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TYPOMORPHIC CHARACTERISTICS OF APATITE MORPHOLOGY OF CAR-BONATE-BEARING VARIATIONS OF COMPLEX ORES IN THE CONTEXT OF KOVDOR DEPOSIT

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ABSTRACT

Purpose. A comprehensive analysis of apatite morphology in carbonate-bearing variations of complex ores in the context of Kovdor deposit as an important typomorphic characteristic of a mineral being of high genetic and applied informativeness.

Methods. The research relies upon ontogenetic approach to analyze typomorphic characteristics of the apatite deposit. Possibilities of both traditional and raster electronic microscopy have been used. Elements of internal morphology were studied using structural etching and compounds with immersion liquid. Typomineralogical observations have helped record peculiarities of spatial variability of the morphological characters.

Findings. The development of an oblong ellipsoidal grain patterns with 0.16 – 0.20 mm prevailing size is the key morphological characteristic of the majority of apatite individua within carbonate-bearing ores. Internal morphology (i.e. anatomical representation) is characterized by the pronounced block structure. Formation of apatite liberation from carbon-bearing groundmass depends upon frontal dissipation of previously developed polyhedral grains of apatite II under the effect of aggressive carbonate fusions-solutions. Surface areas, corresponding to prism planes, experience the most active fuse. Apatite liberation from carbonate ores is characterized by a specific smooth surface in the form of complex combination of flat and riblike face fusion elements. Within the “abnormal” zone of carbonatite core, small apatite individua differ in clear sharp contours, and absolutely even surface of cutting planes which can be explained by gradual intensification of surface defects of the mineral surface as a source of fusion layers at the subsequent carbonization stages.

Originality. Morphological features of apatite from Kovdor deposit are characterized by the pronounced typomorphism being the sensitive indicator of evolution of mineral genesis system. It has been identified that formation of apatite typomorphic characteristics depends upon manifestation activity of carbonization within primary ores which achieves its maximum in an “abnormal” zone of carbonatite core.

Practical implications. The results are interesting from the viewpoint of prognostic and prospecting informativeness, solving engineering problems, and rational mining and homogenizing of apatite-bearing ores before their delivery to a preparation plant. The information is recommended to be used to optimize prospect and evaluation of comparable objects connected with Ukrainian carbonatite complexes.

Keywords: *Kovdor deposit, complex ore, carbonatites, phosphorites, apatite, ontogeny, typomorphism*

1. INTRODUCTION

Kovdor deposit of complex magnetite-apatite-baddeleyite ores is confined to a cognominal formation of ultrabasic alkali rocks and carbonatites located south-west of Kola Peninsula at the distance of 30 km from Finland frontier. Kovdor Mining and Processing Plant Ltd (Kovdor MPP), integrated currently in EvroKhim Group, is engaged in the deposit development. Open cast mining is applied in Zheleznyy ore mine. In accordance with the project, reserves of the rock mass, being extracted, is 190 Mt. Prospective resources for the scheduled superdeep (more than 800 m) are considered to be 590 Mt. In future, underground ore mining is planned (Zhirov, Klimov, & Melikhova, 2014).

Activities of the industrial complex are unique even for the world practices since it implements sequential processing chain to produce magnetite, apatite, and baddeleyite concentrates. Currently, the Kovdor MPP is the second Russian manufacturer of apatite concentrate, and the only world manufacturer of baddeleyite concentrate. Apatite concentrate by Kovdor MPP is used to produce the defluorinated feed phosphates and nitrophoska. The Company markets its product in the Russian Federation, Czech Republic, Slovakia, Poland, Japan, the USA, and Europe (Bloomberg, 2019; Mining Atlas, 2019).

Such well-known papers as (Kukharenko et al., 1965; Rimskaya-Korsakova & Krasnova, 2002; Krasnova, Balaganskaya, & Garcia, 2004; Afanas'yev, 2011; Zaitsev et al., 2015) represent rather sufficiently various geological, petrographic, mineralogical, and genetic aspects of the deposit. Kovdor complex is within the tectonically weakened zone on the contact of ijolite and pyroxenite series. Morphologically, the ore body combines two unequal areas. Larger southern area (800×200 m) is of oval shape; it is connected with circular fault array. Northern area (200×500 m) is elongated submeridionally which depends upon its confinedness to a system of linear faults (Fig. 1).

