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Geodynamics and metallogeny of the Keivy domain (Baltic Shield)

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Abstract

Geodynamic and petrogeochemical study of the Keivy domain in the Baltic Shield has shown that it was overlapped by surrounding microcontinents in the Archean. As a result, the Baltic Shield was subject to cratonization. Thus, the Keivy microcontinent can be considered as the most ancient known median massif of the continental crust. Specific features of its geodynamic evolution predetermined conditions for formation of unique in scale stratiform deposits of alumina raw materials on the surface of the microcontinent. The paper describes and justifies the mechanism of alumina formation by physical-chemical decomposition of Archean and early Proterozoic metamorphosed sedimentary complexes in the Kola region of the Baltic Shield. Besides, the study of metallogenic features of transformation processes in the Archean continental crust of the Keivy microcontinent and its rimming suggests that carbonaceous schists of the Keivy domain that formed in the sedimentary cover can be significantly rich in nanogold. It will allow considering the central part of the Kola region as a major gold-bearing province. The authors believe that the metallogenic forecast based on geodynamic reconstructions is promising for further research of early Precambrian complexes. This work continues a series of publications on structural-material study of the Keivy domain.

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Геодинамика и металлогения Кейвского домена (Балтийский щит)

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ранний докембрий, неоархей, супракрустальные породы, геодинамическая эволюция, металлогения, нанозолото, глиноземистое сырье, срединный массив

Реферат

Геодинамические и петрогеохимические исследования в пределах Кейвского домена Балтийского щита показали, что в позднем архее на него были надвинуты окружавшие его микроконтиненты, в результате чего Балтийский щит вступил в режим кратонизации. Таким образом, Кейвский микроконтинент можно считать древнейшим из известных на сегодня срединных массивов континентальной коры. Вследствие специфики геодинамической эволюции на его поверхности возникли условия формирования уникальных по объемам стратиформных залежей глиноземистого сырья. В статье описывается и обосновывается механизм формирования глинозема за счет физико-химического разложения метаморфизованных осадочных комплексов архея и раннего протерозоя Кольского региона Балтийского щита. Исследования металлогенической направленности процессов преобразования континентальной коры архея в пределах Кейвского микроконтинента и его обрамления позволяют предположить также, что формировавшиеся в осадочном чехле углеродистые сланцы Кейвского домена могут быть существенно обогащены нанозолотом. Это позволит центральной части Кольского региона стать крупной золотоносной провинцией. Авторы считают, что металлогенический прогноз на основе геодинамических реконструкций представляется перспективным направлением дальнейших исследований раннедокембрийских комплексов. Данная статья является продолжением серии публикаций по структурно-вещественному исследованию Кейвского домена.

Для цитирования

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Introduction

The Keivy domain occupies the northeastern part of the Baltic Shield and borders with the Kola-Norwegian domain in the east and west and with the Murmansk domain in the north. In the south, it is constrained by the Early-Proterozoic rocks of the Pechenga-Imandra-Varzuga-Ust-Ponoy greenstone belt (Fig. 1). The Keivy domain typically includes a proveniance of Archean igneous continental-crust rocks, which are tectonically confined to the Keivy domain overlain by a volcano-sedimentary cover in its southwestern part. This structural unit may be considered as a special domain of the Kola Precambrian deep-seated collision structure (*Митрофанов и др., 1997*).

