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STRUCTURING OF ROCK AND FORMATION OF QUASICRYSTALS

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СТРУКТУРИЗАЦІЯ ПОРІД ТА УТВОРЕННЯ КВАЗІКРИСТАЛІВ

Purpose. To obtain new data about structural formation of rocks and minerals.

Methodology. The research was conducted with the help of optical and electronic microscopes; samples were taken from bore specimen as well as from mine workings at Donetsk coal basin and Kryvyi Rih iron ore basin. The samples were used for preparing thin sections, two-stage carbon replicas, grab samples, and polished sections. There were also studied other solids: minerals, mineraloids, artificial solids, rocks.

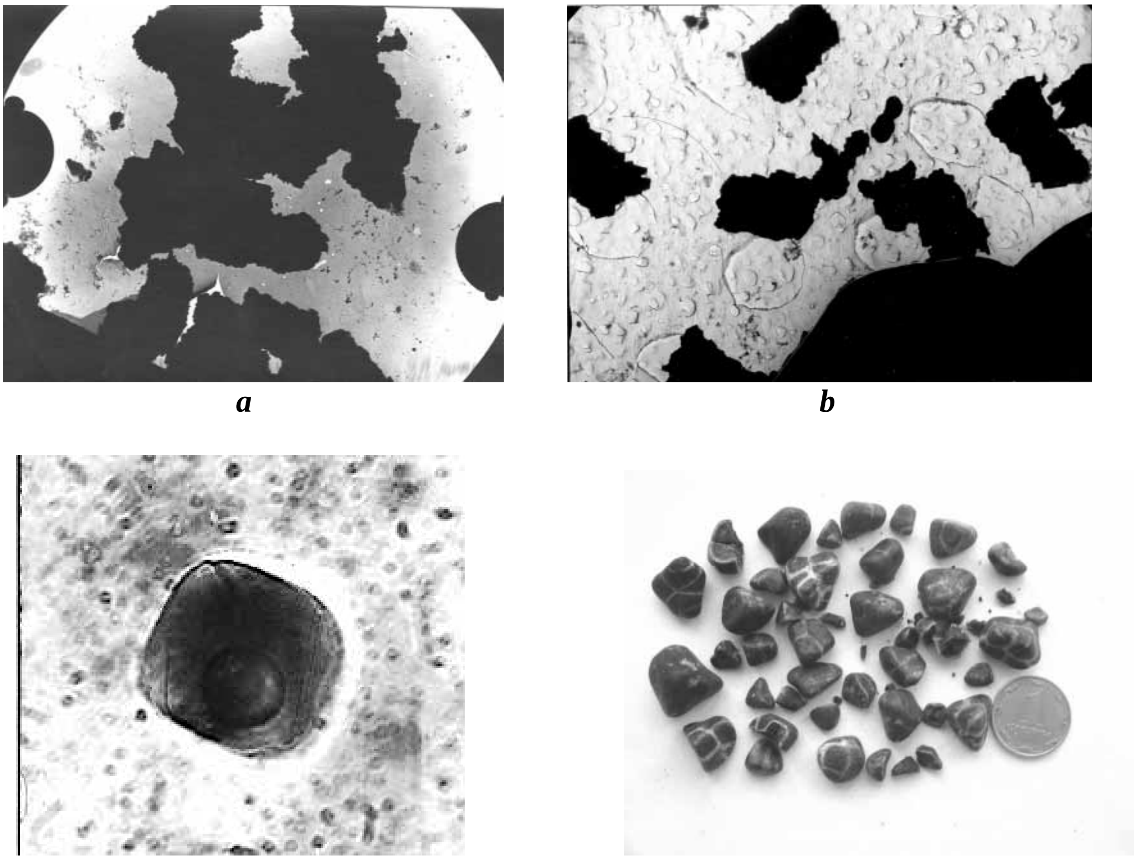
Findings. It is set that under certain conditions structures which have regular geometrical shapes appear in different matters. These forms have different names: jointing, blockiness, negative crystals et al. At the end of the last century it was offered to name them all quasicrystals. These structures are formed in rocks, minerals, living organisms, artificial matters. The findings of the research on formation conditions of quasicrystals in rocks and minerals are presented. We have come to the conclusion that quasicrystal formation results from transformation of solid to the lower energy level, similar to crystallization. Externally derived excess energy is converted into formation of specific quasistructure (similar to long-range order) in rocks, minerals, and mineraloids. The structuring process under changing thermodynamic conditions is characterized by entropy suppression. The described process is often referred to differently: synergetics, self-organizing, structuring. We have drawn the conclusion that this property is transitional form between the crystalline and amorphous state of matter.