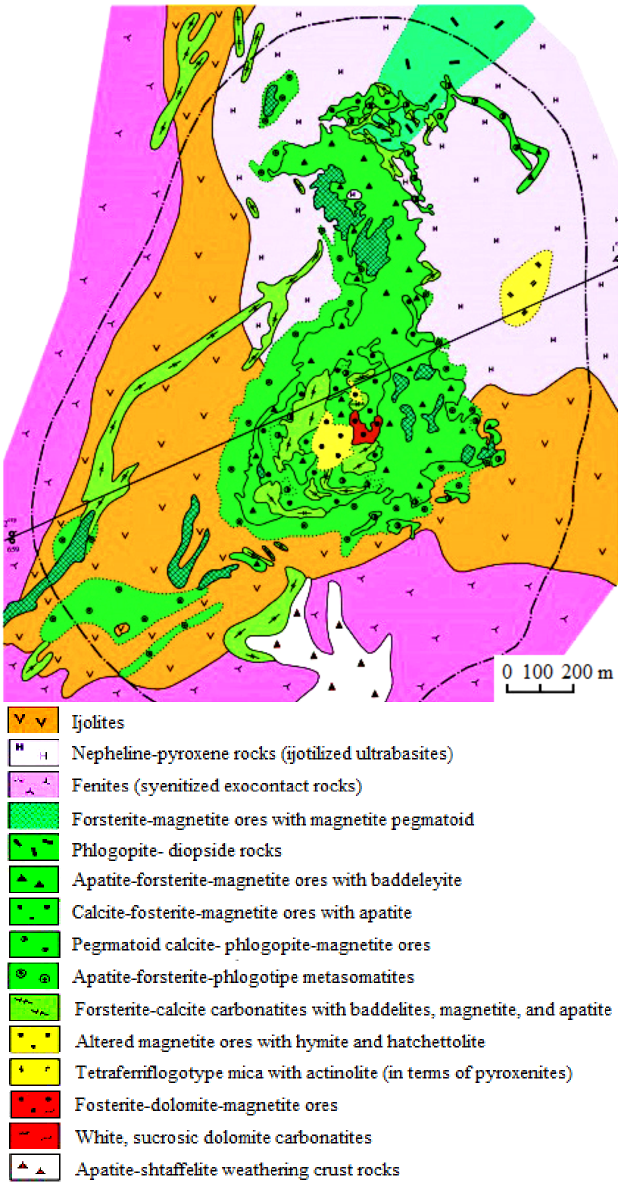


Figure 1. Schematic map of geological structure of Kovdor complex deposit (Afanas'yev, 2011)

The deposit structure shows gradual periphery-centre alternation from foskorite rocks, differing in content (apatite, fosterite, and magnetite are basic minerals), to typical ore carbonatites (i.e. soevites and later bephorsites). Carbonatites core is fixed with the help of a system of ring faults. The core has been formed at a final stage of the ore complex establishing. It is connected with the intrusion of carbonatite fuse-solution which has changed cardinally the initial foskorite rocks. The deposit zonality reflects single spatial and time series of evolution of mineral forming processes (i.e. complex combination of ultrabasic magmatism and gradual metasomatic phenomena in the form of apatitization and carbonization) which variety has stipulated the composition diversity, structural and textural characteristics of ores and rocks as well as variability of the form, type, and characteristics of metal forming minerals. "Abnormal" zone with rare-metal mineralization (pyrochlore, hatchettolite, and zirkelite) is registered within the carbonatite core. The zone forms two ore bodies which total area is more than 20 thousand square meters (Fig. 1).

Together with magnetite and accessory baddelite, apatite is rather important commercial mineral among complex ores. Along with other mineral components, it is the unified and genetically interdependent system. As a subjacent mineral, it is available in ores belonging to each geological and commercial type. Thus, it reflects logically the consequential evolution of mineral forming processes, manifested within the deposit, in terms of the whole range of its characteristics.

The specified distinctive features determine the topicality of the deposit apatite analysis which characteristics are of the pronounced typomorphism. That is important both mineralogically and genetically (i.e. analysis of debateable genetic moments; and determination of effective prospective indicators) as well from engineering viewpoint (i.e. specific apatite behaviour at the stages of ore preparation and floatation).

The authors believe that apatite separation right from carbonate-bearing variations of complex ores of Kovdor deposit is of specific interest. That can be explained by the discovery of Chernihivskyi complex of ultrabasic alkaline rocks and linear type carbonatites in the north-west Pryazovia (Zaporizhzhia Region, Ukraine) in the late 1960s. North block of the complex is connected with the availability of the only Ukrainian Novopoltavske deposit of apatite-bearing carbonatites with the manifestation of rare-metal mineralization. In terms of rock assemblage, mineral components, apatite content, and ore genesis processes, Chernihivskyi complex resembles greatly Kovdor deposit. A number of monographs and publications analyze its geological characteristics (Glevasskiy & Krivdik, 1981; Krivdik, Bezsmolova, & Dubina, 2009; Pogrebnoy, 2013; Shniukov, Lazarieva, Nikanorova, & Morozenko, 2014). To compare with Kovdor deposit, the complex is ready for its development but it has not been under commercial operation yet (Hurskyi et al., 2006). According to the classification by (Hurskyi, 2008), it belongs to "Г" type, i.e. "deposits are not deve-loped and underexplored currently but they may become important strategically for the country economy in the near future". It should be noted that in practice, weathe-ring crust of Novopoltavski carbonatites, represented by apatite-crandallite mineralization, where apatite was accumulated naturally, is of the greater interest (Pogrebnoy, 2013). In addition to Ukrainian Chernihivskyi complex, Proskurov formation of ultrabasic, alkali rocks in the south-western part of Ukrainian shield (Transnistria) is supposed to be promising. However, carbonatite rocks have not been prospected there yet (Shnyukov & Osypenko, 2016).

Currently, fenitization coronae of enclosing rocks are under analysis for the development of potentially productive complex of prognostic and prospecting criteria to explore apatite-bearing deposits of a carbonatite type within the territory of Ukraine. Data concerning material composition, petrography, and structural features are being analyzed; comparison with well known carbonatite deposits inclusive of Kovdor one is being made (Shniukov, Lazarieva, Nikanorova, & Morozenko, 2014; Shnyukov, Lazareva, & Nykanorova, 2015). Constitutional peculiarities of the mineral are being studied (Dubyna, Kryvdik, & Soboliev, 2012; Kalinichenko, Brik, Il'chenko, Kalinichenko, & Kalinichenko, 2018) since it is known that crystal chemistry of apatite is rather sensitive to the parameters of mineral genesis environment (Tacker, 2004; Gornostayev, Walker, Hanski, & Popovchenko, 2004; Tacker, 2008; Fleet, 2014). Nevertheless, at the level of mineral individuum typomorphic characteristics of apatite itself as the research subject are represented insufficiently. In this connection, such apatite observations may become interesting for other, thoroughly studied similar objects.

The paper represents results of the analysis of apatite morphology from carbonate-bearing variations of complex ores of Kovdor deposit. In this context, specific attention is paid to different ontogenic facts. The authors suppose that the methodological approach helps reveal to the fullest extent typomorphic, indicative characteristics of the mineral; and extrapolate the obtained information to analogous objects as an important informative indicator.

