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Recrystallization: A Stage of Rock Formation and Development

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1. Introduction

The goal of the paper is to show the place and mechanism of recrystallization in the complicated and long-term rock evolution. Theoretical preamble to the study, research methods and their results are discussed.

2. Theoretical recrystallization process model

The rock, like any complex system undergoes several significant stages during its development. To each stage of development in time corresponds its own physiographic expression. Let us recall that rock physiography depends on its texture and structure, i.e., relative amount of minerals in the rock, relative and absolute size of mineral grains, their mutual arrangement, orientation and distribution in space. All of these characteristics describe the structure of mineral aggregate (including rock).

We call development stages of mineral individua and aggregates as stages of their ontogenetic development by analogy with the evolution of biological organisms: initiation, growth, and destruction. Inherently, the transition from one stage to another cannot be gradual or smooth. There must be an interval fixed in time between these stages. There are large taxa of rock evolution: effusive, vein, intrusive, orthometamorphic... Rate and duration of crystallization and the formation of magmatic and metamorphic bodies are key evolution factors in this series. Continuing parallels with biological evolution, it is possible to assume that this series corresponds to rocks phylogenesis within one family. Then, for example, basalt - dolerite - gabbro constitute one series of basic rock evolution (phylogenesis). In gabbro mass, there are always mineral aggregate areas that correspond to the processes of late- or post-magmatic alteration, which result in the emergence of new textural and structural relationships in the mineral aggregate. One can observe different development stages of one mineral aggregate. This is our understanding of the difference between ontogenesis and phylogenesis as applied to the rocks.

Rock alterations during its evolution can be recorded at different levels of organization - isotopic, geochemical, mineral. Changes in a mineral aggregate or a real rock that correspond to a certain stage of its development, correspond to the stage of its ontogenesis. Mineral level of investigation taken by the authors assumes that the rock can be polymineral or monomineral, but it is always polycrystalline natural formation, natural mineral aggregate (volcanic glass in this case is not considered). Mineral crystals are formed and exist under conditions of an assembly, collective growth and functioning.

In magmatic rocks, owing to specific character of the crystallization substrate, its dynamic properties and the volume of the crystallization, kinetic characteristics of crystal formation are inconsistent in time. Mineral crystallization takes place under different conditions. This affects the morphology of resulting crystals, their intergrowths and spatial distribution. Usually, mineral crystals in the rock are called “grains”. In metamorphic rocks, all transformations proceed in solid state. Dynamic geological conditions associated with new processes cause changes in the structure and composition of mineral aggregates. In magmatic rock, the rate of mineralization reactions and, consequently, crystal growth usually decreases from first portions of the crystallization to last ones. In metamorphic rocks, kinetic inversions in process parameters are possible both towards the increase in the mineral formation rate and towards the decrease. It is reflected in the increase in the mineral grain intergrowth boundaries area, i.e., the roughness of the boundaries increases. Then the process can follow different scenarios. One of them is the granulation of mineral grains, decrease in their size. Another way of system development is the formation of new grains in the area of inequilibrium boundaries intergrowth. This phenomenon is known to material scientists as “mechanical hardening”. The formation of new generation individua that absorb “excess” local energy. With another set of circumstances, the totality of energy loading may be beyond the elastic and plastic deformation of the crystal assembly that can result in brittle deformation of solid bodies. One of the thermodynamic process scenarios after the selection of the way of development by the system is its “straightening” in the course of time. The mineral aggregate is adapted to this choice of the system by the flattening of its internal boundaries, i.e., migration of individual sections of the boundaries to a plane parallel to the plane crystal structure grid, which energy corresponds to local potential of the mineral aggregate system in the intergrowth boundary area at the given stage of its development.

Rock physiography in the accepted hierarchy of consideration is a mineral sublevel created by morphology of mineral grains or boundaries of their intergrowth. Mineral individua or grains exist within internal boundaries of a mineral aggregate and differ from one other in different internal structure: some grains are zonal, others contain mineral and/or fluid inclusions, low-angle misorientation of individual blocks of the crystal lattice, etc. Using biological terms, it is possible to say that grains of one mineral in the mineral aggregate can be of different anatomy. It is clear that different anatomy of mineral individua is due to different conditions of their formation, including growth and dissolution in different kinetic regimes.

Changes in the texture and structure of mineral aggregate, as well as the coexistence of mineral grains with different internal structure, are closely related to changing geological conditions of their formation and existence. The “geological conditions” are some external (with respect to the aggregate) physical fields, their energy, forces and orientation such as areas of tectonic stress but occurring within elastic deformation of minerals and rocks, the area of heating from fluid flows located and crystallized near magmatic bodies, etc. If external fields of force are changed, the internal energy of the mineral aggregate must come into compliance with the external energy. In the balancing process, the structure of the mineral aggregate adapts the whole system of mineral grains (mineral aggregate) to new conditions. The adaptation of the assembly of grains is due to the adaptation of the framework of their boundaries, by changing the composition and energy of the boundaries, i.e. by changing the orientation and the area of mineral grain intergrowth boundaries in the aggregate, by changing intergrowth matrix. It is necessary to remind here that the internal energy of the grain assembly consists of the energy of crystal lattices of mineral individua and the energy of mineral grain intergrowth boundaries. Also, we would like to remind that in the massive mineral aggregate, individuum intergrowth boundaries are boundaries of the individua, i.e., as a whole, they comprise the morphology of each mineral individuum and the framework of internal boundaries of mineral individuum aggregate.