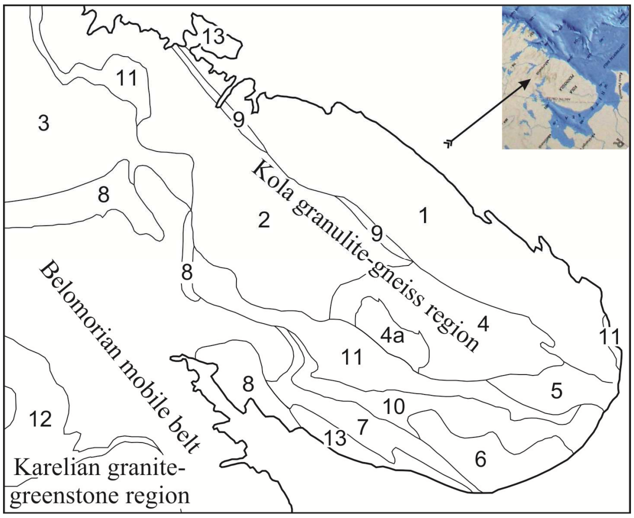

Fig. 1. Schematic zoning of Early Precambrian geostructural elements in the Earth's crust of the northeastern Baltic Shield (*Козлов и др., 2019*). Crustal domains: 1 – Murmansk; 2 – Kola-Norwegian; 3 – Lotta; 4 – Keivy; 4a – Verkhneponoysky; 5 – Eastern Kola; 6 – Chapoma; 7 – Tersky. Greenstone and granulite belts: 8–10 – Archean: 8 – Lapland-Kolvitsa; 9 – Titovka-Kolmozero (Kolmozero-Voronya); 10 – Sergozersky-Strelninsky; 11, 12 – Neoproterozoic: 11 – Pechenga-Imandra-Varzuga-Ustponoysky; 12 – Northern-Karelian; 13 – Riphean rift and continental marginal sediments

Рис. 1. Схема районирования раннедокембрийских геоструктурных элементов земной коры северо-восточной части Балтийского щита (*Козлов и др., 2019*). Домены коры: 1 – Мурманский; 2 – Кольско-Норвежский; 3 – Лоттинский; 4 – Кейвский; 4а – Верхнепонойский; 5 – Восточно-Кольский; 6 – Чапомский; 7 – Терский. Зеленокаменные и гранулитовые пояса: 8–10 – архейские: 8 – Лапландско-Колвицкий; 9 – Титовско-Колмозерский (Колмозеро-Воронья); 10 – Сергозерско-Стрельнинский; 11, 12 – неопротерозойские: 11 – Печенга-Имандра-Варзуга-Устьпонойский; 12 – Северо-Карельский; 13 – рифтогенные и окраинно-континентальные отложения рифейского возраста

The supracrustal units of the Keivy domain are described in (*Бельков, 1963; Геология..., 2002*). The rocks are mainly represented by biotite and amphibole gneisses, two-pyroxene crystalline schists and garnet-biotite gneisses. The intrusive unit is composed of gabbro-anorthosites, potassium and alkaline granites. The U-Pb age of zircons from the metamosphosed rhyodacites of the Lebyazhinskaya Suite is 2,871±15 Ma (*Беляев и др., 2001*). The researchers of the Keivy domain have examined possible reasons for the peculiarities of the composing rock assemblages. One of the reasons includes regional metasomatic processes genetically related to the alkaline granite bodies (*Козлов и др., 2017*). Their age is reliably determined to be 2,751±41 Ma (*Позднеархейский..., 2001*). The studied compositional features at the bottom of the Keivy mafic metamorphic volcanic rocks suggest that their protoliths could be the most ancient formations within the Kola Peninsula (*Kozlov et al., 2018*).

A detailed geological and petrogeochemical study of the Keivy metamorphic rocks allowed the authors to demonstrate earlier that it could be considered as a special domain located within the Kola Precambrian deep-seated collision structure. However, no preferred affinity of the Keivy rocks to any geodynamic structural (granite-greenstone or granulite-gneiss) type has been identified. It shall also be noted that the evolutional nature of the Archean stage in the development of the Keivy domain significantly differs from all the adjacent continental-crust formations in the eastern part of the Baltic Shield.

The cover-type volcano-sedimentary rocks are the earliest within the Keivy domain. The available data indicate their near-constant accumulation in the internal domain areas during cratonization.

The border interaction of the Keivy domain and other circumfluent continental-crust rocks is underexplored. No Late Archean metamorphism has been found within it although traces of collision with other domains should have resulted in a peripheral low-gradient contact metamorphism.

In addition to the volcano-sedimentary rock units, alkaline granites are also common in the domain. The emplacement age of these granites is estimated to vary within 2,630–2,760 Ma (*Батиева, 1976; Bayanova et al., 1998*). The zircon age for the porphyroblastic granites of the Kolovaysky massif cutting through the rocks of the Lebyazhinskaya Series is found to be 2,620±30 Ma (*Пушкарев, 1990*). The syntectonic grabbro-anorthosites intruded near the contact zone between the Upper-Ponoy block and Keivy domain 2,760±80 (*Composition…, 2008*) or 2,659±3 million years ago (*Bayanova et al., 1998*).