2. LITERARY REVIEW

Interest to Kovdor deposit apatite arose in the second half of the 20th century after the ore complex started to be developed in 1962 and when a possibility to manufacture apatite concentrate using magnetic separation tails occurred. Significant activization of the research took place in the late 1970s since in 1975 apatite-baddeleyite plant commenced its operation at the mining and preparation integrated works which involved solution of a number of scientific and applied problems. It became necessary to analyze thoroughly different apatite characteristics, to single out those being principal for preparation and determining the mineral behaviour at the stages of technological conversion of the apatite-bearing complex ores. The authors believe that (Kurbatova, 1974; Rimskaya-Korsakova, Krasnova, & Kopylova, 1979; Gornostayev, Crocket, Mochalov, & Laajoki, 1999; Pirogov & Trunin, 2000; Pirogov, Trunin, & Kholoshin, 2001; Zaitsev et al., 2015; Pirogov, Trunin, & Kholoshin, 2016) are the most relevant papers representing various mine-ralogical aspects of Kovdor ore complex apatite. The papers consider typomorphic, topomineralogical, and generic problems of the apatite as well as problems of its applied mineralogy.

Currently, efforts of researchers are aimed at analysis and generalization of large volumes of factual information accumulated during many years. Among other things, it concerns the development of three-dimensional model of spatial distribution of the basic ore-forming mineral components (Ivanyuk et al., 2016; Kalashnikov et al., 2016; Mikhailova et al., 2018). Such a model makes it possible to represent variability of mineralogical and geochemical indices within the field limit; to perform reasonable perspective and operational planning of mining activities; to optimize charge calculation of geological and commercial ores; and to stabilize qualitative characteristics of the manufactured concentrates. Processing behaviour of apatites, belonging to the ore complex, are still under in-depth analysis (Mikhaylova & Garanichev, 2010) and possibilities to manufacture apatite concentrate, using technogenic waste of complex ore processing, are under consideration (Andronov & Perunkova, 2018). Bodies of calcite carbonatites as well as apatite-francolite ores formed within their weathering core, which mining started in 2015, are of keen scientific interest. The new commercial ore types are localized in the form of an arch-like area within south-west flank of the ore complex inside the open pit actual envelope. The above involves the necessity to analyze actively mineralogical and geochemical characteristic, textural and structural indices, geological structure, and preparability of the ores (Dunaev, 2011; Dunaev & Yanitskiy, 2013; Lapin & Lyagushkin, 2014; Stepanova & Petrov, 2018). As it has been mentioned, similar weathering core with commercial apatite localization is in Chernihivski rock mass (Ukraine) (Pogrebnoy, 2013).

It should mentioned particularly that current science is experiencing significant splash of interest to the study of apatite resulting from rapid progress of innovative schools in tissue engineering, in the development of promising biomimetic nanomaterials, and in the studies of specifics of bone tissue mechanics (Yoder, Pasteris, Krol, Weidner, & Schaeffer, 2012; Deymier et al., 2017; Drouet, 2018; Hiroyuki, Miake, Matsumoto, & Hayakawa, 2018; Yoder, Bollmeyer, Stepien, & Dudrick, 2019).

In spite of the represented numerous publications, the topic of apatite metamorphism of Kovdor deposit is still of current interest owing to the problem manysidedness. Among other things, it is necessary to actualize visualization of morphological nature of granular apatite separation in complex ores inclusive of their carbonate-bearing variations; the correlation between apatites from apatitization zones, and following carbonization needs clarification of certain topomineralogical tendencies within a zone of a carbonatite core. The paper analyzes the problems.

The research purpose is to study thoroughly morphology of apatite within the carbonatite core of Kovdor ore complex, using ontogenic approach, as a key typomorphic mineral characteristic being of great genetic informativity. The authors consider morphology to a wide extent of the property: form of individua and aggregates; internal morphology (i.e. anatomy of individua); surface state; nature of spatial variability of characteristics; and mineralogenetic processes which stipulated the current state of morphological characteristics of apatite.

3. METHODOLOGY

The research continues complex studies of Kovdor deposit apatites which findings are represented in earlier publications (Pirogov & Trunin, 2000; Pirogov, Trunin, & Kholoshin, 2001; Pirogov, Trunin, & Kholoshin, 2016). Unique collection, consisting of more than 500 mineralogical samples, has become material for the research. The samples were selected with a view to the performance of contractual activities by the Department of Mineralogy of Kryvyi Rih Mining Institute (Kryvyi Rih National University now) at Kovdor deposit in the 1980 – 1990 under the supervision of Professor B.I. Pirogov. The samples correspond evenly to the whole outline of the ore complex; moreover, they represent carbonatite core zone.

Methodologically, the research relies upon ontogenetic approach to analyze typomorphic characteristics of the deposit apatite which favours deepening of informativity of the obtained results. The research used possibilities of traditional electronic microscopy and scanning one. Spatial variability of morphological characteristics was registered, i.e. topomineralogical observations were carried out. Apatite monofractions were separated using binocular microscope and gravitational method (i.e. vibrating table). Anatomy of the apatite was analyzed at the polished sections with the help of structural etching by a dilute hydrochloric acid; in terms of separate grains, compounds with immersion liquids were applied.

4. RESULTS AND DISCUSSION

Earlier research studies have helped singled out objectively four basic morphostructural and inherent types of apatite of complex ores alternating each other successively from the deposit periphery to its central part together with various apatite-bearing ores enclosing them (Pirogov & Trunin, 2000; Pirogov, Trunin, & Kholoshin, 2001; Pirogov, Trunin, & Kholoshin, 2016). Fine xenomorphic separations of apatite I (i.e. those which average grain size is 0.10 mm) (Fig. 2a) are represented in apatite-forsterite low-chamoisite ores of the hardened zone bordering the deposit. Relatively large polyhedral individua (up to 1.5 mm when average value is 0.47 mm) of apatite II evolved in the apatitized ores of foskorite composition which are the most developed in the ore body outline (Fig. 2b).