One of initial processes of the framework adaptation of aggregate internal boundaries to the changed conditions is its recrystallization, sometimes accumulative recrystallization. In Russian geological literature, it is common practice to call the process of changing the size and shape of mineral grains in the solid state the recrystallization, but there are two types of recrystallization – one with decrease in the size of mineral individua (it is called *recrystallization*) and another with increase in the medium-sized grains (in Russian literature "perecristallizatsia" or *"overcrystallization"*). We would like to repeat that the grain boundaries migration changes the texture of the mineral aggregate. The accumulative recrystallization controls the structure of the mineral aggregate. The mineral individuum boundaries change the orientation relative to the crystal lattice of mineral grain and possibly in space, taking the position that provides them with such an amount of stored energy that can save the grains under new geological, i.e., thermodynamic and kinetic conditions.

However the grain boundaries migration to a stable state under new conditions requires an initial impulse to overcome stable nonequilibrium. A heat flow from approaching or crystallizing intrusion or a fluid flow either an energy flow of tectonic nature can serve as such an impulse. Not only a new compression or stress can be such an impulse, but the decompression as well. In this case, the system of mineral individua adapts to new growth conditions of individuum well-oriented in a new field of force, or the process of accumulative recrystallization. The authors believe that good orientation of the mineral individuum in the field of force is when an individuum occupies a position when the most stable, i.e., the most atomically dense mineral individuum face occurs normally towards the acting stress. Probably, the schistose structure of mica schist forms in such a manner. It is quite possible that this phenomenon is the cause of gneissose structure. It is not inconceivable that that the interaction of external fields of force and aggregate mineral grains hinders the realization of the described scenario. Then the aggregate adaptation will involve the accumulative recrystallization process. Grains of one mineral form glomero-grained clusters, i.e., subaggregates consisting of grains of one mineral. But there were cases when generated monomineral subaggregates formed rather stable distinct boundary between the subaggregate and grain matrix in the aggregate. The monomineral subaggregate attains crystal-like morphology, i.e., a shape when part of its boundaries with mineral aggregate look like simple forms inherent in this mineral. The process of levelling, balancing of intergrowth energy of mineral individua (recrystallization) continues inside the subaggregate. (Fig. 1, 2, 3)

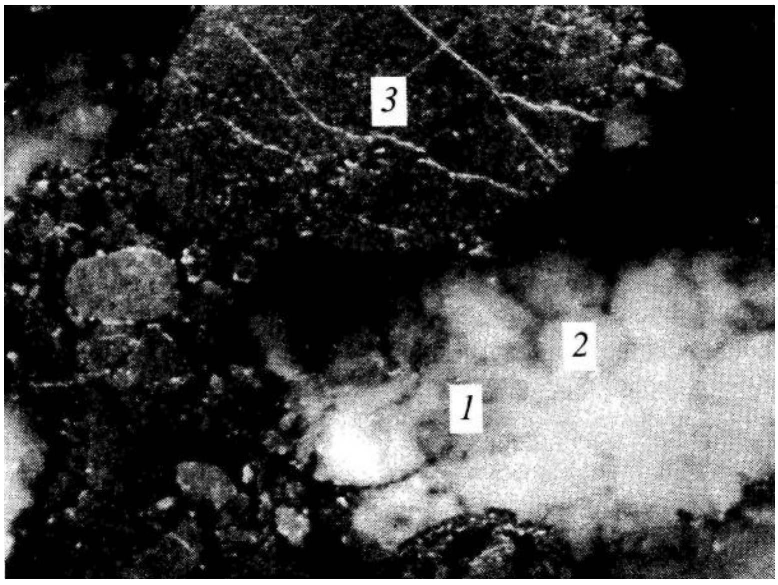

Fig. 1. Fragment of conglomerate from Carbon–Lider ridge. 1- quartz pebble; formation stage of inner boundaries of subaggregate, which is relevant to grain faces - attractor(2); 3 – pebble of pyrite grain. 1.5x.

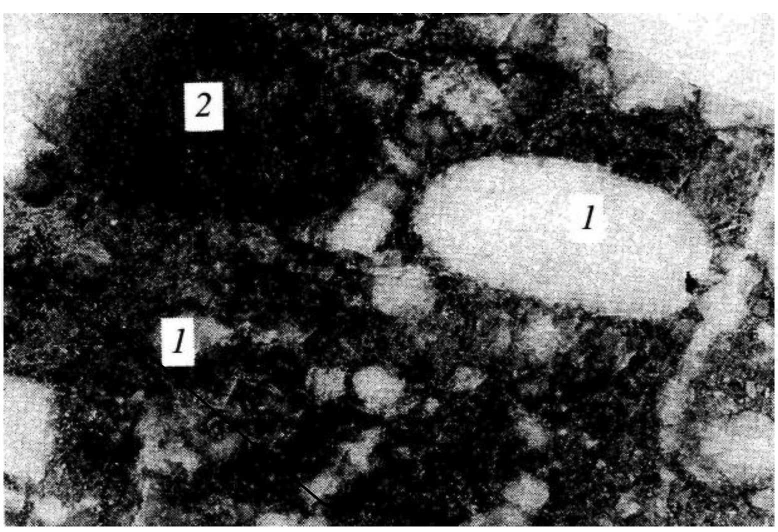

Fig. 2. Fragment of conglomerate from Ventersdop ridge. 1 – pebble of quartz of 1 kind; 2 – quartz pebble of 2 kind (amoebic contours, in the center quartz are free from inclusions, chlorite micrograins paint margin to dark-green color). White points on the right – accumulation of fine grained pyrite. Gray angular segregations are phyllite. 1.2x.