The geodynamic and petrogeochemical studies executed within the Keivy microcontinent have demonstrated that it was buried at some depth in Late Archean by the adjacent overthrusted continental-crust domains of the Kola region. As a result, the Keivy microcontinent may be considered as the oldest median massif of the continental crust within the worldwide Late Archean collision areas (Fig. 2).

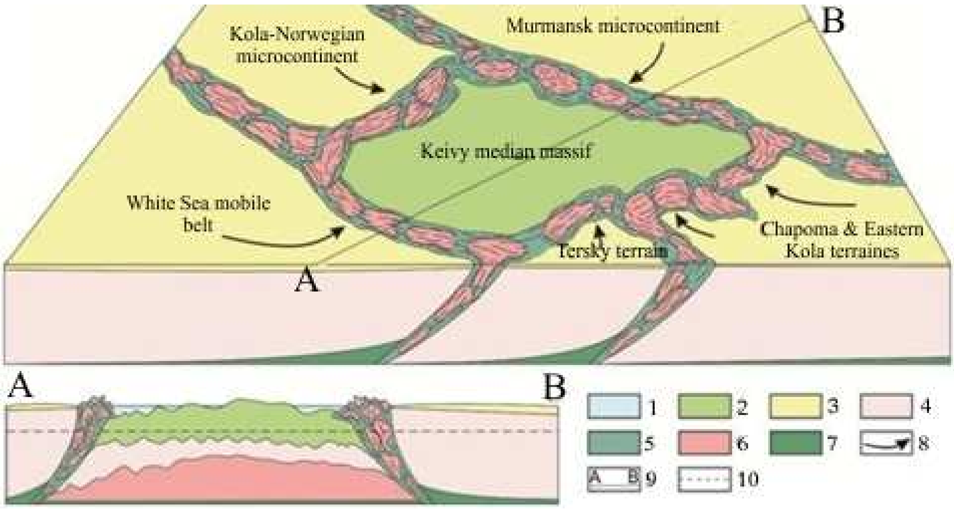

Fig. 2. Peculiar features of the Keivy median massif formation in the late Archean:
1 – water basin; 2 – sedimentary cover of the Keivy median massif; 3 – sedimentary cover of adjacent terrains and microcontinents; 4 – continental crust; 5 – folds of the greenstone type; 6 – synorogenic tonalite-trondhjemites, granodiorites, migmatite granites, and remobilized crust of the Keivy median massif; 7 – subcrustal mantle; 8 – direction of collisional thrusting of microcontinents and terrains over the Keivy median massif; 9 – section line; 10 – contemporary level of the erosional truncation (*Козлов и др., 2019*)
Рис. 2. Закономерности формирования Кейвского срединного массива в позднем архее: 1 – водный бассейн; 2 – осадочный чехол Кейвского срединного массива; 3 – осадочный чехол сопредельных террейнов и микроконтинентов; 4 – континентальная кора; 5 – складчатые образования зеленокаменного типа; 6 – синорогенные тоналит-трондьемиты, гранодиориты, мигматит граниты и ремобилизованная кора Кейвского срединного массива; 7 – подкоровая мантия; 8 – направление коллизионного надвигания микроконтинентов и террейнов на Кейвский срединный массив; 9 – линия разреза; 10 – современный уровень эрозионного среза (*Козлов и др., 2019*)

For example, the South-Chinese and Chinese-Korean lithospheric plates may be regarded as younger analogues to this type of geological structures. In accordance with available geological and geophysical data, the dip azimuths of all domain borders are oriented towards its junction with other crust areas; the domain itself has a shape of a truncated pyramid.

Materials and methods

This research attempts to find compositional features of supracrustal rock units that argue for or against the above geodynamic reconstructions at a substance level. It is based on an assumption that, within a proposed emplacement model for the Keivy rock units, its various areas should have been compositionally similar to the substance of adjacent domains to a different extent. Its northern part should have demonstrated a more significant similarity with the Murmansk domain rocks than the southern one. The latter, on the contrary, should have been closer to the Tersky domain and White Sea mobile belt rock assemblages than the northern one. The resemblance between the western and eastern parts of the Keivy and Kola-Norwegian blocks should have manifested in a similar way (Fig. 1–3).