Originality and practical value. The study of the new state has both scientific value (determination of principles of formation of quasicrystals in different minerals, ores and nonmetallic minerals) and applied relevance (prediction of fault zones in coals and on boundaries of blocks of different size, association of augmented ore content in these zones (especially in joints, i.e. point of intersection of fracture zone), influence of the above mentioned zones and conditions of quasicrystals formation on the minerals' treatment and further enrichment methods. Structuring of the solid and formation of quasicrystals are two interrelated processes reflecting the conditions of formation and transformation of rocks and hosted minerals.

Keywords: *quasicrystals, structure, rocks, minerals, entropy, destruction, structuring*

Introduction. Since mid-80s of the 20th century the author of the article has conducted research in the Institute of Geotechnical Mechanics of the NAS of Ukraine on new property of the solid: the formation of regular solids under certain energy conditions, these solids being called *quasicrystals* (Fig. 1). These solids represent different kinds of blockiness, jointing, minerals, artificial solids and have proportional parameters for corresponding levels. The quasicrystals usually form under external factors, such as temperature, pressure, physical-chemical, physical and mechanical, biochemical and other energy transformations. The dimensions of these formations range from nanometers to thousands of kilometers and are probably limited by the dimensions of the studied levels, rather than their absolute dimensions. Geological dictionary defines jointing as ranging from centimeters (lower limit) to hundreds of meters (upper limit). Blockiness differs from jointing only in dimensions; however the latter term has not been used in connection with gas-liquid occlusion, amorphous solids (glass, amber, glue) or concrements (growing in living organisms). This conditions the need for the general term, quasicrystal [1].

The conducted research shows that the factors forming jointing, blockiness, suture and stylolitic seams in different rocks, ore and nonmetallic mineral resources, previously considered to be different, are actually of common nature. This nature is the structure formation of the solid when there changes the occurrence condition of specific rock or mineral. To put it simply, we can speak about the change in energy state of the solid. Change in temperature, pressure, chemical property of host medium and other energy transformations, according to Le Chatelier's principle of negative feedback, result in transition to lower or higher energy state. The transition to a higher energy level presumes amorphisation of solid matter or breakdown of complex system. The transition to a lower energy level presumes structure complication or structuring. These two ways of structure transformation depending on the change in external conditions are described by Ya.A. Vinkovetsky in terms of geological studies. Structure breakdown or amorphisation is referred to as entropic changes by referred author. Explosion or destruction of solid can be mentioned as an example. Transformation of chaotic structures into complex organized structures is called organizational transformation. The evolution of the Universe can serve as a model, where hydrogen makes the base for all other elements including heavy elements composing stars and planets. Physicists experimentally reproduce this process in the Hardon Collider. Basing on the existing factors, the above mentioned author puts forward a hypothesis that in isolated system entropy is divided into energetic (destruction, increase of entropy) and structural one (structuring, increase of structure complexity).



a ***b*** ***c*** ***d***

Fig. 1. Quasicrystals of amorphous solids: a – glass; b – amber; c – gas-liquid occlusion; d – concrements in human body; a and b – 2000^X, two-stage carbon replica, transmission electron microscope ЭМВ-100Л; c – thin section, optical microscope, 1000^X; d – photo of concrements

Ya.A. Vinkovetski refers to planetary evolution as to organizational or forming processes. Rrecently this process has commonly been referred to as structuring [1–3]. Many geologists describe the process of earth crust structure complication as formation of new and partial transformation of earlier structural forms. Among apparent organizational processes is sediment formation, regional metamorphism, increasing variety of genetic kinds of deposits, change in composition of extrusive rocks from mafic to acidic resulting in thickening sialic (granite) shell of the Earth.

In our view, quasicrystal formation results from transformation of solid to the lower energy level, similar to crystallization. In other words, externally derived excess energy is converted into formation of specific quasistructure (similar to long-range order) in rocks, minerals, and mineraloids. The structuring process under changing thermodynamic conditions is characterized by entropy suppression, this issue being studied earlier [4 and others]. The described process is often referred to differently: synergetics, self-organizing, structuring. We prefer the last term as it presupposes external influence on the object under study, as without this influence structural transformation of solid is impossible. A priory a process cannot go on without changes in conditions, primarily in energy state.