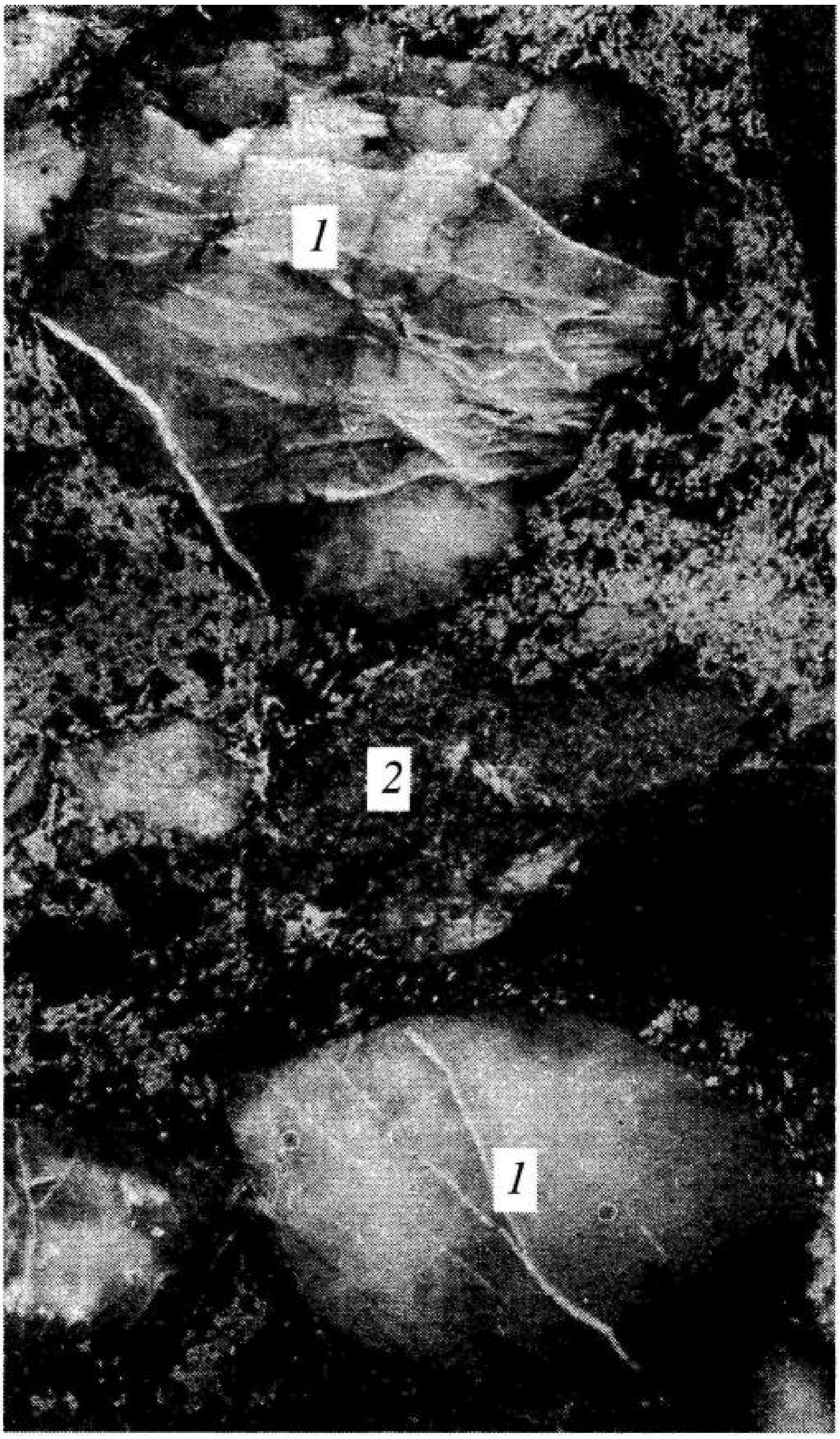

Fig. 3. Fragment of conglomerate from Carbon–Lider ridge. Cataclastic quartz pebble of 1 kind; 2 – pebble of third kind, composition and color is similar to basic matrix. White mass around pebble – aggregate of pyrite. 1,5x.

External flow or the initial impulse induces the energy flow from each mineral grain. This is the energy of edge dislocation of mineral individuum, energy of its boundaries. Energy of dislocations and defects in the crystal lattice of each mineral individuum is involved in the general flow. Thus, the stable equilibrium becomes unstable. Trace elements located in defects and dislocations migrate from their places together with induced energy flow. The flow is directed towards the edge dislocation of mineral grain – its boundary. This energy and its flows provide the grain distillation from trace elements, mineral and fluid inclusions, subboundaries – low-angle boundaries within the crystal lattice (e.g., subboundaries between blocks of cloud extinction in quartz, "loops" and "oblique walls" in olivine). When the impulse energy is sufficient, the process of solid solution disintegration is being formed. Many minerals represent such solid solutions of one mineral in another one. The process of solid solution decomposition results in the appearance of specific, easily recognizable decomposition structure (Fig. 4 (a, b). This is a new instability, which activates migration of subboundaries within the grain. It's possible to indentify by means of displacement character of subboundaries and stimulated movement forces two types of recrystallization - rotational and migrational (Fig. 5,6). This is the way of changing the anatomy of mineral individua; this is the way of replenishing the impulsive force energy for the formation of new mineral grain boundaries. Accumulative overcrystallization within the grain, i.e., the aggregation of micro- and nano-individua clusters takes place simultaneously with the migration of boundaries. Trace elements and newly formed mineral phases are "squeezed-out" to grain boundaries to generate their own mineral form with its own boundaries. This is the mechanism of overcrystallization and mineral formation at grain boundaries in the solid state (Fig.7).

