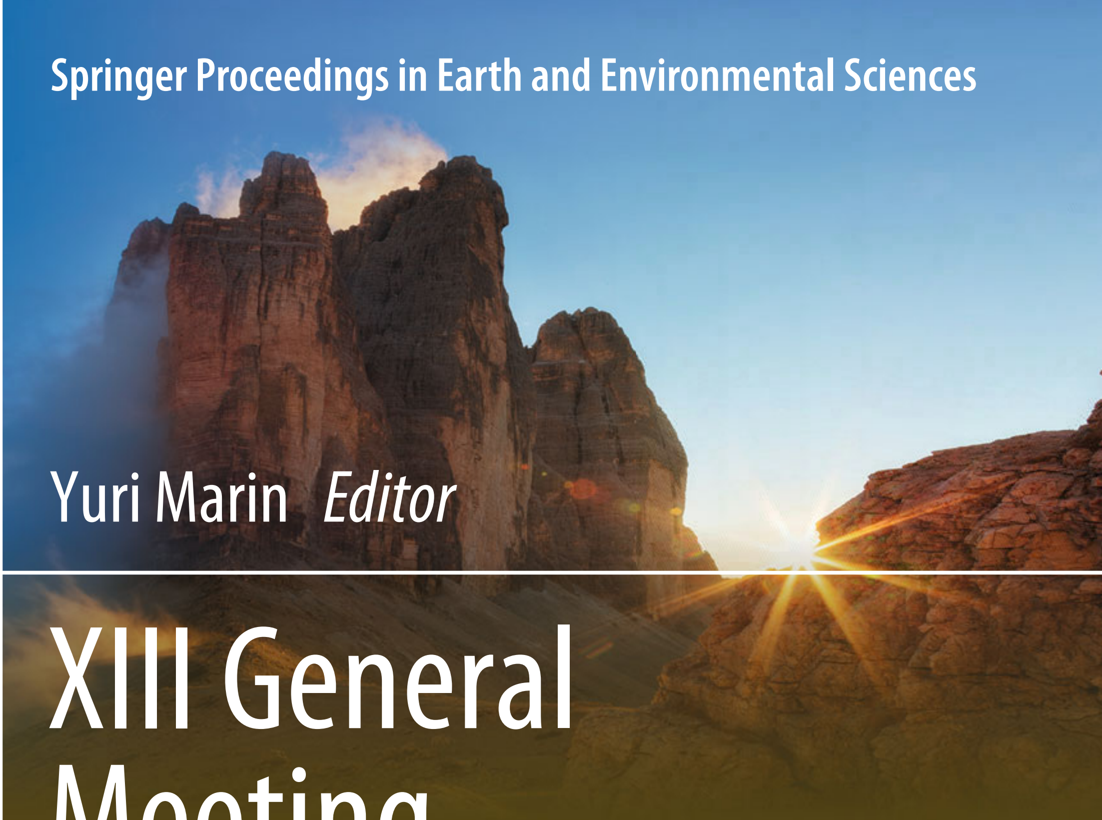

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Yuri Marin *Editor*

XIII General Meeting of the Russian Mineralogical Society and the Fedorov Session

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Preface

The XIII General Meeting of the Russian Mineralogical Society (the oldest existing mineralogical society in the world; it will celebrate its 205th anniversary on 19 January 2022) was held at St. Petersburg Mining University on 5–7 October 2021.

The proceedings of the international scientific conference "XIII General Meeting of the Russian Mineralogical Society and the Fedorov Session" is dedicated to the discussion of the results of fundamental and applied research in a wide range of related disciplines, covering the study of minerals and mineraloids, rocks, ferrous and non-ferrous raw materials, natural mineral formations as applied materials and cultural objects, and artificial analogs of minerals and rocks, used in various fields of human activity.

The chapters of the book represent the thematic sections: The XIII General Meeting and the Fedorov Session: fundamental issues of mineralogy, mineral diversity and evolution of mineral formation; minerals—indicators of petro- and ore genesis and new methods of its identification; mineralogy and formation conditions of strategic minerals deposits; problems of applied (technological and ecological) mineralogy and geochemistry; natural stone in art and architecture. Modern methods of research in the field of gems, semi-precious stone raw materials and gemology; new achievements in the field of mineralogical crystallography, crystal chemistry and mineralogy of new minerals; history of science, museumification and popularization of the natural science knowledge.