Study of the new state has both scientific value (determination of principles of formation of quasicrystals in different minerals, ores and nonmetallic minerals) and applied relevance (prediction of fault zones in coals and on boundaries of blocks of different size, association of augmented ore content in these zones (especially in joints, i.e. point of intersection of fracture zone), influence of the above mentioned zones and conditions of quasicrystals formation on the mineral treatment and further enrichment methods.

Research. The research was conducted with the help of optical and electronic microscopes; samples were taken from bore specimen as well as in mine workings at Donetsk coal basin and Kryvyi Rih iron ore basin. The samples were used for preparing thin sections, two-stage carbon replicas, grab samples, and polished sections. There were also studied other solids: minerals, mineraloids, artificial solids, rocks.

The issue of structure transformation of the solid under energy influence has always drawn researchers' attention. According to Zeroth law, the energy accumulated during geological transformation is directed at the change of the structure of the solid. For example the process of clathrates formation in gas hydrates, the process of formation of regular groups of clathrates with hexagonal plates in extinguished volcanoes, the process of fullerene formation, i.e. hollow carbon polyhedrous football-like body; tetrahedrons, pentahedrons or hexahedrons on the soil surface resulting from frost clefts [1–3] and others.

The listed processes can be represented as follows. Let us express all energy spent on qualitative transformation of the matter into different state (for instance, from solid to liquid) in percent and conventionally represent it as 100%. Then any influence on this matter: compression or expansion, exposure to ultrasound or other energy field, makes part of this 100%. Conventionally we can, for example, destroy a certain amount of rock with explosion spending 10% of energy, and then melt it using the rest 90% of energy.

In the research paper [5] it is noted that the formation of ductile deformation like Boehm lamellae in granites occurred under triaxial compression in laboratory conditions. Microfractures formed under 30% stress were of crinkled or ladder character. This indicates that there is both ductile and brittle deformation in the test specimen. Ladder character of microfracture zones in the experimental granite specimen is an interesting and important result. Similar facts are rarely described in research of structure in general, and microstructure in particular.

Kobelev N.P. with colleagues studied the influence of dislocations on dispersion of ultrasonic waves speed in crystals. They came to the conclusion that attenuation of ultrasonic waves in copper and some other crystals is connected with micro inhomogeneities of the medium, and primarily dislocations. The crystals were compressed up to the formation of slipbands with typical distance between bands about 300÷600 my. Internal stress of the range of samples measured by photoelastic method showed that typical stress field change period approximately equals to the distance between the bands, and their span approximately equals to the stress under which the crystal was deformed.

This conclusion is interesting because we observed similar systems of slipbands with the help of optical and electronic microscopes in jaspilites of Kryvyi Rih, and later in quartz of sedimentary and igneous rocks, glass, amber, coal, epoxide resin and other solids. Initially the research was conducted with the help of transmission electron microscope (ЭМВ-100Л) with the well-known two-stage carbon replica technique, and later in rock samples with the help of optical microscope. The distance between the bands varies depending on magnification. Electronic microscopy allowed establishing average distance between slipbands at 7÷15 my, the majority being about 8÷10 my, whichever metter was under investigation. It is noticeable that minimum size of quasicrystals found at fractures of different solids made 1÷3 my. However the slipbands with such distances have not been found. There may be many reasons for this. Probably it was necessary to change working magnification to more than 2000x. Alternatively, the applied method of producing two-stage carbon replicas might not allow receiving the desired result and it has to be improved, or other research method should be applied. Anyway, there has been established the fact that particles of such size form in different solids. As formation of quasicrystals can result exclusively from ductile deformation of the solid, there is no doubt that ductile deformation of such size exists.

We studied glade plane with the help of optical microscope and found the following: glade plane is represented by two systems – the main, clear and pronounced, system, and the subordinate one. Average distance between glade planes of the main system changes between 60÷100 my, with the majority around 80 my. The subordinate system is characterized by average distance between glade planes within 30÷50 my, with the majority in around 40 my. The given distances are obtained empirically in naturally deformed quartz grains. The dimensions of deformation obtained by the researchers [5] by stressing copper crystals might represent the next level of structuring of the solid.