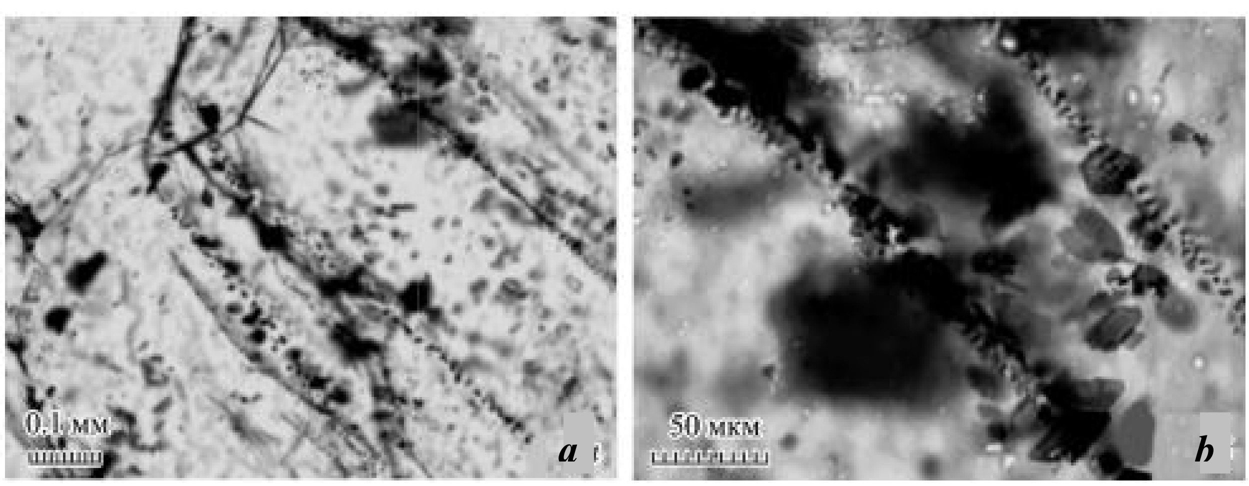

Fig. 4. (a,b) Structures of the solid solutions decomposition in olivine; the newly formed phase is chrome spinelide. Dunite, Gulinsky massif; photographs in transparent light, without analyzer

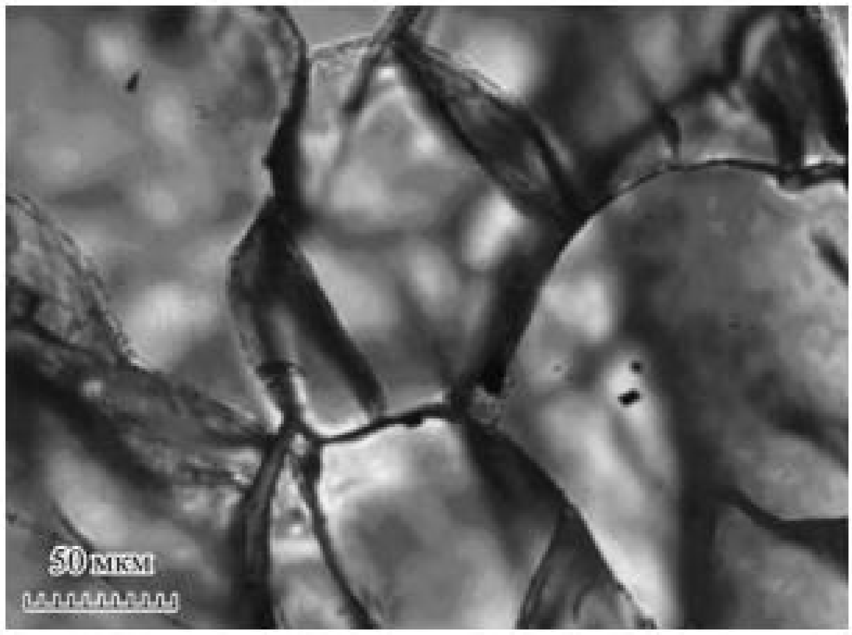

Fig. 5. Rotational recrystallization of the olivine aggregate from dunite of Gulinsky massif; photograph in transparent light, with analyzer.

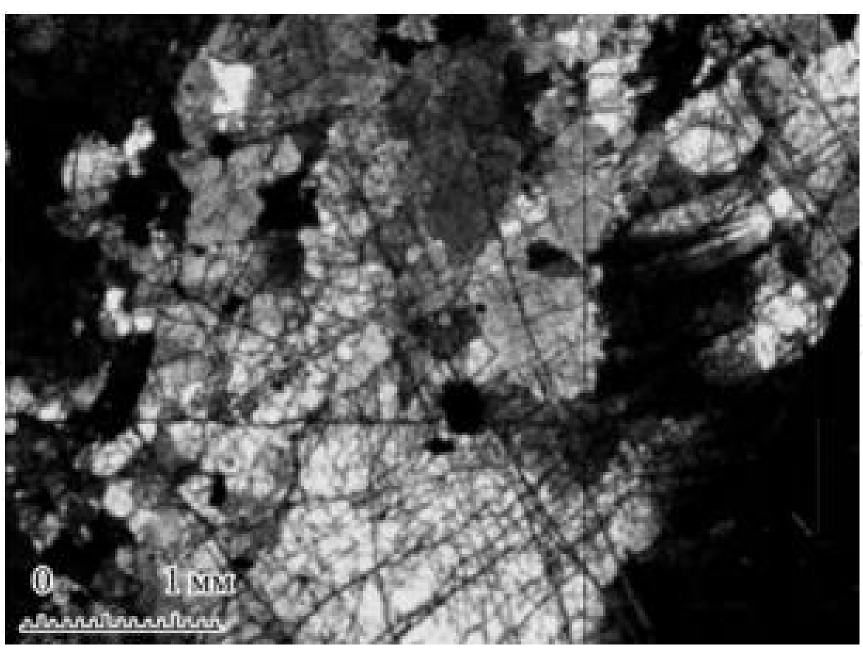

Fig. 6. Migrational recrystallization of the olivine aggregate from dunite of Galmoenansky massif; photograph in transparent light, with analyzer.