Proceedings of the participants of the XIII General Meeting of the Russian Mineralogical Society and the Fedorov Session is given in the chapters of this book. We hope that they will be interesting to a wide range of specialists.

Yury Borisovich Marin

Contents

Problems of Applied (Technological and Ecological) Mineralogy and Geochemistry

Fundamental Issues of Mineralogy, Mineral Diversity and Evolution of Mineral Formation

Priorities of Modern Mineralogy

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Abstract. This message continues traditions of Russian mineralogy, which has always paid special attention to general methodological discussion of the state and prospects for the development of mineralogical science. The author wrote the message on the occasion of the 25th anniversary of the publication of the programmatic article of Academician N. P. Yushkin "Priorities of mineralogy on the threshold of the 21st century" (Vestnik of the Institute of geology, Komi SC UB RAS, 1996, No. 5). We offer the author's list of priority problems that are now attracting the most attention and from the solution of which breakthrough results are expected. These are mainly problems or research trends entrenched in the large mineralogical agenda in the last decade ("growth points"). This list is named the "mineralogical list" for brevity. It is compiled by analogy with the famous list of important and interesting physical problems by Academician V. L. Ginzburg. The "mineralogical list" as well as the "physical minimum" is addressed to young researchers and can be perceived as a minimal educational program for mineralogists.

Keywords: Mineralogy · The most important problems of mineralogy · Mineralogical list · New ideas in mineralogy in the 21st century · Frontiers of mineralogical science

1 Introduction. About the Priority Problems of Mineralogy

Extensive discussion of fundamental problems, ideas, the structure of mineralogy itself, relationships with other sciences are widespread among the mineralogical community. Moreover, in mineralogy this happens even more often in mineralogy than in other sciences. This is especially typical for Russian mineralogy, which is reflected in textbooks (Bulakh 1999) and analytical papers (Borutskiy 2007; Grigoriev 1990). In Russia, even special training courses were made (Koschug and Eremin 2015). Yu. B. Marin recently published a generalizing paper on the methodological principles of mineralogy, on the transition of mineralogical research to a qualitatively new level, and on the application of mineralogical information to solve fundamental problems of mineralogy. However, sometimes, in addition to analyzing the most important areas of mineralogical science, questions are also raised about whether mineralogy exists at all as an independent science with its own objects and methods. Even such a thesis was expressed about mineralogy as a part of the chemistry of inorganic compounds formed in nature (Bokiy 1997). In a

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number of his works (Grigoriev Yushkin 1988; Yushkin 1988, 1996, 2002; Yushkin and Kuznetsov 2008), Academician N. P. Yushkin discussed general issues of mineralogy, problems and prospects of its development. Moreover, a quarter of a century ago, N. P. Yushkin published a list of mineralogy priorities (Yushkin 1996), according to which, in his opinion, the development of mineralogy will take place in the twenty-first century. Yushkin's list included the following ten items:

1. Development of a new "real" crystal chemistry of minerals based on high-resolution methods of electron microscopy to observe individual crystal-forming particles (molecules and atoms).
2. Studies of dispersed and ultradispersed states of matter.
3. Analysis of atomic-molecular and supramolecular structures, structural studies of protoindividuals.
4. Problems of syngenesis, interaction and co-evolution of the living and mineral worlds. Clarification of the role of minerals in the origin and maintenance of life, the role of organisms in the process of mineral formation and ore formation.
5. Geotechnogenesis and technical mineral formation.
6. Study of minerals as genetic indicators, as letters from the geological past.
7. Development of a scientific system of applied mineralogy, including topomineralogical study of ore-bearing regions, mineralogical forecasting, prospecting and evaluation and technological mineralogy.
8. Development of regional mineralogical research, creation of regional mineralogical generalizations.
9. Creation of a national machine database on minerals.
10. Creation of a methodological apparatus for solving a wide range of geological problems based on mineralogical data.