The mentioned transformations, according to obtained empirical data, usually do not occur simultaneously, but as a result of several transient stages. Initially, rock-forming grains (usually the largest ones) accumulate considerable amount of elastic energy that is realized under progressive process into ductile deformation. Ductile microdeformations start to appear, accumulate and transform: Boehm lamellae, deformation bands and belts, irrational and contorted quartz. Further, under increasing external influence due to lithostatic, tectonic and thermal effects (mainly), there occurs aperture of discontinuity along the most energetically unstable ductile deformations. In other words, there occurs brittle deformation represented by grains breaking into blocks, granulation and appearance of structures that are more energetically stable to external influence.

The energy accumulated in grains being in contact results into the mentioned ductile microdeformations. Its kind or sub-kind, as well as its geometrical structure, depends on how the stress was applied: compression, compression along with shift, tension with shift and other combinations. Each stress mechanism results in formation of this or that kind and sub-kind of structural microdeformation (detailed consideration of this mechanism is beyond the scope of the given paper).

The resulting deformation plane or set of planes, as well as any breach of structure leaves a 'scar' in the grain. Further evolution of rock massif: further foundering or, on the contrary, inversion, involvement in faults, overthrust fault, fissure displacement or other macro-level deformation results in formation of new mineral and rock structures.

The experiments conducted by authors [6] showed that the energy released into crystal lattice is distributed differentially. There occurs nonuniform distribution (domain, cellular) of mechanical stress. Fracture emerges in one of maximums. It emits dilatational wave of dynamic stress, inducing fractures in adjoining maximum and so on. With the longitudinal sound velocity there emerges broken line of intergrown fractures located near cleavage plane. These intergrown fractures make one main fracture with many lamellae on surface resulting from transition from one cleavage plane to the parallel one. The same was observed while studying the surface in the microscope.

Similar results are obtained by the author of this article while studying rock-forming jaspilite quartz, glass, amber and other solids with electronic and optical microscope, however we interpret these data differently from the above.

Detailed microscopic study of the above mentioned planes restricting the fracture allowed establishing their ladder character which, with further brittle deformation, results in forming quasicrystals [7] (Fig. 1, *a-b*). These quasicrystals have well-marked indented (ladder, suture-like) surface in all studied solids of both crystal and amorphous structure.

The study also showed that along with ladder structure there occurs hierarchical pattern of formation of the given glade plane sets. Every level of study (from micron to macro and mega levels) has its own feasible parameters of organizing these sets. Thus, for the electronic microscopes level the quasicrystals with dimensions 1÷3, 6÷15, 20÷30 my and so on are typical. Microscopic level has its own feasible parameters, macroscopic one has its own and so on.

Researchers in [2] ground the transformation of tectonically stressed zones. Herewith, homogeneous isotropic state gets unstable and there appears preferential direction, and stressed zone is no longer isotropic. That is, in the isotropic space under certain energy influence the conditions for anisotropization of the properties of system under investigation are formed.

Let us take a detailed look at this 'preferential direction' in the context of rock. In the solid there form the levels of energy concentration and dissipation under vector energy flux (regardless of its source: thermal, dynamic, lithostatic etc.). In other words, energy flux is of wave character with certain frequency, while interference is manifested as formation of nonequilibrium zones (layers) perpendicular to the energy flux characterized by additional kinetic component. The latter is manifested in the form of the solid structuring in an isolated zone and, similarly to well-known Bénard instability results in space organization of the solid (I.I. Prigozhin). Unlike the authors considering this process to be self-organizing, the author of this article holds to an opinion that all processes are consumptive of energy and cannot occur on their own terms. It is more accurate to speak of structuring of the solid, this process being conditioned by both external factors and the properties of the solid under investigation. Bénard cells differ from solid to solid, as solids differ in properties.

The above mentioned space organization of the solid is exclusively characteristic of the maximum concentration zone of the energy flux, where the ladder (suture-like) zone is formed. In case of compression stress succeeded by tensile stress or compression along with shift there appears standard master joint of suture-like form (Fig. 2, *a*).

Thus, the above scheme of structuring of unisotropic space in isotropic layer can be presented as follows. Directed flux of energy conditions the interference of energy waves (stress waves) forming non-equilibrium (metastable) zones in which the solid is structured in the form of tridimensional grid with regular geometric configuration. Their dimensions are functionally dependent on initial conditions: the degree of energy exposure, composition and properties of the solid, dimensions of an object and occurrence time. The formation of jointing or quasicrystals can be considered as the result of the solid structuring.