Medium (i.e. when average size is 0.38 mm in terms of elongation) ellipsoidal, columnar grains of apatite III are registered within the carbonatite core zone where carbonate-bearing variations of complex ore dominate; they pass to carbonatite in spots (Fig. 2c and 2d). Individua of apatite IV are separated in so called "abnormal" zone of carbonatite core where rare-metal mineralization is manifested (Fig. 1). Differences between apatite III and apatite IV are determined mainly by means of aggregate of crystalochemical characteristics reflecting specific nature of evolution of physical and chemical parameters of mineralogenetic environment. External difference of the two types of apatites is problematic. Lower granulometric indices of apatite IV within "abnormal" zone should be noted (its average grain size is 0.26 mm).

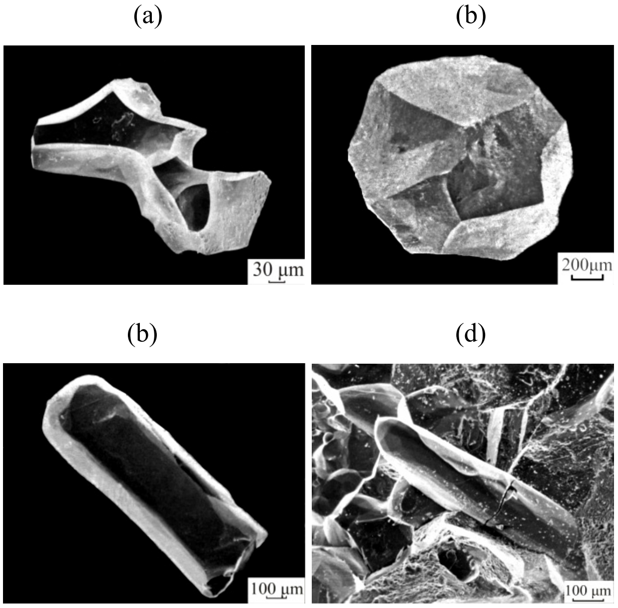


Figure 2. Apatite morphology within the deposit ores. Find explanations in the text. Raster electron MSM-5 microscope

Formation of the carbonatite core complicated critically mineralogical and petrographic characteristics of the deposit ores, and stipulated conceptually new features of the whole range of typomorphic characteristics of orogenetic minerals.

Moreover, it varied significantly morphological and structural apatite characteristics. The development of the elongated grain is the basic morphological feature of the majority of apatite individua within carbonatite assemblage (Fig. 2c and 2d). Crystalline formations of the mineral with habitual appearance features are very rare.

Depending upon elongation value (i.e. length-width ratio within the individua sections), rounded grains (1.00 – 1.39), ellipsoidal grains (1.39 – 2.56), and columnar grains (more than 2.56) are singled out. Among the samples, which have been analyzed, ellipsoidal grains are the major part (62.9%), and columnar grains (20.0%) together with the rounded ones (17.1%) are less common. The mentioned grain forms are available jointly stipulating morphological apatite variety even in the context of one mineralogical sample (Fig. 3).

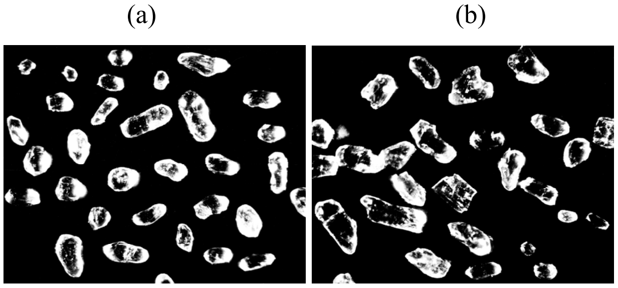


Figure 3. Variety of apatite individua morphology in the samples of the deposit carbonate-bearing ores. Binocular microscope. 40^x zooming

Systematic increase in the share of ellipsoidal individua (47 up to 69%) is registered from enclosing rocks towards the deposit central part when content of the rounded ones experiences its decrease (22 down to 11%). Frequency of columnar grains occurrence does not vary significantly. As a result, minor increase in average elongation is observed from 2.05 on the contact with enclosing rocks up to 2.09 within the central part of the deposit carbonatite core. 0.16 – 0.30 mm grain size prevails within the carbonate-bearing ores.

Internal morphology, i.e. anatomical pattern of the apatite, is characterized by the pronounced block structure which is manifested clearly after the individua have been etched (Fig. 4).

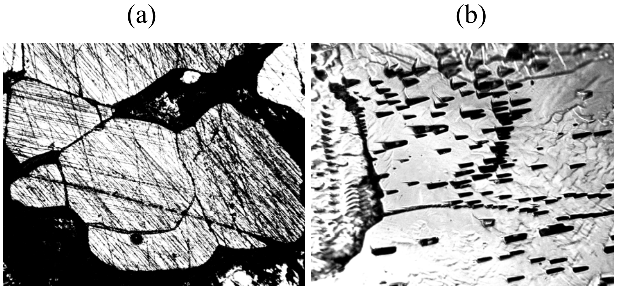


Figure 4. Block structure of apatite individua of carbonate-bearing ores determined during etching with the help of HCl: (a) polished section, 70^x zooming; (b) apatite grain surface after etching. Obtained with the use of microhardness ПМТ-3 tester. 1680^x zooming

Boundaries between the blocks are traced both in the process of the apatite etching at the polished sections (Fig. 4a), and in the process of the mineral grain etching (Fig. 4b). Allocation of the blocks is stipulated by intersection of two systems of thin fissures being developed along elongation of the grains, and perpendicularly to it. The larger the grain is, the greater number of blocks it involves.

Anatomy of the individual is also emphasized by a specific nature of distribution of gaseous and liquid spots in them. The latter are characterized by predominantly ellipsoidal and columnar shapes. The rounded shape is rare. As a rule, they are oriented along the apatite individua elongation (Fig. 5a and 5b). Decrease in granulometric separations of the mineral is followed by the decreased spots down to their complete nonavailability (Fig. 5c and 5d). Slip joints help determine allocation of secondary spots.