At the same time, N. P. Yushkin noted that "these main directions do not, of course, determine the entire front of mineralogy development, but trace the main research impacts that ensure a breakthrough into the future" (p. 4). On the one hand, this list indicated directions that are really important for mineralogy, which are still relevant to this day. On the other hand, over the past years, dramatic changes have occurred in mineralogy, primarily due to the penetration into the nanoworld and borderline areas of knowledge, the emergence of new ideas and research methods. This prompted us to compile a certain list of priority problems that characterize the state of mineralogical science today. The list is named the "Mineralogical list" for brevity, and includes 17 items.

2 Priority Issues in Mineralogical Science

("Mineralogical List")

1. Discovery of new minerals.
2. Forecast and design of mineral structures.
3. Mineralogy of mantle and core.

4. Mineral formations at the ocean bottom.
5. Mineral phases in extreme conditions.
6. Minerals as promising materials.
7. Surface of minerals. Two-dimensional mineral phases.
8. Protominerals and protomineral state of matter.
9. Non-classical mechanisms of mineral formation.
10. Dispersed and nanostructured mineral substance.
11. Mineral nanostructures and nanoindividuals.
12. Organic minerals and organomineral formations.
13. Minerals in biological systems.
14. Evolution, irreversibility and self-organization in mineral systems.
15. Complexity, modularity and hierarchy of mineral structures.
16. New tools and objects of mineralogical research.
17. Digital mineralogy. Big data and artificial intelligence in mineralogy.

3 Comments and Remarks on the "Mineralogical List"

Before proceeding to some necessary comments and remarks on the list, we quote the words of Academician V. L. Ginzburg, that he accompanied his famous "list of important and interesting problems of physics and astrophysics" ("physical minimum") (Ginzburg 2004). "Any such list cannot but be subjective. It is also clear that the "list" must change over time. It is clear, finally, that all the questions not included in the "list" can in no way be considered unimportant or uninteresting… Those who know important and interesting things that are beyond the "list" have no reason to be offended and should only supplement or change the "list"" (p. 1253).

The "Mineralogical list" mainly includes problems or areas of research that have become entrenched in the large mineralogical agenda in recent decades. These are relatively new problems ("growth points"). They are mostly directed towards the future of mineralogy as a fundamental science. Mineralogy appears in this list as part of the vast science of mineral matter, developing in close cooperation with other related branches of natural sciences, primarily physics, chemistry and biology. It is this aspect (the fundamental nature of mineralogy) that is important here, and not that mineralogy is a geological science. Calls for the geologization of mineralogy change little in its modern appearance. A number of key positions in the list, as expected, are directly related to or repeat the directions from the Yushkin's list of mineralogy priorities. The appearance or reformulation of some items in the list is related to the fact that the corresponding problems have recently come to the frontiers of mineralogical science and are attracting wide attention. For example, this refers to a new problem of analyzing the complexity of mineral systems, indicated in paragraph 15, alongside with the issue of modularity and hierarchy of mineralogical structures (Krivovichev et al. 2018). Certainly, I will not deny that the list includes problems to which the author is not indifferent or in the field of his own scientific interests.

There is no particular need for detailed decifration and explanations of the content of the items briefly formulated in the list, in the preparation of their "passports". It is clear that their content is broader than indicated in this or that paragraph. We will not forget about some conventionality of division into paragraphs and about their certain interdependence. Some points, perhaps, should have been combined, and some, on the contrary – divided. So paragraph 3 – "Mineralogy of mantle and core" – is unlikely to be disclosed without discussing issues related to the stability and prediction of the existence and behavior of minerals under conditions of high pressures and temperatures. The problem of deciphering the mechanisms of mineral formation, which is most urgent today and close to the author, turns out to be directly tied to the study of pre-nucleation clusters (quatarons) – new objects of the protomineral world – the world of creation of minerals (Askhabov 2019).

Active theoretical and experimental research is underway on all the items indicated in the list. With some advance, the list includes items 16 and 17, in which mineralogy will inevitably be involved in the coming years. At the same time, in paragraph 16, we are talking more about completely new methods of mineralogical research, which, possibly, will be associated with the so-called megascience devices (new types of electron microscopes, synchrotrons, free electron lasers, etc.). New objects are today not minerals and not even materials of inorganic origin. So, quite recently, the objects of mineralogical studies are e.g. bone remains (Silaev et al. 2017).