In case of sufficient, although short-term stresses the above process either does not occur at all or occurs partially, which may lead to formation of directed fracturing, i.e. cleavage, schistosity, a range of faults and other directed deformations of different scale.

Conclusion. The above material graphically allows observing the naturally existing cyclic recurrence in transformation of the rock and minerals structure under changing thermobaric conditions. On the basis of factual data it can be concluded that every stage of rock transformation happens under changing conditions of its occurrence: change of depth, thermal conditions, regional or local tectonic stresses. In any case, the energy balance of the solid is changed. The solid responses to changes via adaptation to new conditions. This is manifested through the formation of considerable amount of ductile microdeformations resulting in the metastable state of the solid. Further change of thermodynamic parameters finally results in formation of new structure and new rock (metamorphic, igneous). This completes the stage of structure transformation giving rise to the new stage. The new stage is characterized by similar changes: accumulation of energy potential, transition of the structure from stable to metastable state, development of ductile microdeformations and realization of the potential energy accumulated in the rock as a new, more stable structure. On local level similar transformations occur in the zones of tectonic faults, where jointings of different levels are formed. Here, the smaller the dimensions of quasicrystals are, the greater stress was placed on the rock in this zone. In other words, structuring of the solid and formation of quasicrystals are two interrelated processes reflecting the conditions of formation and transformation of rocks and hosted minerals.

We plan to conduct further research in the area of geological modeling and practical implementation of the studied properties, e.g. development of the methods of predicting fault zones (excessive fissuring zones) and fault zones commissure (potentially ore-bearing zones).