Due to the absence of necessary data on the rock composition of the Chapoma and East-Kola terrains, possible similarity or difference from the rocks of the eastern and southeastern frame of the Keivy domain has not been studied.

This task was solved using a method for the identification of affinity between the study objects on the basis of selecting homogenous groups (*Kozlov et al., 2018*), and namely, between the rock assemblages of the

Keivy domain and surrounding rock units such as the Murmansk domain from the north, White Sea mobile belt and Tersky domain from the south, Kola-Norwegian domain from the west, and Chapoma and East-Kola terrains from the east. The essence of the method is as follows.

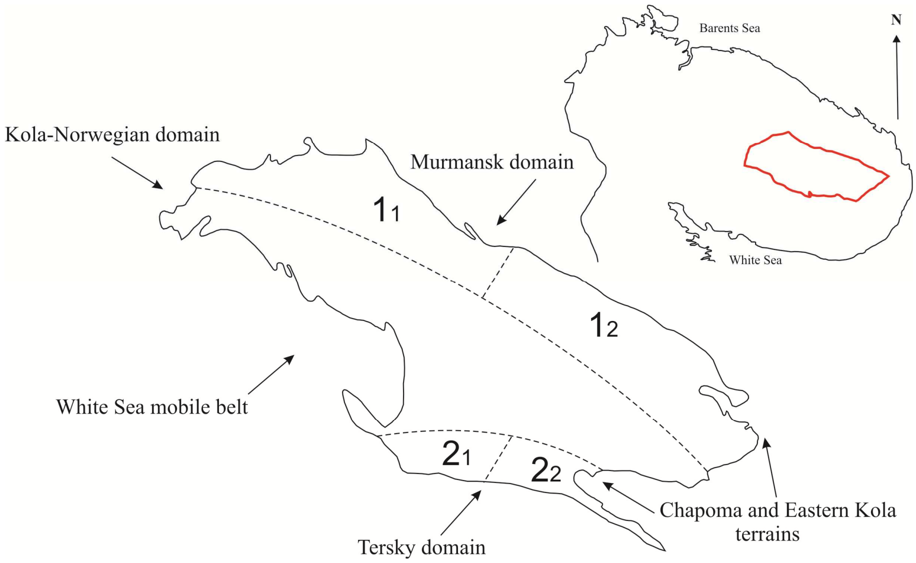

Fig. 3. Scheme of location of the study areas within the Keivy domain (*Козлов и др., 2019*)
Рис. 3. Схема расположения исследуемых участков в пределах Кейвского домена (Козлов и др., 2019)

The initial stage of correlation is based on the first pair of targets (Fig. 4), for example, the Keivy (X) and the Murmansk domains (Y) represented by the sets of n-dimensional vectors $X = \{X_i \mid 1 \le i \le l\}$ and $Y = \{Y_i \mid 1 \le i \le m\}$. It is necessary to evaluate the distance from the set of points X to the set of points Y. This is proposed to rely on the following procedure:

1. The set Y is divided into homogenous groups $\{Y_k\}$. For each vector $X_i \in X$ the Euclidean distance (or proximity) to the convex hull of each found homogenous groups $\{\text{co}(Y_k)\}$, i. e. $\rho(X_i,\text{co}(Y_k))$. After that, minimum distances to the convex hull of each homogenous group Y_k, i. e. $r_{ik} = \min_k \rho(X_i,\text{co}(Y_k))$ are derived from the set $\{\rho(X_i,\text{co}(Y_k))\}$.
2. The median value $\text{Me}(R_1)$ is calculated for the resultant set $R_1 = \{r_{ik}\}$.
3. The median value $\text{Me}(R_1)$ is taken as the proximity estimate between the study objects X and Y, i. e. $R(X,Y)$.

This procedure is repeated through steps 1, 2 and 3 performed for further compared pairs:

- Keivy domain and Kola-Norwegian domain;
- Keivy domain and White Sea mobile belt together with the Tersky domain.