Origin of apatite separation within the carbonate rock mass depends directly upon the process of the superimposed carbonization of the earlier formed silicate-bearing variations of complex ores. As a result, almost complete substitution of silicate minerals (i.e. forsterite, and phlogopite) is observed. By contrast, magnetite experiences accumulative recrystallization. It is represented by (up to the first centimeters) octahedral crystals. Sometimes, rhombidodecahedron faces are made visible.

Carbonate fusion-solution elevation was followed inevitably by the temperature increase and especially pressure within enclosing rocks. Along with the formation of powerful system of ring fractures within the central part of the southern isometric share of the deposit, renovation of previously formed linear disturbances took place inclusive of those governing manifestations of the superimposed apatitization.

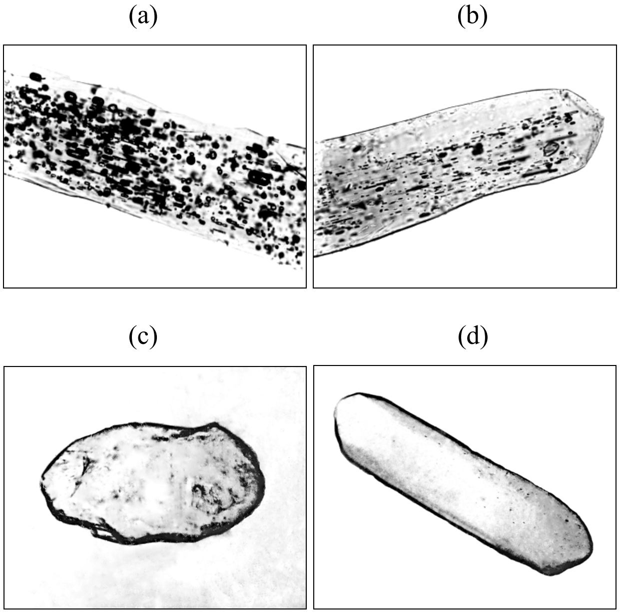


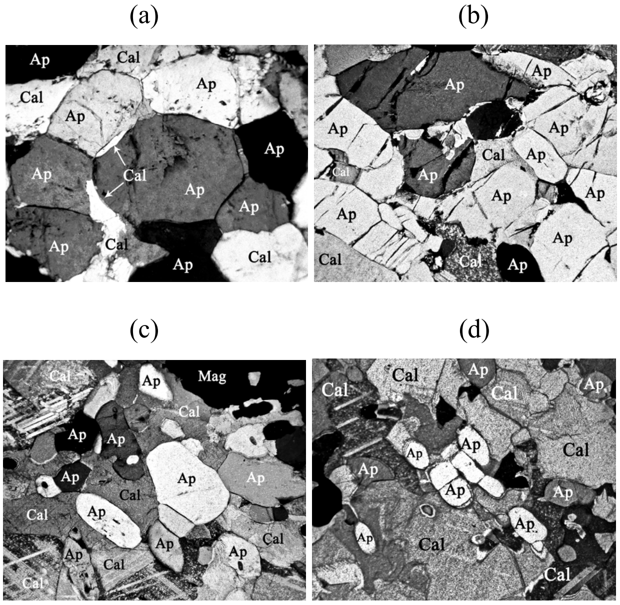
Figure 5. Morphology and distribution of gaseous and liquid spots within the apatite grains of carbonate-bearing ores. Find explanations in the text. Samples with immersion liquid. Obtained with the help of Amplival microscope. Zooming: (a) and (b) – 270^x; (c) and (d) – 90^x

In such a way, the development of ore carbonatization out of the carbonatite core zone is explained; first of all, it concerns disintegration areas of brittle granoblastic textures of apatite II. The intensive disintegration of mosaic apatite aggregates favoured penetration of CO_2 – enriched agents in shallow fissures along the intergrain boundaries. The fact supports high mobility of carbonate fusion-solution.

It is worth noticing that on the contact with calcite (dolomite is uncommon), polyhedral apatite individua become rounded visibly and angles between “faces” smooth out. On the contact with primary apatite II separations, the same grains show typical angular contours with straight-line boundaries at their sections (Fig. 6a).

If carbonate rock mass envelopes apatite individua in full, then their size reduction is registered as well as “elongation” along the long axis (Fig. 6b – 6d) which position is controlled by the characteristic orientation of gaseous and liquid spots in the grains (Fig. 5a and 5b). Consequently, gradual substitution (i.e. solution) of apatite II separations for carbonate fusion-solution takes place. Nonavailability of thin intruding fissures, filled with the guest calcite or penetrating of “attacking islands” of carbonate structure is indicative of the liquid phase-solid phase interaction right at the substitution front when the matter circulates either within intergrain space or along the front. Reaction carracks around the apatite grains cannot be traced depending upon rather high diffusion velocity of the system components.

Generally, independent apatite individua are localized at the boundary between carbonate grains. Together with separations of other primary minerals, they form eutaxic, maculose ore structure. Texture of the aggregates is close to porphyroblastic one. Certain apatite grains contain hangovers of small, rounded forsterite individua.


(a) (b)

(c) (d)

***Figure 6.** Consequent carbonatization episodes of mosaic aggregates of apatite II with following formation of elongate apatite individua within carbonate matrix (a → d): Ap – apatite; Cal – calcite; Mag – magnetite. Obtained with the use of MPS-2 microscope. Incident light; with analyzer. 90^x zooming*

The fact supports direct genetic interaction of ellipsoidal mineral separations within carbonate-bearing ores with polygonal grains of apatite II also containing silicate spots (Fig. 7). Sometimes, xenolites of granoblastic (i.e. mosaic) apatite aggregates are seen. Frequently, apatite individua "stretch" in one direction demonstrating in such a way displacement dynamics of the carbonate rock mass.