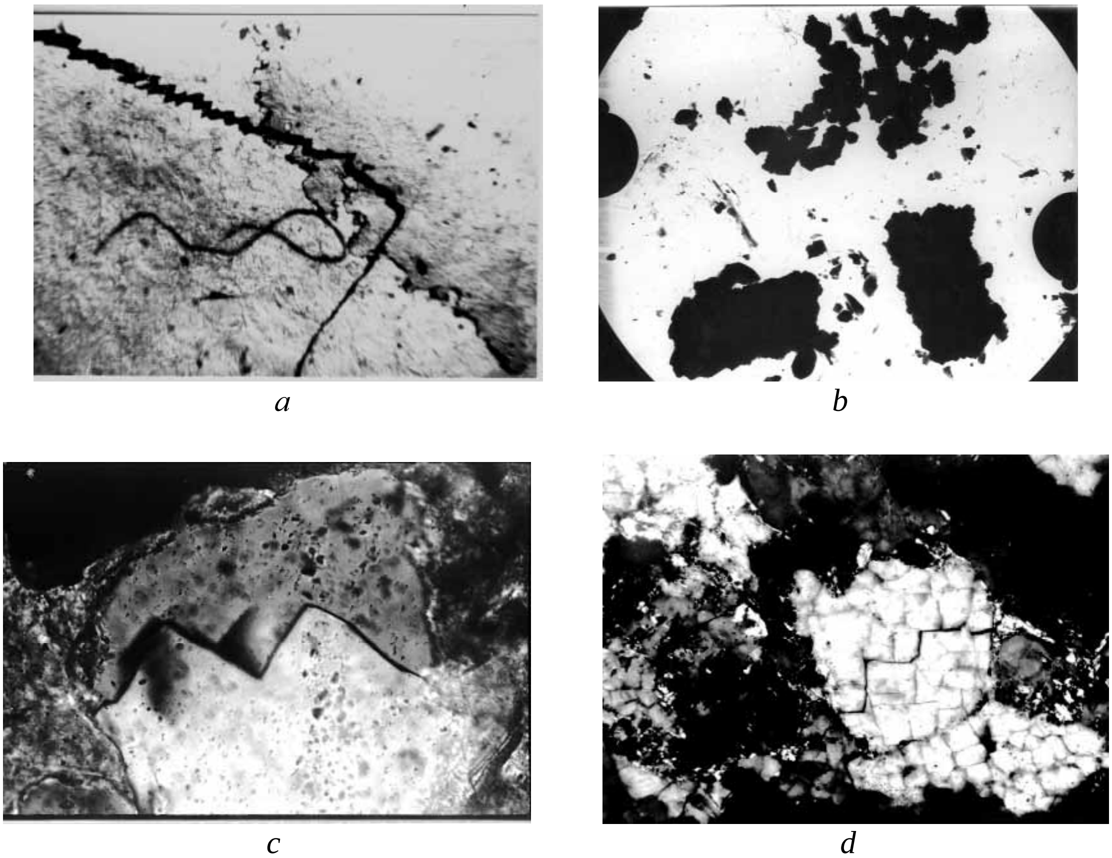


Fig. 2. Suture-like forms and quasicrystals: a – suture-like joints in quartz vein of Kryvyi Rih jaspilite, thin section, 100^x; b – quasicrystals of quartz from Donbass sandstones, replica, 2000^x; c – suture-like joint in quartz grain, ductile deformation, thin section, 250^x; d – suture-like joint in quartz grain, brittle deformation, thin section, 100^x

References / Список літератури

1. Baranov, V.A. (2000), Structural transformation of Donbass sandstones and prediction of outburst hazard. Abstract of Dr. Sci. (Geol.) dissertation, National Mining Academy of Ukraine, Dnipropetrovsk.

Баранов В.А. Структурные преобразования песчаников Донбасса и прогноз их выбросоопасности: автореферат диссертации на соискание ученой степени доктора геологических наук / В.А. Баранов – Днепропетровск: НГА Украины, 2000. – 35 с.

2. Baranov, V.A. (1997), "One-way (directed) isotropy in rocks as a consequence of structuring nonequilibrium systems", *Proc. of the Conf. "High-energy-rate processing of materials"*, National Mining Academy of Ukraine, Dnipropetrovsk, pp. 138–141.

Баранов В.А. Односторонняя (направленная) изотропия в горных породах как следствие структурирования неравновесных систем: матер. конф. „Высокоэнергетическая обработка материалов" / В.А. Баранов – Днепропетровск: НГАУ, 1997. – С. 138–141.

3. Baranov, V.A. (1997), "One-way (directed) isotropy in rocks as a consequence of structuring nonequilibrium systems", *Proc. of the Conf. "High-energy-rate processing of materials"*, National Mining Academy of Ukraine, Dnipropetrovsk, pp. 138–141.

Баранов В.А. Результаты исследований квазикристаллов различных веществ под электронным микроскопом / В.А. Баранов // Геотехническая механика. – Днепропетровск, 2001. – № 27.– С. 140–144.

4. Klimontovich, N.Yu. *Bez formul o sinergetike* [On Synergetics without Formulae], Vysshaya shkola, Minsk, Belarus.

Климонтович Н.Ю. Без формул о синергетике / Климонтович Н.Ю. – Минск: Высш. шк. – 223 с. – Режим доступа: http://chelib.ru/main/index.php

5. Volarovich, M.P., Tomashevskaya, I.S. and Budnikov, V.A., Mekhanika gornykh porod pri vysokhihkh davleniyakh [Mechanics of Rocks under High Pressure], Nauka, Moscow, Russia.

Воларович М.П. Механика горных пород при высоких давлениях / Воларович М.П., Томашевская И.С., Будников В.А. – М.: Наука. – 152 с. – Режим доступа: http:// www. geolcom.ru/lib/geofizika/fizicheskie-svoistva-mineralov-i-gornykh-porod-pri-vysokikh-termodinamicheskikh-parame

6. Vaisburd, D.I., Semin, B.M. and Tavanov, Z.G., [High-Energy-Rate Electronics of a Solid Body], Nauka, Novosibirsk, Russia.

Высокоэнергетическая электроника твердого тела / Д.И. Вайсбурд, Б.М. Семин, З.Г. Таванов и др. – Новосибирск: Наука. – 225 с. – Режим доступа: http: // urss.ru/cgi-bin/ db.pl?lang = Ru&blang=ru&page=Book&id=125250

7. Baranov, V.A. (1998), “Quasicrystals in quartz of Donbass sandstones”, Geotekhnicheskaya mekhanika, no. 10, pp. 35–40.
Баранов В.А. Квазикристаллы в кварце песчаников Донбасса / В.А. Баранов // Геотехническая механика. – 1998. – № 10. – С. 35–40.

Мета. Одержати нові дані про структурні перетворення гірських порід і мінералів.

