим данным

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Реферат
Введение. *Эксплуатация месторождений полезных ископаемых, добываемых открытым и подземным способами, сопровождается выемкой и перемещением огромных масс горной породы. В результате происходит нарушение естественного напряженного состояния геологической среды. Восстановление ее равновесия сопровождается различными по форме и интенсивности динамическими явлениями, нередко катастрофическими. Поэтому проблема безопасной эксплуатации месторождений актуальна в научном и практическом отношениях. На территории Уральского региона есть несколько районов, в пределах которых уровень техногенной нагрузки на геологическую среду оценивается как потенциально опасный. Одним из таких районов является Соликамско-Березниковский, где с 1932 г. ведется разработка крупнейшего в мире Верхнекамского месторождения калийных солей (ВКМКС), месторождений углеводородов, подземных вод, других полезных ископаемых, а также имеется крупное водохранилище. Геологическая среда в пределах месторождения находится в состоянии неустойчивого равновесия, о чем свидетельствуют катастрофические динамические явления, произошедшие в 1986, 1995, 1999 и 2006 гг.*
Целью работы *является обобщение опыта изучения динамических событий, произошедших на ВКМКС, и обоснование критериев их прогнозирования.*

Методика исследований. *Обобщение и анализ результатов геолого-геофизических исследований, выполненных на ВКМКС.*
Результаты исследований. *Построены структурно-тектонические модели Верхнекамского месторождения и его отдельных участков, в пределах которых произошли опасные динамические события.*
Выводы. *Сформулированы признаки, характеризующие участки месторождения, в пределах которых произошли динамические события. Эти признаки можно рассматривать в качестве критериев для прогнозирования мест возможного проявления динамических событий.*

Ключевые слова: *Верхнекамское месторождение калийных солей; динамические явления; прогнозирование; критерии; геолого-геофизические данные.*

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