As for the first item on the list, the discovery of new minerals is and will be for a long time an exciting field of mineralogy, which ceases to be just an exciting field of competition for mineralogists, in a significant system influencing the prestige of science.

The list, we have compiled, is not intended to embrace the immensity. In our opinion, it more sets some thematic landmarks and characterizes the current situation in mineralogical science. The "Mineralogical list" does not answer the question: what should be mineralogy, Yushkin's priorities were aimed at that, but indicates the problems that most attract attention today, judging by the contents of magazines and conference programs. It is, as it were, the current "temporal" section of mineralogical science. It is easy to see that the list contains questions of varying degrees of elaboration and theoretical justification. But they are all, as they say, by ear and equally important and interesting, regardless of the order in the list.

The addressees of the "mineralogical list" are mainly young researchers. They should have at least a general idea of the problems (directions) indicated in the list, and not only of the state of affairs in their narrow fields of science. This is, to some extent, the minimum educational program for mineralogists. In this sense, our list is close to the "physical minimum" of V. L. Ginzburg, which is also focused on educational goals.

It is also necessary to pay special attention to the interdisciplinary nature of almost all the problems (topics, if you like) listed in the list. For example, points 2 and 3 play a key role in expanding our understanding in related areas of earth sciences, in understanding the composition and structure of deep geospheres. Items 5–8 deal with interdisciplinary issues at the intersection of mineralogy, chemistry, physics and materials science. It should be emphasized that a great material science potential is contained in clauses 6 and 7. Clauses 9 and 10 include issues on the border of mineralogy and biology (from the interaction between minerals and organic molecules, syngenesis and coevolution of living and mineral worlds to general issues of organic mineralogy and the role of organic matter and the processes of mineral and ore formation). The same points are directly related to the complex problem "mineralogy and life" formulated by N. P. Yushkin.

4 About Possible Additions to the List

The "Mineralogical list" should include a number of other areas that retain their relevance and importance, and have become integral parts of modern mineralogy. The extended list, in particular, could include problems of mineral diversity, mineralogy of ore deposits, genetic-informational mineralogy and typomorphism of minerals, experimental research in mineralogy and mineral synthesis. The latter may receive a "second breath" in connection with the development of a direction focused on obtaining new materials based on mineralogical information. An independent direction in mineralogical materials science can be the design and invention of potential minerals, the assembly of mineral structures by adding layers consisting of one or several layers of different minerals, thus obtaining peculiar mineral heterostructures and heterophase objects. This would be a significant advance for point 6. There is a sharp increase in interest in the problems of technological mineralogy and technogenesis of minerals, which is associated with their very important practical importance. Mineralogy of astroblemes, the study of meteorites does not lose its relevance. Research on space mineralogy (the Moon, planets, near-planetary dust complexes with a promising swing to solid exoplanets) is promised to revive. It would hardly be fair to leave the extended "Mineralogical list" without such classical sections as mineralogical crystallography and physics of minerals. At various mineralogical forums, it increasingly appears as a promising direction and medical mineralogy with the pharmaceutical industry on a mineral basis. These directions, despite their more traditional character, will be considered by many people to be even more important for progress in mineralogical science in general. It is clear that they will not go anywhere and the corresponding problems will be in the arsenal of modern mineralogy, it is possible that some of them will become super-priority at a certain stage.

5 Conclusion

In conclusion, we note once again that the "Mineralogical list", as well as all other similar lists, of course, can be continued, supplemented, changed. But all directions and interesting problems of mineralogical science cannot be covered. "Mineralogy in the entire space of this word" is broader and richer.

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E. S. Fedorov's "Drusites": Metamorphic Reaction Structures in Paleoproterozoic Metagabbronorites of the Belomorian Province of the Fennoscandian Shield

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Abstract. The reaction structures (coronas) in metagabbronorites from the Belomorian Province were resulted from two stages of high-grade metamorphism. The early garnet-free coronas were formed at olivine/plagioclase boundary. They formed radial new-formed clinopyroxene and orthopyroxene grains after olivine with simultaneous replacement of magmatic plagioclase by metamorphic one + spinel. The early coronas were formed during low-pressure granulite metamorphism at 750–950 °C and 3–5 kbar. The late garnetiferrous coronas and peak mineral assemblage after olivine gabbronorites were formed during high-pressure high-temperature metamorphic event at 700–850 °C and 15–28 kbar. The retrograde high-pressure amphibolite metamorphism resulted in garnet-bearing and garnet-free antophyllite amphibolites after olivine gabbronorites.