The surface energy of mineral grain edge dislocations and the boundaries of their intergrowth in the aggregate is, as already mentioned, an instrument in the mechanism of balancing between the internal energy of the aggregate and the external energy of the field of force under changing geological conditions. The amount of the mineral grain surface energy consists of the edge dislocation energy of the crystal lattice of mineral individuum and the presence of some admixtures, i.e., first of all, depends on the orientation of the boundary (edge dislocation) relative to the individuum crystal lattice (Fig. 8 (a, b, c). However, main role in boundary migration is traditionally given to the specific energy of the surface area rather than to the surface energy.

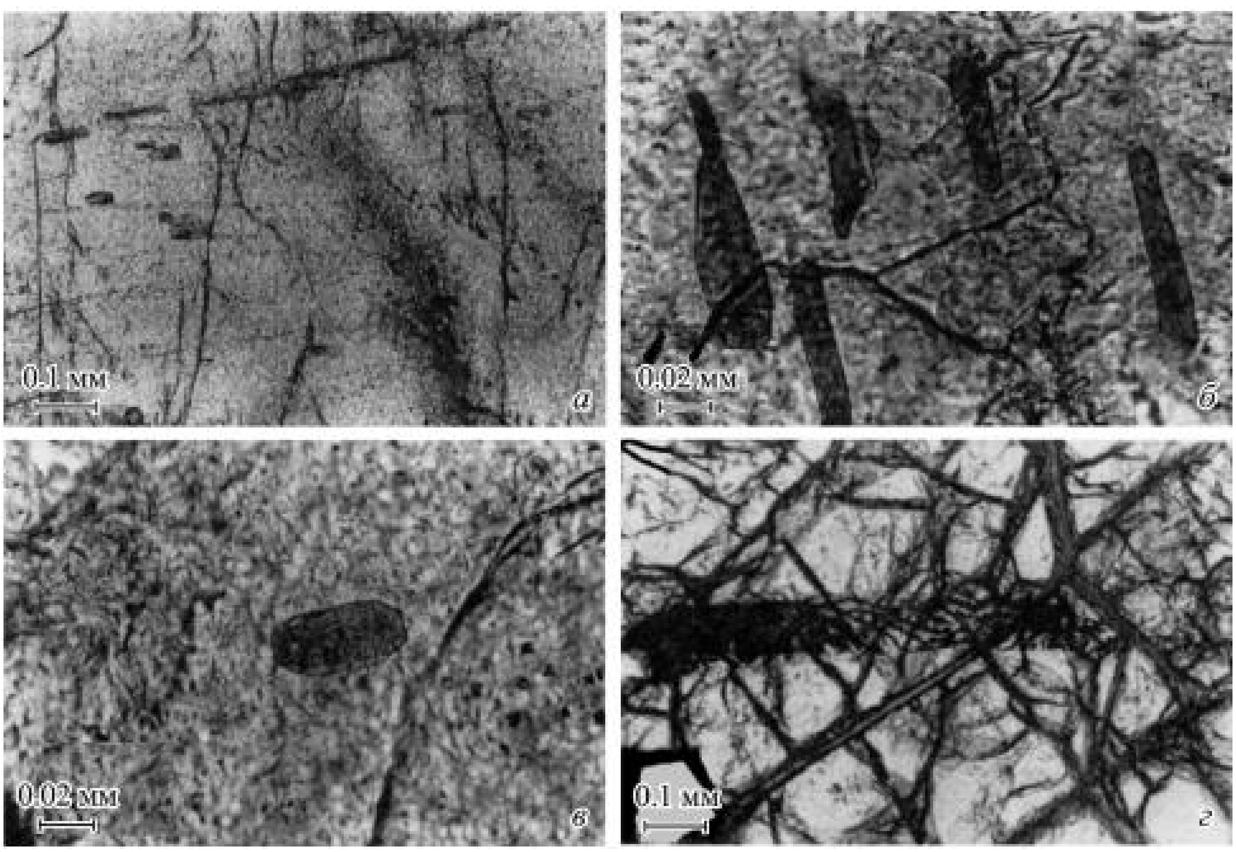

Fig. 7. Forming of new minerals in deformational substructures of olivine (Arai Shoji, 1978). Photographed with different magnifications in transparent light