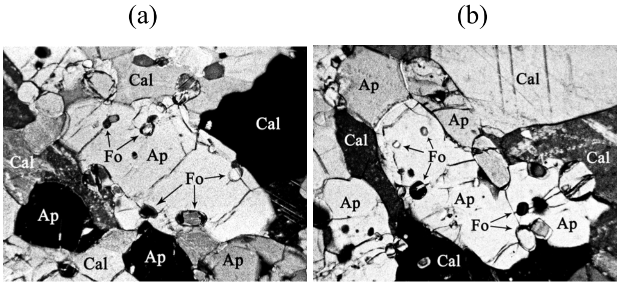

(a) (b)

***Figure 7.** Hangovers of small, elongated forsterite within apatite III individua: Ap – apatite; Cal – calcite; Fo – forsterite. Obtained with the use of MPS-2 microscope. Incident light; with analyzer. 120^x zooming*

Formation of ellipsoid, columnar pattern of the majority of the mineral separations can be explained by preferential solution of primary apatite II individua in terms of a prism. Probably, it is connected with carbon admixture adding to phosphorus during carbonatization (i.e. manifestation of concentration isomorphism). As a result, structure of the apatite becomes incomplete due to the origin of deficit of Ca^{2+} cations replaced by water molecules (Bliskovskiy, 1983). At the same time it is known that hexagonal prism faces are characterized by maximum density of distribution of calcium atoms: 244 atoms per 1000 square angstroms (Yashchenko, 1981). Thus, areas of apatite II polyhedrals, correspond-ding to the prism faces, turn out to be the most incomplete as well as unstable places of grain surface; solution will start from them. Papers (Yoder, Pasteris, Krol, Weidner, & Schaeffer, 2012; Deymier et al., 2017) also mention the increased apatite solubility in connection with carbonate-ions adding to its structure.

It is quite possible that anisotropy of thermal conductivity of apatite along different crystallographic lines plays a key role in the process which stipulates progress of ellipsoidal shape of the individua. The above mentioned results in non-uniform solution of original mineral grains and in their elongated shape. Rising availability of hydrogen bond OH – F, represented clearly within IR spectra of the mineral, should also be taken into consideration as for the structure of apatites from carbonate-bearing ores (Pirogov, Trunin, & Kholoshin, 2001). Corresponding absorption bands achieve their peak intensity within the spectra of apatite IV from the "abnormal" deposit area. Progress of the bond favours hexagonal structure axis strengthening: sharp decrease in the mobility of hydroxylic groups takes place; and ion-exchange process along sextic axis becomes more difficult. Apatite solvability decreases drastically along the line (Knubovets & Kislovskiy, 1975).

Hence, mineral grains in carbonate ores are characterized by a shape derived from isometric, polygonal separations of apatite II. Preferential solution along a prism "faces" stipulated domination of ellipsoidal and columnar apatite individua within the area of core of the deposit.

Block structure of the mineral separations simplifies penetration of highly mobile carbonate fusion-solution inside the individua (apatite corrosion within areas of the dispersed allocation of atoms) with following division of the grains into independent subindividual parts acting as autonomous, smaller mineral separations which, in turn, experience further substitution (solution) at the subsequent carbonatization stages (Fig. 8). Boundaries between blocks are "reentrants" along which the most dynamic solution of the individua takes place.

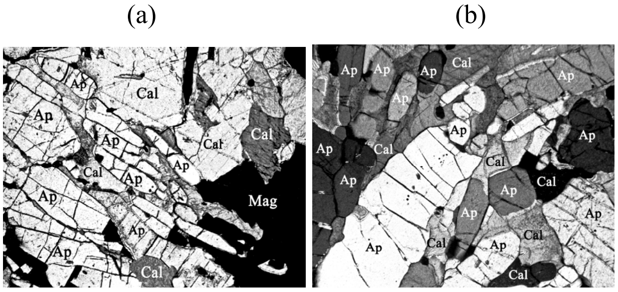

(a) (b)

***Figure 8.** Division of apatite grains into subindividua within carbonate-bearing ores: Ap – apatite; Cal – calcite; Mag – magnetite. Obtained with the use of MPS-2 microscope. Incident light; with analyzer; (a) 100^x zooming; (b) 170^x zooming*

The grain division is connected with longitudinal fracture system, and with transversal one. Columnar separations are formed predominantly in a case one. If joint superposition of systems takes place then ellipsoidal and elongated separations are formed (Fig. 8). Transversal fracture system is the most typical for apatite; it is stipulated by the manifestation of imperfect cleavage in terms of pinacoid which concerns mainly the elongated grains.

Hence, each block is a potential apatite grain. If the separated individuum left rather large and preserved its block structure, then its further fragmentation took place with the involvement of smaller simple grains. Thus, apatite "recrystallization" was of a multistage nature. Figure 9 represents logic diagram of apatite grain transformation in the connection with the multistage carbonatization.

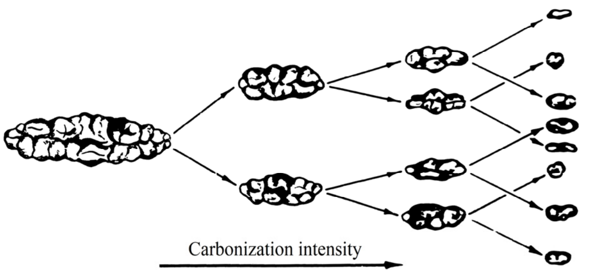


Figure 9. Logic diagram of apatite individua "fragmentation" during carbonatization

The block nature of the majority of apatite grains within the carbonatite ores stipulates the variety of the individua morphology and geometry being recorded even within one mineralogical sample (Fig. 3).