Keywords: Metabasites · Corona textures · Belomorian Province · Thermobarometry · TWEEQU

1 Introduction

During him petrographic studies of the Karelian coast of the White Sea, famous crystallographer and petrographer E.S. Fedorov identified a group of basic igneous rocks and called them "drusites" (Fedorov 1896). Further studies showed that the group of "drusites" included several Paleoproterozoic plutonic mafic complexes with ages from 2.5 to 2.15 Ga (Stepanov and Stepanova 2010; Stepanova et al. 2022), intruding the supra- and intracrustal Archean metamorphic rocks of the Belomorian Province of the Fennoscandian Shield. The "drusite" textures (in modern terminology "corona textures": Best, 2003) of these basites are reaction textures originated from metamorphic transformations of the Late Paleoproterozoic (~ 1.95–1.85 Ga) age (Alekseev et al. 1999; Stepanova et al. 2022). The prevailing group rocks among basic and ultrabasic rocks of the "drusite" complex rocks is the lherzolite-gabbronorite complex including quartz-free and olivine gabbronorites and plagiolerzolites with an age of 2.40–2.45 Ga (Stepanov and Stepanova 2010). The intensity of metamorphic transformations of these rocks is

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not very great, so that relics of magmatic minerals were preserved. Metamorphic minerals, as a rule, are present as zonal reaction rims between grains of primary magmatic minerals. It is because of these structures that the rocks have been called “drusites”. The study of reaction structures in metabasites of the Belomorian Province allows us on the one hand to behold the process and mechanisms of transformations of igneous rocks into metamorphic ones, and on the other hand to determine the thermodynamic conditions of these transformations.

2 Geology and Petrography

The Belomorian Province (BP) of the Fennoscandian Shield is composed of Meso- and Neoarchean supra- and intracrustal rocks (Hölttä et al. 2008). At the end of the Neoarchean (~2.7–2.6 Ga) it was reworked during the collision formed the Kenorland continent (Lubnina and Slabunov 2011). By the beginning of the Paleoproterozoic, the BP was part of the Archean craton. At the Early Paleoproterozoic, the BP was repeatedly intruded by continental mafic and ultramafic plutonic rocks of various compositions (Stepanova et al. 2022). The closure of the Lapland-Kola Ocean ~1.95–1.85 Ga ago led to a collision of continental masses, fragments of which are the modern Karelian and Murmansk Provinces of the Fennoscandian Shield. During this collision, BP rocks, including Paleoproterozoic intrusions, underwent high-grade metamorphism (Volodichev et al. 2012; Slabunov et al. 2016; Babarina et al. 2017; Li et al. 2017).

A detailed study of the metamorphic transformations in gabbronorites was carried out for the rocks of two small gabbronorite massifs (Jokivarakka and Vuatvarakka) in the area of the Verkhnee Pulongskoye Lake in the central part of the Belomorian Province. The massifs are small boudinated fragments of intrusive bodies among aluminous and tonalitic gneisses of the Chupa Gneiss Belt (Babarina et al. 2017). Both massifs are composed of alternating olivine and olivine-free gabbronorites with magmatic parageneses $Opx + Cpx + Pl + Ol \pm Bt$ and $Opx + Cpx + Pl \pm Bt$. The alternation of rocks is caused by primary magmatic layering. Gabbronorites were reworked during high-grade metamorphism. The strongest metamorphic transformations are manifested in the marginal parts of the massifs at the contacts with gneisses, where mafic rocks are converted into amphibolites without relics of magmatic structures. Most of the rocks in these massifs contain relics of magmatic minerals, and the degree of transformation varies from almost fresh rocks to rocks that are almost entirely composed of metamorphic minerals. The best-preserved relic mineral is magmatic orthopyroxene.