Методика. Дослідження виконувалися оптичним і електронно-мікроскопічним методами, проби відбиралися з керна свердловин і в забоях на шахтах Донецького вугільного басейну та Криворізького залізорудного басейну. Відібрані проби використовувалися для приготування стандартних шліфів, двоступеневих вуглецевих реплік, штуфів і пришліфовувань. Окрім цього, досліджувалися різні речовини – мінерали, мінералоїди, штучні речовини, гірські породи.

Результати. Встановлено, що за певних умов у різних речовинах утворюються структури, що мають правильні геометричні форми. Ці форми мають різні назви: окремість, блоковість, негативні кристали та інші. Автором у кінці минулого століття запропоновано їх називати квазікристалами. Ці структури формуються в гірських породах, мінералах, живих організмах, штучних речовинах. Формування квазікристалів є наслідком переходу речовини на нижчий енергетичний рівень, подібно кристалізації. Надмірна енергія, одержана ззовні, реалізується у формування своєрідної квазіструктури (подібність дальнього порядку) в гірських породах, мінералах, мінералоїдах. Процес впорядковування структури речовини під дією термодинамічних умов, що змінюються, характеризується зменшенням ентропії. Вказаний процес часто йменується різними термінами: синергетикою, самоорганізацією, структуризацією. Зроблений висновок про те, що вказана властивість є перехідною формою між кристалічним і аморфним станом речовини.

Наукова новизна та практична значимість. Дослідження нової властивості має як наукове значення – визначення закономірностей формування квазікристалів у різних мінералах, рудах і нерудних корисних копалинах, так і прикладне значення – прогнозування порушених зон у вугіллі, на межах блоків різних масштабних рівнів, приуроченість до цих зон підвищеної рудоносності (особливо у вузлах – місцях перетину зон тріщинуватості), вплив вказаних зон і умов формування в них квазікристалів на способи відпрацювання й подальше збагачення корисних копалин. Структуризація речовини та формування квазікристалів – це два взаємозв'язані процеси, що відображають умови утворення та перетворення гірських порід і мінералів, що вміщуються.

Ключові слова: *квазікристали, структура, породи, мінерали, ентропія, деструкція, структуризація*

Цель. Получить новые данные о структурных преобразованиях горных пород и минералов.

Методика. Исследования выполнялись оптическим и электронно-микроскопическим методами, пробы отбирались из керна скважин и в забоях на шахтах Донецкого угольного бассейна и Криворожского железорудного бассейна. Отобранные пробы использовались для приготовления стандартных шлифов, двухступенчатых углеродных реплик, штуфов и пришлифовок. Кроме этого, исследовались различные вещества – минералы, минералоиды, искусственные вещества, горные породы.

Результаты. Установлено, что при определенных условиях в разных веществах образуются структуры, которые имеют правильные геометрические формы. Эти формы имеют разные названия: отдельность, блочность, негативные кристаллы и другие. Автором в конце прошлого века предложено их называть квазикристаллами. Эти структуры формируются в горных породах, минералах, живых организмах, искусственных веществах. Формирование квазикристаллов является следствием перехода вещества на более низкий энергетический уровень, подобно кристаллизации. Избыточная энергия, полученная извне, реализуется в формирование своеобразной квазиструктуры (подобие дальнего порядка) в горных породах, минералах, минералоидах. Процесс упорядочивания структуры вещества под действием изменяющихся термодинамических условий характеризуется уменьшением энтропии. Указанный процесс часто именуется разными терминами: синергетикой, самоорганизацией, структурированием. Сделан вывод о том, что указанное свойство является переходной формой между кристаллическим и аморфным состоянием вещества.

Научная новизна и практическая значимость. Исследование нового свойства имеет как научное значение – определение закономерностей формирования квазикристаллов в различных минералах, рудах и нерудных полезных ископаемых, так и прикладное значение – прогнозирование нарушенных зон в углях, на границах блоков разных масштабных уровней, приуроченность к этим зонам повышенной рудоносности (особенно в узлах – местах пересечения зон трещиноватости), влияние указанных зон и условий формирования в них квазикристаллов на способы отработки и последующеее обогащениее полезных ископаемых. Структурирование вещества и формирование квазикристаллов – эта два взаимосвязанных процесса, отражающих условия образования и преобразования горной породы и вмещаемых минералов.

Ключевые слова: *квазикристаллы, структура, породы, минералы, энтропия, деструкция, структурирование*

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