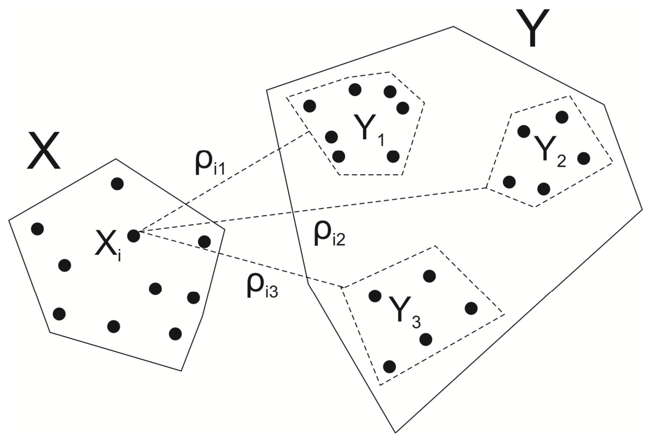

Fig. 4. Defining the proximity between study objects X and Y, where X_i is the selected n-dimensional vector, $\{Y_1,Y_2,Y_3\}$ – homogenous groups (hatching indicates borders of convex hulls of homogenous groups), $\{\rho_1,\rho_2,\rho_3\}$ – distances from X_i to convex hulls of homogenous groups, i. e. to $\{\text{co}(Y_1),\text{co}(Y_2),\text{co}(Y_3)\}$ (*Козлов и др., 2019*)
Рис. 4. Определение близости между исследуемыми объектами X и Y, где X_i – выбранный n-мерный вектор, $\{Y_1,Y_2,Y_3\}$ – однородные группы (штриховкой обозначены границы выпуклых оболочек однородных групп $\{Y_1,Y_2,Y_3\}$), $\{\rho_1,\rho_2,\rho_3\}$ – расстояния от X_i до выпуклых оболочек однородных групп, т. е. до $\{\text{co}(Y_1),\text{co}(Y_2),\text{co}(Y_3)\}$ (*Козлов и др., 2019*)

Thus, there are three sets, and namely: R_1 for the proximity of the Keivy domain rocks to the Murmansk domain rock assemblages, R_2 for the proximity of the Keivy domain rocks to the Kola-Norwegian domain rocks and R_3 for the proximity of the Keivy metamorphic rocks to the supracrustal rock units of the White Sea mobile belt together with the Tersky domain rocks.

The final modeling stage involves calculation of the Puri-Sen-Tamura statistics for the sets R_1, R_2 and R_3, which allows evaluating the statistical significance of the resultant difference of the Keivy metapelites from the surrounding rocks. The below table shows proximity factors (Me(R_1), Me(R_2) and Me(R_3)) for the composition of the studied Keivy rocks to the relevant compared objects and values of the Puri-Sen-Tamura statistics. The less the values of the given factors, the closer the compared objects.

Further, the correlation was carried out consequently with the rocks of each domain surrounding the Keivy domain to evaluate the similarity of substance in any part of it with each of the domains, excluding possible influence of substance from any of the domains on the result in case of absolute predominance of the Keivy metasedimentary rocks in its lithologies. The central part of the Keivy domain, where the substance of the surrounding domains could be mixed to an ultimate degree, was dismissed from the research.

Results and discussion

The reconstruction of the rock composition for feeding provinces most frequently relies on the data about the composition of conglomerate pebbles and sandstone fragments. However, such geological buildups are quite exotic for the Precambrian and hardly accessible for study. This is the reason why the emplacement peculiarities of the Precambrian sedimentary rock units have long been successfully studied using data about the composition of metapelites with low permeability for post-sedimentation fluids and much better mixed and homogenized as compared to larger-grained deposits (*Maslov et al., 2008;Podkovyrov et al., 2015*). This paper examines their composition due to the abundance in the Keivy domain.

The correlation results obtained in the course of mathematical modeling confirm the above geological and geophysical model of the Keivy domain evolution in the Early Precambrian.

The results obtained during the research of the metapelite composition within various parts of the Keivy domain are not in conflict with a model earlier proposed on the basis of geological and geophysical data about the emplacement model under the conditions typical of median massifs. This, in turn, allows a somewhat different view of the issues related to the Keivy metallogeny. It is believed that the landscape of the Keivy median massif formed at the border of the Archean and Early Proterozoic corresponded to a plain locked by high mountain masses.