In olivine gabbronorites reaction rims are formed between olivine and plagioclase. It is possible to distinguish two generations of such borders. The first generation is formed by zoned two-pyroxene coronas replacing olivine and contain no garnet (Fig. 1). Simultaneously alumina spinel and new-formed (metamorphic) plagioclase formed after magmatic plagioclase. The outer zone of two-pyroxene rims may contain spinel–clinopyroxene symplectites. Biotite with ilmenite inclusions is associated with these garnet-free rims. Sometimes pyroxene rims are overgrown with an outer zone composed of pale green pargasite. During further metamorphic transformations magmatic pyroxenes are replaced with an aggregate of metamorphic pyroxenes and fine-grained pargasite. The replacement began at the edges of the pyroxene grains and along the cleavage planes. Numerous submicroscopic ingrowths of alumina spinel in plagioclase led to brown colour of plagioclase in thin sections and blue or blue-green colour in samples. At the same time, magmatic plagioclase was replaced by more acidic metamorphic one. Relict grains of magmatic orthopyroxene contain brown submicroscopic chromite ingrowths, while clinopyroxene grains contain yellowish ingrowths of titanium minerals. The chromite ingrowths in orthopyroxene grains often emphasize growth zoning and sector zoning. Such ingrowths are a distinctive feature of relic magmatic pyroxene grains in the Belomorian metagabbronorites. In the pyroxene grains formed during metamorphism there are neither small ingrowths of chromite and titanium minerals nor a manifested zoning or sector zoning.

The second generation of reaction rims in metagabbronorites consists mainly of garnet, sometimes with inclusions of pargasite hornblende and/or aluminous spinel. These rims formed at the pyroxene/plagioclase boundary. They also contain radial ortho- and clinopyroxene grains after olivine. In some cases, garnet can contact with olivine without obvious signs of its replacement. In areas where garnet rims are manifested inclusions of ilmenite in biotite were transormed to rutile. Quartz in metamorphosed olivine gabbronorites is absent.

The most complete metamorphic transformation of olivine gabbronorites led to the formation of pale-green or greenish-gray plagioclase-free orthopyroxene–anthophyllite–pargasite rocks (±garnet, ±magnesian biotite). For these rocks black coarse pyroxene grains are common. Usually, they are relics of magmatic grains. The garnet in these rocks is pale pink and rather magnesian. The molar part of the pyrope component in this garnet can reach up to 25%. Fine-grained anthophyllite and pargasite form fine intergrowths in the matrix. However, such fully transformed rocks are rare and tend to form thick veins or zones along fractures that were as fluid conduits. During the retrograde metamorphic stage garnets in these rocks were replaced by biotite-plagioclase symplectitic rims, amphiboles formed after orthopyroxenes. Finally, the rocks were transformed into garnet amphibolites and then into garnet-free amphibolites. In these amphibolites two amphiboles (anthophyllite and hornblende-pargasitic clinoamphibole) may coexist.

In olivine-free gabbronorites two generations of reaction rims can also be distinguished. In the early rims magmatic orthopyroxene was replaced by metamorphic orthopyroxene with hornblende, whereas clinopyroxene was replaced by metamorphic metamorphic clinopyroxene or hornblende. The magmatic plagioclase was replaced by metamorphic plagioclase (without spinel), sometimes with amphibole ingrowths. Metamorphic biotite may contain ilmenite ingrowths. The second generation of garnet rims arose at plagioclase/orthopyroxene boundary. The garnet was in an assemblage with metamorphic orthopyroxene, clinopyroxene, and quartz. Rutile arose in biotite, whereas plagioclase disappeared. During intense metamorphic transormation mineral assemblage Opx + Cpx + Grt + Qtz ± Hbl ± Bt (without olivine) formed after olivine-free gabbronorite.

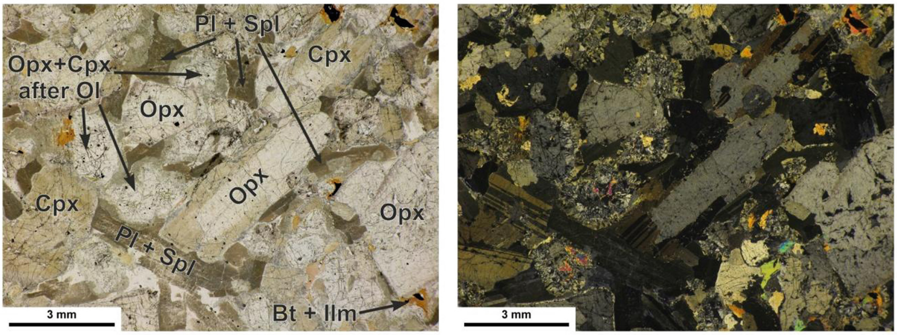

Fig. 1. Garnet-free two-pyroxene rims after olivine and clouded plagioclase with spinel ingrowths in metagabbronorite from Jokivarakka olivine gabbronorite massif.