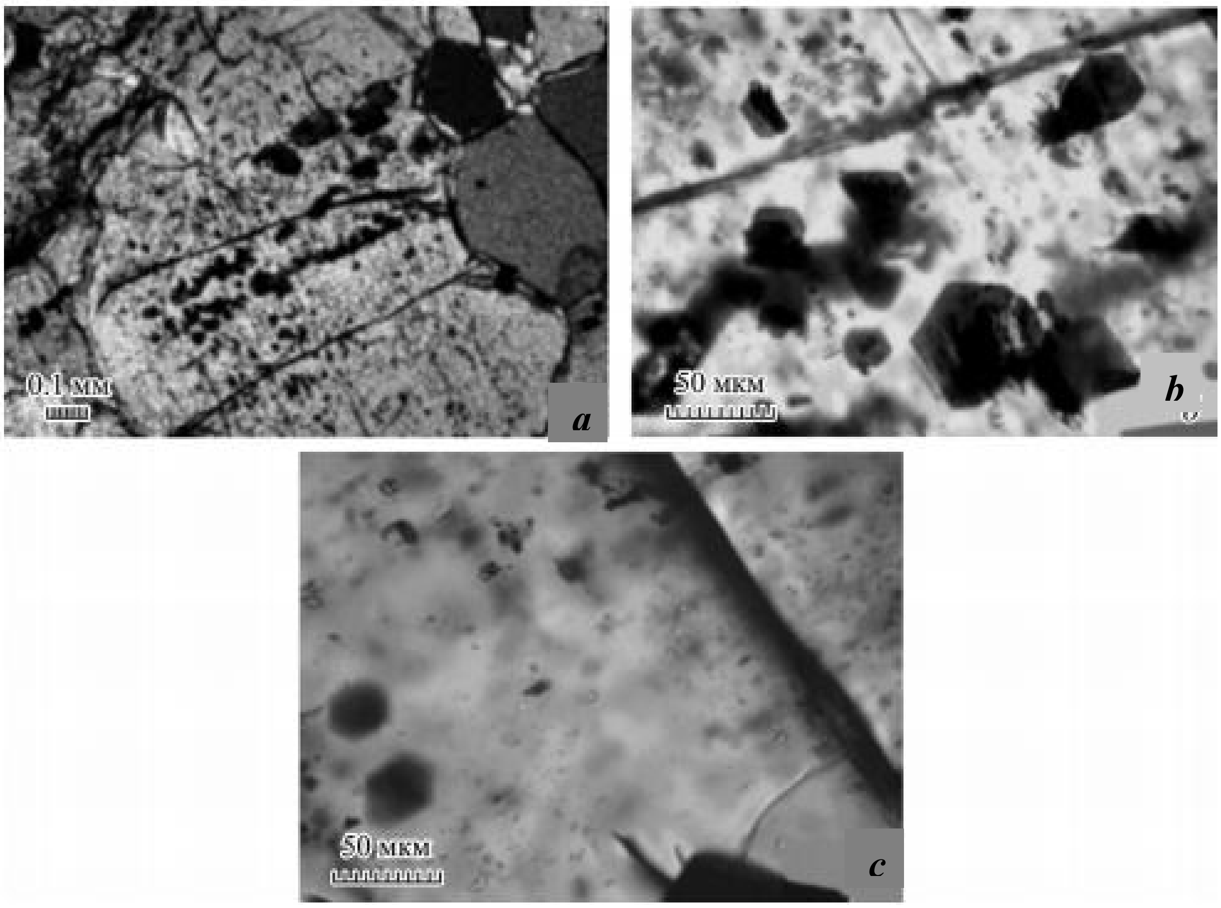

Fig. 8. (a, b, c). Regularly oriented lamellae of chrome spinelide and the skeleton inclusions of spinel in the olivine grain. Dunite, Gulinsky massif; photographs in transparent light, without analyzer, in different thin sections

Increase in some components of the external field of force (stress, lithostatic pressure, fluid flow pressure, heat flow) results in the increase in the amount and energy of internal boundaries of mineral aggregate. This process inspires the increase in the boundary density in the mineral aggregate space as well as the specific surface energy. The decrease in the external energy flow necessitates the decrease in the internal energy of the mineral aggregate. To this change in external geological conditions the aggregate is adapted due to the decrease in the surface energy of mineral individua. In the first case (increase in the field of force) porphyraceous structures form, in the second - monomineral subaggregates. The selection of the development path system depends on the necessity to decrease the internal energy. This is possible owing to increase in the area of mineral individuum boundaries and decrease in its specific surface energy. This is also possible due to the decrease in the grain intergrowth energy of one mineral. In polymineral aggregate, the least amount of the energy is absorbed by intergrowth boundaries of one mineral.

At grain boundaries of one mineral, the intergrowth energy is lower than in intergrowths of different minerals. Most likely, just the "energy benefit" is the motivation of the accumulative recrystallization that covers vast mineral aggregate spaces. This is the way of formation of glomo-grained subaggregates within the massif aggregate matrix with regular grain distribution of all the minerals. Which mineral in the "struggle for survival" will decrease or increase the density of its boundaries depends on marginal conditions of existence of this or that mineral in the aggregate. It is quite possible that material supply into the crystallization system can result in the generation of such conditions (Fig. 9).