In accordance with this research, the surface of the Keivy domain represented a shallow-water basin formed in a subequatorial zone. This assumption appears from the point that the first supercontinent (Monogea or Pangea-0) in the Earth's history took shape back then on its surface, and this could only form near the equator in accordance with the Earth's rotational mechanism (*Sorokhtin et al., 2011*). The chemical rock composition of the mountains encircling the Keivy domain was typical of the Archean. These are mainly tonalite-trondhjemites and granodiorites, subalkaline basaltoids, ultramafic rocks, and anorthosites. Their decomposition resulted in a series of typical sedimentary sequences rich in aluminum and potassium. These deposits accumulated in tectonically quiet and possibly warm lagoonal Neoarchean climate.

Table. Comparison of metapelite compositions in respective areas of the Keivy structure with rocks of surrounding domains (see Fig. 3)

Таблица. Сравнение состава метапелитов соответствующих частей Кейвской структуры с породами окружающих ее доменов (см. рис. 3)

	Northern part of the Keivy domain (groups 1_1 and 1_2 in Fig. 3)	Southern part of the Keivy domain (groups 2_1 and 2_2 in Fig. 3)
MB*	**7.898****	9.432
WS+Ter	9.402	**8.781**
	Western part of the Keivy domain (groups 1_1 and 2_1 in Fig. 3)	Eastern part of the Keivy domain (groups 1_2 and 2_2 in Fig. 3)
KN	**7.773**	10.435

Notes. * MB – Murmansk block; WS+Ter – White Sea mobile belt and Tersky domain combined into a common group of rock units framing the Keivy domain from the south; KN – Kola-Norwegian domain; ** proximity factors of the Keivy metapelites to the rocks of any geological unit. The values describing the maximum proximity of compared objects at a chosen significance level of 0.01 are put in bold.

The geodynamic setting affected the Keivy median basin to accumulate an extensive sedimentary cover on its surface. The buried continental-crust rock assemblages at a high temperature gradient in the Late Archean inevitably underwent partial melting and remobilization. It is due to this process numerous alkaline granite intrusions peripherally intruded the sedimentary sequences of the Keivy domain through the weakened zones.

Their emplacement time complies with the cratonization of the system and generation of tectonic relief setting for the domain mainly at the expense of the reducing geothermal gradient. This resulted in an overall and essential cooling of the system triggered numerous faults in the domain's peripheral areas and intrusion of abundant and imminently fluid-saturated magmas for alkaline granites, which represented the remobilized lower-crustal matter.

It is worth emphasizing in this regard that the geodynamic setting of the median massif implies relative confinement of denudation of adjacent orogens. This resulted in removing all clastics to its surface, physical and chemical transformations of sediments and accumulation of thick sedimentary cover sequences. In our opinion, this favoured generation of giant aluminum deposits and wide fields of potassium metasomatism after terrigenous sediments within the Keivy median massif.

In order to trace the process of chemical transformations within the Keivy sedimentary cover, a series of main reactions should be examined. Thus, at the denudation of orogenic units in the adjacent domains of the continental crust, orthoclase ($K(AlSi_3O_8)$), albite ($Na(AlSi_3O_8)$), anorthite ($Ca(AlSi_2O_8)$), and microcline (orthoclase polymorph) are among the major rock-forming minerals in trondhjemites, tonalities and granodiorites, which decompose in the presence of water by the following reactions:

$$\underset{\text{orthoclase}}{K(AlSi_3O_8)} + nH_2O + CO_2 \rightarrow \underset{\text{kaolinite}}{Al_4[Si_4O_{10}](OH)_8} + \underset{\text{potash}}{K_2CO_3} + \underset{\text{opal}}{SiO_2 \times nH_2O},$$

or:

$$\underset{\text{anorthite}}{2Ca(AlSi_2O_8)} + 6H_2O \rightarrow \underset{\text{kaolinite}}{Al_4[Si_4O_{10}](OH)_8} + \underset{\text{calcium hydroxide}}{2Ca(OH)_2}$$

and

$$\underset{\text{albite}}{Na(AlSi_3O_8)} + 2H_2O \rightarrow \underset{\text{kaolinite}}{Al_4[Si_4O_{10}](OH)_8} + 4NaOH + \underset{\text{hydrated silica}}{8H_4SiO_4}.$$