3 Thermobarometry

Since complete equilibrium in rocks with reaction structures is practically not achieved, the most difficult problem for thermobarometry is the identification of equilibrium mineral asseblages and equilibrium compositions. The equilibrium degree varies greatly not only within one thin section, but also in the vicinity of one grain. Therefore, the use of classical thermobarometry in rocks with reactive structures is very difficult. To determine the PT–conditions of metamorphism the TWEEQU multi-equilibrium thermobarometry technique based on the identification of local equilibria between minerals (Berman 1991) was used. The calculations were performed using the WinTWQ program (Berman 2007) with the internally-consistent thermodynamic dataset JUN92 (Berman 1988) and BA96a (Berman and Aranovich, 1996; Aranovich and Berman 1996). To calculate and analyze the results we also used free add-ons for the TWQ program: TWQ_Comb (Dolivo-Dobrovolsky, 2006a) and TWQ_View (Dolivo-Dobrovolsky 2006b).

Calculations of the PT–conditions of early rim formation in olivine gabbronorites were carried out using the mineral association $Ol + Pl + Cpx + Opx$ with three independent reactions (IR): (1) $Fo + 2\ Hd = Fa + 2\ Di$, (2) $En + 2\ Hd = Fs + 2\ Di$, (3) $2\ An + 2\ Fo = En + 2\ Di + aOpx$ (Al_2O_3), while late rims using the mineral association $Opx + Cpx + Grt \pm Bt$ with 4 independent reactions (5 or 6 independent reactions in the presence of biotite): (4) $Alm + 3\ En = Prp + 3\ Fs$, (5) $Alm + 3\ Hd = Grs + 3\ Fs$, (6) $En + 2\ Hd = Fs + 2\ Di$, (7) $2\ Prp = 3\ En + aOpx$, (8) $Alm + Phl = Prp + Ann$. Calculations were also carried out for rocks with peak mineral assemblage. For this case the mineral relations in the system can be described by 3 independent reactions: (4), (7) and (8).

Calculations have shown that gabbronorites of Jokivarakka and Vuatvarakka massifs underwent two stages of metamorphic transformations. Early metamorphic coronas were formed under conditions of low-pressure granulite facies (750–950 °C and 3–5 kbar, Fig. 2). Later coronas and garnet-bearing mineral asseblages were resulted from high pressure – high temperature metamorphism (700–850 °C and 15–28 kbar, Fig. 3).

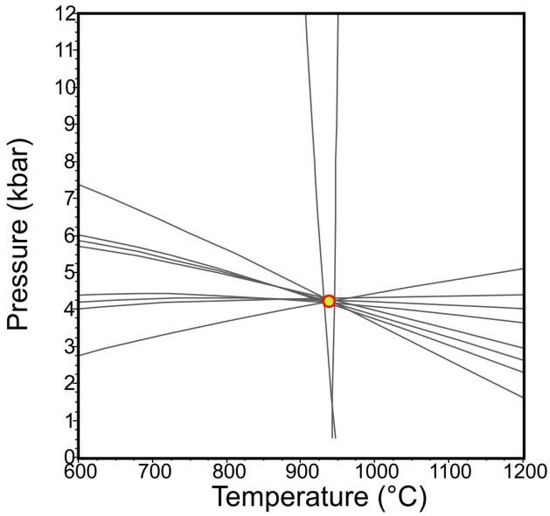

Fig. 2. TWQ-diagram for garnet-free two-pyroxene corona after olivine in metagabbronorite from Vuatvarakka olivine gabbronorite massif; 3 IR (independent reactions).