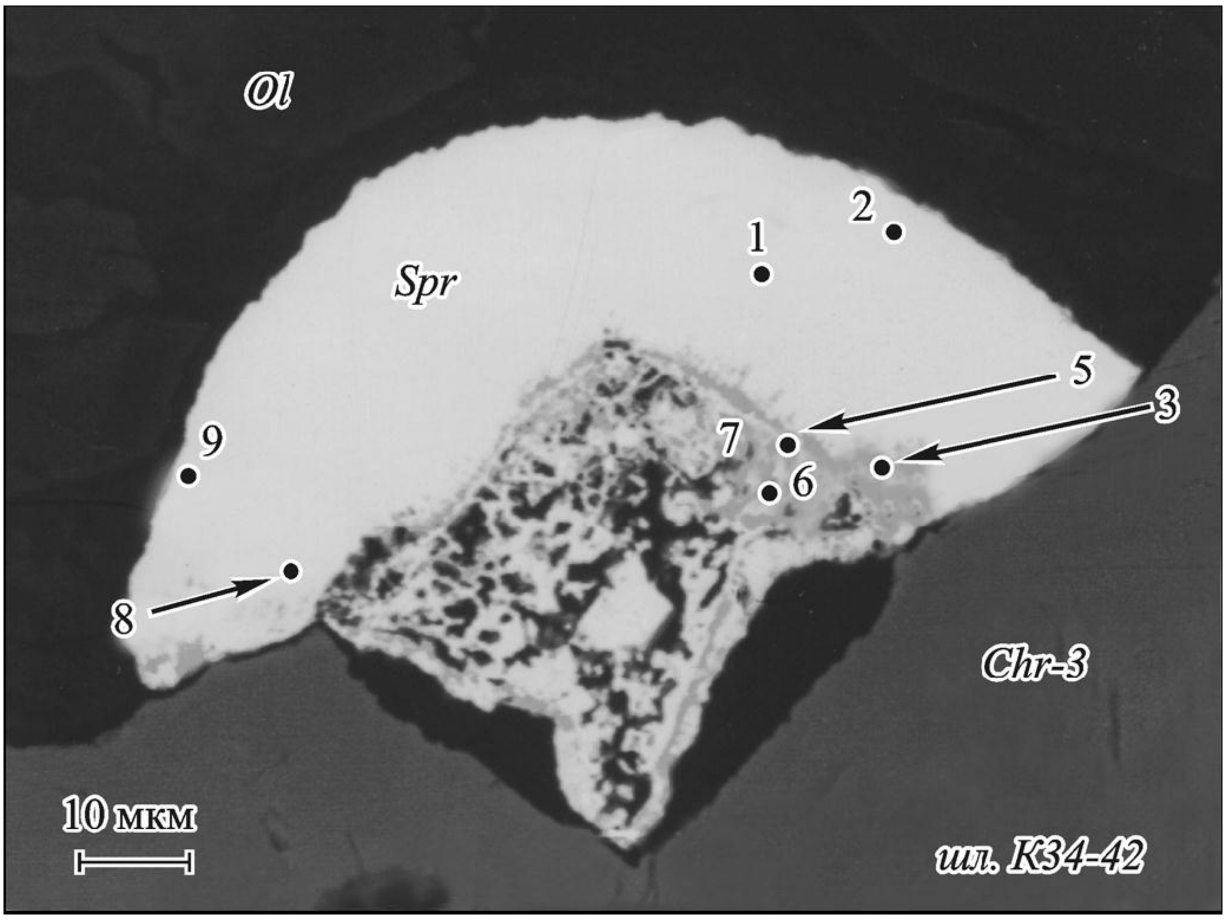

Fig. 9. Subaggregate of grains of platinum and iridium arsenides at the boundary of intergrowth with subaggregates of the third generation chromite (*Chr-3*) and olivine; numbers of points correspond to microprobe analyses: *1*, *2*, *8*, *9*—sperrylite, *5*, *6*—raresite (transparent polished section K-34-42); electron microscope.

The character of subaggregate boundaries is an important kinetic feature of the occurring processes. It may be flat or irregular to variable degrees. Under some conditions, the migration of grain boundaries results in their straightening and integration into intergrowths, i.e., increase in the grain volume.

Studying the energy models of internal boundaries relationship in the mineral aggregate shows that changed position of mineral individuum intergrowth boundaries or recrystallization is a response of the mineral grain assembly to new geological conditions under which the mineral aggregate occurs. Main tool of aggregate adaptation to new conditions is the migration of individuum intergrowth boundaries to such a position in space and relative to the crystal lattice of each of the intergrown grains that ensures its stability in the field of changing force and energy. It is quite possible that not all boundaries and not all minerals have to migrate when they change their orientation in space. Thus, atomically dense boundaries, i.e., simple-shape faces are the most stable mineral individuum boundaries. Boundaries of mineral grains, which in crystallographic coordinates have sufficiently high symbols, i.e., have relatively low store energy, are capable of migration in the aggregate space. It is natural that the boundary migration is possible until they reach equilibrium state with one another. But other situations are also possible. For example, if recrystallization accompanies metasomatosis with additional supply of some material. In this case, growth of this material from new crystallization centers is possible either the growth due to the increase in mineral individuum volume if its composition corresponds to that of the supplied material. Porphyroblast growth is possible when supplied material flow rates are rather high.

3. Mineral aggregate ontogenesis and physiography

Earlier it was said that the necessity to decrease the internal energy of mineral aggregate during its adaptation to the external energy (e.g., while decompression) results in the change of the structure of the mineral grain assembly – accumulative recrystallization. Probably the spotty structure of phyllite slate is a result of this process. Quartz grains are accumulated into such glomero-grained subaggregates characterized by irregular distribution and rather variable volume in the rock space. High rate of changes in external conditions can result at some stage or other in the arrangement of a boundary between a monomineral glomero-grained unit and aggregate matrix. In this case, the external boundary is formed by the combination of identical boundaries of mineral grains located at edges of glomero-grained bundles. Individuum boundaries usually correspond to a simply-shaped face of this mineral with relatively high stability factor under given kinetic conditions. The authors came to this conclusion while studying texture of the so-called quartz pebbles in auriferous reefs of Witwatersrand. Macroscopic investigations of samples from conglomerate outcrops of the Carbon Leader and Ventersdorp reefs, suggest the similarity of the morphology of "pebbles" and that of quartz crystals due to the presence of surfaces in the pebble that resemble prism face. Thin sections were made of several quartz "pebbles", which had in their faceting external prism "faces". In the quartz grain subaggregate, microscopic investigations revealed the presence of sections, which boundaries were similar to those of external morphology of the pebbles. The authors interpreted this fact as an existence of a grain-attractor within quartz individuum subaggregate. It is just these boundaries are the most stable for quartz, and therefore most beneficial for the conservation of quartz subaggregate in the regime of unstable parameters of changes in geological conditions, which also imply thermodynamic ones. Most likely, this is the alternation of compression and decompression in the course of compression and extension of host rocks during hydration and dehydration of intergranular space of mineral aggregate. Occurrence of hydrofilms in the mineral aggregate not only increases the plasticity of the rock as a whole, but also helps to increase the resistance of mineral individua to elastic and plastic deformations. Under certain conditions, such quartz monomineral subaggregates can be transformed into blastoporphyric quartz "crystals" if quartz individua will be able to adapt to each other not only by boundaries of appropriate density, but also due to coherent orientation of crystal lattices of porphyroblasts. Such examples are recorded not only in Witwatersrand, but also among porphyraceous dunite aggregates of the Inagli, Galmoenan massifs. It is interesting that in these cases, grains-attractors with orientation and morphology of the subaggregate are also observed inside olivine subaggregates.