Active tectonic mode, followed by carbonization events, favoured successive failure and solution of the mineral separations. To the fullest extent, the process has been demonstrated within the deposit carbonatite core area. Gradual decrease in the average apatite grain size within carbonate-bearing varieties of the complex ores (i.e. 0.58 down to 0.18 mm) is seen from the contact with enclosing rocks to the carbonatite core central part. Moreover, variability of the individua granulometry decreases significantly. Apatite separations in the carbonatite ores are characterized by the specific smooth surface (Fig. 10a). Negative shapes, being typical for solution microrelief, are not available. Probably, the etching figures, originated initially at the surface of the grains, were gradually destroyed by the solution layers spreading from apices and edges. Apatite grains become smoother and more rounded. It should be noted that crystal apices and edges (in this context, apatite II polyhedrals are meant) are the most powerful source of solution stages especially at early stages of the process.

At the same time, apatite surface within the carbonate-bearing ores is characterized by combination flat noncrystallographic shapes and edge ones. The edges are of curly contours. They are not connected with a contact of the faced surfaces. Generally, they are allocated along the individua elongation. The flat shapes are numerous, varied in form 4- and 6-sided polygons interlocking at an obtuse angle making apatite grain rounded. It is seen very clearly within the apical shares of the grains (Fig. 10b). Each polygon has smooth surface which is relatively plane. Origination of such faced and flat shapes is connected with the anisotropy of the individua dissolution velocity.

Large mineral separations (for instance, the least dissolved ones) are characterized by edge flattening within the joints of bordering polygons. The latter also differ in the minor surface wrap (Fig. 10b). Small apatite separations (i.e. the most dissolved ones) are notable for their distinct straight contours as well as absolutely smooth surface of boundary planes (Fig. 10c and 10d).

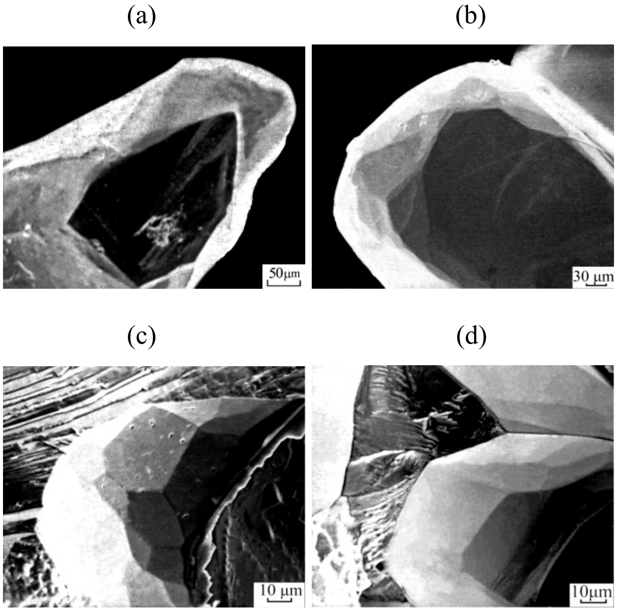


Figure 10. Nature of surface and morphology of apatite separations within the carbonate-bearing ores. Find explanations in the text. Raster electron MSM-5 microscope

Such a transition can be explained by gradual strengthening of a role of defects of the mineral surface as a source of solution layers; at the subsequent stages of the process that can be explained by a result of the increased undersaturation of the system relative to the apatite. Among other things, the abovementioned increased defectiveness of a prism faces stipulates maximum velocity of their solution. As a result, prismatic faceting may originate on certain individua. It is common knowledge that during solving, a crystal may demonstrate the faces being characterized by the maximum solution velocity. Getting back of individua to a crystallomorphic prismatic habitus should be considered as a manifestation of morphological memory of apatite.

Thus, against consistent increase in undersaturation of mineralogenetic system, one can trace a transition from the "edge" mechanism of solution of apatite of carbonate-bearing ores to the predominantly "defective" one being typical for solutions of apatite experienced repetitive carbonization (solution). Hence, apatite individua within the central share of the deposit carbonatite core experienced the most intensive effect of the "defective" solution mechanism. First of all, it concerns the areas of rare metal mineralization coverage ("abnormal" zone) where finely granular separations of apatite IV have evolved.

5. CONCLUSIONS

Ontogenic approach has turned out to be extremely informative and efficient technique to analyze apatite characteristics in the context of rather complex genetic (i.e. polygenic, polychronous, and spatially heteroge-neous) rocks of Kovdor deposit. Apatite morphology of carbonate-bearing variations of complex ores is a direct reflection of the convoluted history of continuous mineral-environment interaction which has appeared to be extremely aggressive as for the apatite. Moreover, it has transformed typomorphic characteristics of the mineral fundamentally.

Morphological properties are determined by the combination of internal factors (i.e. mineral anatomy and crystallochemistry) and external ones (i.e. metasomatosis and the process time). Metasomatic carbonization has turned out to be the dominant event for a fast and dynamic formation of apatite individua. Internal factors have predetermined delicate specific nature of the process.

Formation of apatite grains within the carbonate ores result from logical solution of polygonal individua of apatite II in terms of a prism "faces" as a consequence of intensive carbonization of earlier ores of foskorite composition.

The most important typomorphic characteristics of apatite morphology in carbonate-bearing variations of complex ores are as follows: mainly ellipsoidal (rarely columnar), rounded grains with no habitus limitation; specific smooth surface of the individua being a combination of numerous flat noncrystallographic shapes and edge ones; pronounced block structure of the mineral separations stipulating further division of the grains into independent parts – subindividua; availability of relic small, rounded forsterite impurities; and gradual transition from the "edge" apatite solution mechanism to the "defective" one while nearing the central part of carbonatite core. Visually, it is expressed by the essential smoothing of a surface of bordering faces (i.e. pseudofaces). The rounded contours of apatite individua become more angular. Most of all, the tendencies are typical for apatite IV separations within the "abnormal" area of the ore complex which is of absolute interest from the viewpoint of prognostic and prospecting informativity of the considered typomorphic mineral characteristics. It is also important to prospect apatite-bearing areas of carbonatite complexes being perspective from the viewpoint of rare metal mineralization.