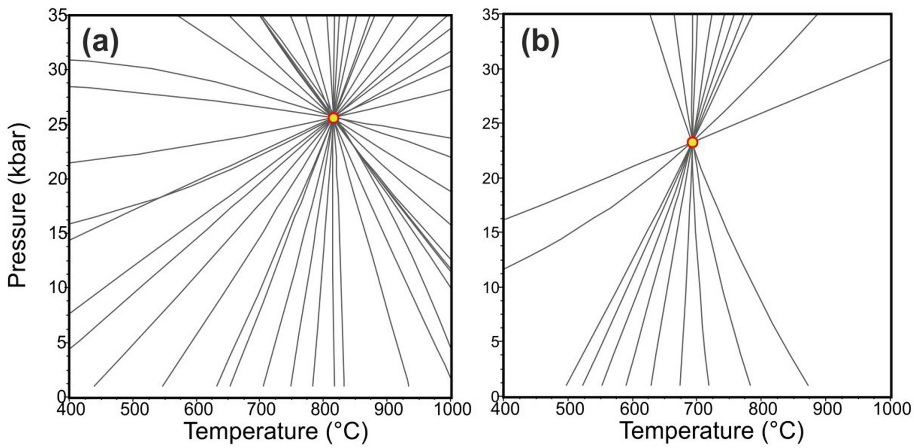

Fig. 3. TWQ-diagrams for garnet-bearing reaction rims in metagabbronorite from Vuatvarakka olivine gabbronorite massif: (a) Grt–Opx–Bt assemblage, 4 IR; (b) Grt–Opx–Cpx assemblage, 3 IR.

4 Discussion

The revealed sequence of rims is in good agreement with experiments on subsolidus equilibria in basic-ultrabasic rocks (Kushiro and Yoder 1966; Borghini et al. 2011). The melt crystallized at low pressures (under the conditions of the upper crust). As a result, the Ol+Pl assemblage was stable in the crystallized rocks. When an early (low pressure) granulite event is superimposed on igneous rocks, unstability of the olivine-plagioclase assemblage resulted in the crystallization of the Opx+Cpx+Pl+Spl metamorphic assemblage. The newly formed plagioclase together with spinel replaced the original (magmatic) one, and the clinopyroxene-orthopyroxene coronas replaced olivine. Thus, early rims are formed due to the reaction

$$\mathrm{Ol} + \mathrm{Pl}_1 \rightarrow \mathrm{Opx} + \mathrm{Cpx} + \mathrm{Pl}_2 + \mathrm{Spl}.$$

Metamorphic plagioclase (Pl_2) is more acidic than magmatic (Pl_1), since the formation of aluminous spinel and clinopyroxene happened due to the decomposition of the anorthitic plagioclase component. The incomplete course of the reactions led to incomplete replacement of the original metamorphic minerals, despite the high temperatures. This incompleteness is primarily determined by the small amount of fluid in the system.

The second metamorphic event occured under high pressure conditions, in which spinel together with pyroxene becomes unstable, as well as Opx+Pl mineral assemblage. Due to this unstability garnet was formed. In highly magnesian rocks, such as olivine gabbronorites and plagiolerzolites, plagioclase was consumed in the reaction faster than orthopyroxene. It led to the formation of the Grt+Opx assemblage. Na and Ca in the rock were redistributed into pargasite. The presence of amphibole indicates the participation of the fluid in metamorphic transformations. However, in the second (high-pressure) metamorphic event the lack of fluid also led to incompleted reactions.

Both high-temperature metamorphic episodes (low-pressure and high-pressure) were related to the evolution of the Lapland-Kola orogen in the Late Paleoproterozoic (Daly et al. 2006; Slabunov et al., 2016; Babarina et al., 2017). The high-pressure event corresponded to the conditions of the continent–continent collision. The subsequent transformation of gabbronorites into amphibolites observed in the marginal parts of these and other massifs was resulted from the retrograde metamorphic processes during late stages of the same Lapland-Kola orogeny.

5 Conclusions

1. The reaction structures (coronas) in metagabbronorites from the Belomorian Province were resulted from two event of high-grade metamorphism which differ in pressure.
2. First event was low-pressure granulite metamorphism (750–950 °C and 3–5 kbar).
3. Second event was high-pressure high-temperature metamorphism (700–850 °C and 15–28 kbar) at its peak.

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