4. General procedure of quantitative ontogenetic analysis

Stereometric analysis of rocks and ores made in thin sections and polished sections was the main method of implementing the above mentioned ideas. Quantitative assessment of the parameters of the structure allows the estimation of the recrystallization degree of the aggregate and mineral individua. Structural characteristics become parameters of the texture and structure because of the application of crystallographic and topological methods of analysis. Anatomy, i.e., internal structure of mineral individua also has its quantitative measure. Density of subboundaries, density of fluid and mineral inclusions and other features of refining mineral individua during recrystallization are estimated here.

This research trend (quantitative ontogenetic analysis) allows unbiased assessment of the stage of mineral aggregate evolution by distinguishing individual generations and paragenetic (simultaneous) associations of mineral generations. Not only is the history of mineral aggregate restored, but a place of mineralization in ontogenesis as well.

Thus, the main method of mineral aggregate structure interpretation is the ontogenetic analysis of the mineral aggregate and its individua. Main method of implementation of the expressed ideas is stereometric analysis of rocks and ores. A procedure of studies using polished sections and thin sections was elaborated. A representative area is necessary to obtain metric assessment of the mineral aggregate structure under the microscope. Standard area of thin sections is used, but the design of the integration device MIU-5M allows analysis of thin sections with an area of no more than 40×40 mm. Analysis sensitivity is not worse then 4 μm. It means that using scanning table, it is possible to get grid coordinates of points occurring within the specimen plane spaced at a distance of 8-10 μm from one another. Quantitative measure of fabric parameters allows evaluation of degree of recrystallization of the aggregate and mineral individua. Structural characteristics become texture/structure parameters due to simultaneous employment of well-known crystal-optic, crystallographic, geometric, and topologic analytical methods. Anatomy of mineral individua has quantitative measure. Following features are estimated here: subboundary density within mineral grain, density of fluid and minerals inclusions and other features both residual, primary, and refinement features of mineral individuum anatomy while recrystallization. Roughness of intergrowth boundaries of all mineral grains or grains of one mineral in the aggregate either grains of individual mineral generations can be changed and calculated using several methods.

Such parameters of mineral aggregate fabric as total area of internal boundaries of mineral aggregate, modal portion of individuum boundaries of each mineral, modal and normative granulometric compositions, character of mineral grain distribution in aggregate or frequency index of individuum intergrowth of one mineral with grains of other minerals, etc. are measured simultaneously while scanning a specimen (thin section or polished section). These are the so called integral characteristics of rock structure. Frequency characteristics of mineral grain boundaries can be obtained in the course of their analysis using the device of fractal dimensions or Fourier harmonic decomposition. All quantitative characteristics and fabric parameters necessary for ontogenetic analysis of mineral aggregates are real functional capabilities of the Mineralogical Integration Device (MIU-5M in Russian). The elaborated procedure enables to get and use 22 fabric parameters or part of them in any combination and amount.

This trend of studying rocks and ores can be named quantitative ontogenetic analysis. Its use in investigating thin sections and polished sections allows unbiased assessment of stage of mineral aggregate evolution and identify separate generations and paragenetic (simultaneous) associations of mineral generations. Not only the history of the mineral aggregate, but also a place of mineralization in the ontogeny is reconstructed in the transformations sequence of mineral individua assembly.

5. Conclusions

We discussed the recrystallization process in a mineral aggregate as a migration process of mineral individuum boundaries, mineral grain intergrowth boundaries, as the process of changes in the framework of internal boundaries of the aggregate. Migration reasons were formulated as a mechanism of mineral aggregate adaptation to changed (as compared to initial conditions of formation) geological conditions of rock existence. On the way of aggregate adaptation to changing geological conditions, the recrystallization, similar to accumulative recrystallization, is possible at all levels of mineral matter existence.

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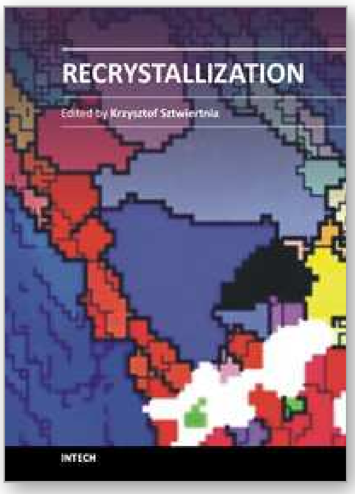

Recrystallization
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Recrystallization shows selected results obtained during the last few years by scientists who work on recrystallization-related issues. These scientists offer their knowledge from the perspective of a range of scientific disciplines, such as geology and metallurgy. The authors emphasize that the progress in this particular field of science is possible today thanks to the coordinated action of many research groups that work in materials science, chemistry, physics, geology, and other sciences. Thus, it is possible to perform a comprehensive analysis of the scientific problem. The analysis starts from the selection of appropriate techniques and methods of characterization. It is then combined with the development of new tools in diagnostics, and it ends with modeling of phenomena.