As well, under the hypergenesis conditions and in warm humid climate, orthoclase may decompose into hydromicaceous minerals, which further form kaolinite. For example:

$$6K(AlSi_3O_8) + 2CO_2 + 2H_2O \rightarrow 2KAl_2[AlSi_3O_{10}](OH)_2 + 2K_2CO_3 + 12SiO_2.$$

Muscovite, in turn, may form kaolinite and potassium carbonate in the presence of carbon dioxide and water by the following reaction:

$$4KAl_2[AlSi_3O_{10}](OH)_2 + 2CO_2 + 8H_2O \rightarrow Al_4[Si_4O_{10}](OH)_8 + 2K_2CO_3.$$

Further hydrolysis processes occurred at the Archean and Proterozoic boundary in the Keivy domain could result in generation of laterite (red clay mineral) and silicon oxide:

$$Al_4[Si_4O_{10}](OH)_8 \rightarrow H_2Al_2O_4 + SiO_2 \times nH_2O$$

or hydrargillite and opal:

$$Al_4[Si_4O_{10}](OH)_8 \rightarrow Al(OH)_3 + SiO_2 \times nH_2O.$$

The hydrargillite contains over 65 % of silica (Al_2O_3).

Further, when the evolved sedimentary cover of the Keivy domain was overlain by younger sediments and tectonic thrusted plates of framing orogenic units in the Kola region, the sedimentary cover was dehydrated, heated up and yielded famous kyanite schists. This process is described by a simple endothermic reaction:

$$\underset{\text{kaolinite}}{Al_4[Si_4O_{10}](OH)_8} \rightarrow \underset{\text{kyanite}}{Al_2OSiO_4} + 2H_2O.$$

The same reaction may be presented in a simpler and understandable way:

$$Al_2O_3 \times 2SiO_2 \times 2H_2O \rightarrow Al_2O_3 \times 2SiO_2 + 2H_2O.$$

In our opinion, the unique kyanite deposits could occur in the Neoarchean.

In addition to the above processes, it should be noted that the decomposition and redeposition of the tonalite-trondhjemite and granodiorite series rocks were accompanied by the generation of abundant potassium salts (K_2CO_3). These are highly water-soluble and most likely resulted in salinization of the Keivy water-saturated sedimentary sequences of that time. Later, during their metamorphic transformations potassium served as a building material for metasomatic microcline (alkaline) granites, which are abundant in the periphery of the domain.

The established affiliation of the Keivy domain to the units similar to Phanerozoic median massifs, e. g. to the Tarim massif in terms of geodynamic features allowed Ye. N. Fomina and coauthors (*Fomina et al., 2019*) to draw, based on carbon isotopic data, a conclusion of possible Precambrian oil-and-gas-being basin existed in the sedimentary cover of the Keivy domain. This seems reasonable, but it has to be understood that almost over the past 3 billion years high-carbon rock sequences were naturally transformed into graphite. The sulfur contained in the hydrocarbons of that time passed into sulphides. Thus, the entire data pool about the geodynamic history of the Keivy domain may indicate a high chance of finding carbonaceous shale deposits there with promises of gold content. This follows from the point that Early Proterozoic hydrocarbon basins had a bacterial origin, accumulated in warm and humid settings and could concentrate certain metals. Their main part was oxidized with time and removed by hydrothermal flows as a result of superimposed metamorphic processes. More inert gold, though, could remain in situ and form finely dispersed impregnations in graphite schists. This is still an assumption, which requires further close examination.

Conclusions

The data related to the geodynamic evolution of the Keivy rock units obtained during this research allow implying that the metallogenic prediction on the basis of geodynamic reconstructions seems to be a promising trend for further studies. It is particularly essential for Early Precambrian regions since the authors have earlier described and validated a polycyclic and multistage mechanism for the enrichment of the continental Earth's crust with ore elements, which results in the increasing concentrations of commercial components in ore bodied from ancient to juvenile complexes both in the Phanerozoic and Precambrian. The present geodynamic and geochemical research allows explaining generation of aluminum feedstock unique in terms of volume within the Keivy median massif. As well, the paper scrutinizes a multistage transformation mechanism of the regional continental-crust rock assemblages and generation of commercial aluminum raw material. It is also believed that the carbonaceous shales of the Keivy domain may be enriched with nanogold and become one of the major gold-bearing provinces of the Kola Peninsula along with high-alumina formations.

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