The obtained information, concerning typomorphic characteristics of Kovdor deposit apatite, should be used to optimize determination and estimation of similar objects connected with Ukrainian carbonatite complexes.

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ТИПОМОРФНІ ОЗНАКИ МОРФОЛОГІЇ АПАТИТУ КАРБОНАТВМІСНИХ ВІДМІН КОМПЛЕКСНИХ РУД КОВДОРСЬКОГО РОДОВИЩА

О. Трунін, С. Тіхлівець

Мета. Всебічне вивчення морфології апатиту в карбонатвмісних відмінах комплексних руд Ковдорського родовища як важливої типоморфної ознаки мінералу, що володіє високою генетичною та прикладною інформативністю.

Методика. Дослідження засновані на онтогенічному підході для вивчення типоморфних якостей апатиту родовища. Використовували можливості традиційної та растрової електронної мікроскопії. Деталі внутрішньої морфології вивчали із застосуванням структурного травлення й препаратів з імерсійною рідиною. Топомінералогічні спостереження дозволили фіксувати особливості просторової мінливості морфологічних ознак.

Результати. Найважливішою особливістю морфології більшості індивідів апатиту в карбонатвмісних рудах є розвиток подовженого, еліпсоїдального вигляду зерен із переважаючим класом крупності 0.16 – 0.30 мм. Внутрішня морфологія (анатомічний рисунок) характеризується яскраво вираженою блоковою будовою. Формування виділень апатиту в карбонатному матриксі пов'язано з фронтальним розчиненням раніше утворених поліедрічних зерен апатиту II під впливом агресивних карбонатних розплавів-розчинів. Найбільш активно розчиняються ділянки поверхні, що відповідають “граням” призми. Виділення апатиту в карбонатних рудах характеризуються специфічною згладженою поверхнею у вигляді складного поєднання плоских і ребрових гранних елементів розчинення. У “аномальній” зоні карбонатитового ядра дрібні індивіди апатиту відрізняються чіткими прямолінійними контурами та абсолютно рівною поверхнею площин, які ограняють, що пояснюється поступовим посиленням ролі дефектів поверхні мінералу, як джерела шарів розчинення, на більш пізніх етапах карбонатизації.

Наукова новизна. Морфологічні ознаки апатиту Ковдорського родовища характеризуються яскраво вираженим типоморфізмом, є чуйним індикатором еволюції системи мінералогенезу. Виявлено, що формування типоморфних якостей апатиту залежить від активності прояву карбонатизації в первинних рудах, яка досягає максимального розвитку в “аномальній” зоні карбонатитового ядра.

Практична значимість. Результати представляють інтерес з позицій прогнозно-пошукової інформативності, вирішення питань технологічного порядку, а також раціонального відпрацювання та усереднення апатитвмісних руд перед подачею їх на збагачувальну фабрику. Інформацію рекомендується використовувати для оптимізації пошуку й оцінки аналогічних об’єктів, пов’язаних з карбонатитовими комплексами, на території України.

Ключові слова: *Ковдорське родовище, комплексні руди, карбонатити, фоскорити, апатит, онтогенія, типоморфізм*

ТИПОМОРФНЫЕ ПРИЗНАКИ МОРФОЛОГИИ АПАТИТА КАРБОНАТСОДЕРЖАЩИХ РАЗНОСТЕЙ КОМПЛЕКСНЫХ РУД КОВДОРСКОГО МЕСТОРОЖДЕНИЯ

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Цель. Всестороннее изучение морфологии апатита в карбонатсодержащих разностях комплексных руд Ковдорского месторождения как важного типоморфного признака минерала, обладающего высокой генетической и прикладной информативностью.

Методика. Исследования основаны на онтогеническом подходе для изучения типоморфных качеств апатита месторождения. Использовались возможности традиционной и растровой электронной микроскопии. Детали внутренней морфологии изучались с применением структурного травления и препаратов с иммерсионной жидкостью. Топоминералогические наблюдения позволили фиксировать особенности пространственной изменчивости морфологических признаков.

Результаты. Важнейшей особенностью морфологии большинства индивидов апатита в карбонатсодержащих рудах является развитие удлиненного, эллипсоидального облика зерен с преобладающим классом крупности 0.16 – 0.30 мм. Внутренняя морфология (анатомический рисунок) характеризуется ярко выраженным блоковым строением. Формирование выделений апатита в карбонатном матриксе связано с фронтальным растворением ранее образованных полиэдрических зерен апатита II под воздействием агрессивных карбонатных расплавов-растворов. Наиболее активно растворяются участки поверхности, соответствующие “граням” призмы. Выделения апатита в карбонатных рудах характеризуются специфической сглаженной поверхностью в виде сложного сочетания плоских и реберных гранных элементов растворения. В “аномальной” зоне карбонатитового ядра мелкие индивиды апатита отличаются четкими прямолинейными контурами и совершенно ровной поверхностью ограняющих плоскостей, что объясняется постепенным усилением роли дефектов поверхности минерала, как источника слоев растворения, на более поздних этапах карбонатизации.

Научная новизна. Морфологические признаки апатита Ковдорского месторождения характеризуются ярко выраженным типоморфизмом, являются чутким индикатором эволюции системы минералогенеза. Выявлено, что формирования типоморфных качеств апатита зависит от активности проявления карбонатизации в первичных рудах, которая достигает максимального развития в “аномальной” зоне карбонатитового ядра.

Практическая значимость. Результаты представляют интерес с позиций прогнозно-поисковой информативности, решения вопросов технологического порядка, а также рациональной отработки и усреднения апатитсодержащих руд перед подачей их на обогатительную фабрику. Информацию рекомендуется использовать для оптимизации поиска и оценки аналогичных объектов, связанных с карбонатитовыми комплексами, на территории Украины.

Ключевые слова: *Ковдорское месторождение, комплексные руды, карбонатиты, фоскориты, апатит, онтогения, типоморфизм*

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