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Article

The Keivy Domain of the Kola Granulite–Gneiss Area on the Baltic Shield: Most Ancient Median Massif of the Continental Crust

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Abstract: Studies of lithotectonic formations within the Keivy domain of the NE Baltic Shield have shown that the domain was tectonically overlapped by adjacent microcontinents during regional collision processes in the Late Archean. As a consequence, the continental crust of the Keivy domain was submerged, relative to other blocks of the continental crust, and the described domain acquired the features of a classical median massif. Surrounded on all sides by collision systems, the Keivy median massif entered the cratonization regime. This led to intensive processes of denudation of the surrounding domains of the crust and the accumulation of a thick sedimentary cover on the surface. The described processes occurred during the formation of the first supercontinent (Monogea) in the history of the Earth and the manifestation of the Early Precambrian Huronian glaciation, which left its traces on most domains of the Earth's continental crust. Thus, the processes of peneplain formation within the Keivy massif occurred under the cold weather conditions, high volcanic activity in the peripheral zones, and sedimentary cover saturation with the products of the physical and chemical mineral transformation of tonalite–trondhjemite and greenstone rock assemblages. The unique combination of certain geodynamic and climatic cycles on the Baltic Shield in the Late Archean led to the accumulation of extensive stratiform deposits of alumina raw materials within the Keivy median massif.

Keywords: median massif; Early Precambrian; Neoarchean; supracrustal rocks; Huronian glaciation; geodynamics; metallogeny; geochemistry; alumina raw materials; kyanite

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1. Introduction

The formation of the Earth's continental lithosphere began about 4.0–3.8 billion years ago. The first supercontinent, Monogea, was formed at the Archean–Proterozoic transition (~2.6 Ga). It united all the relatively small and uneven-aged blocks of the Earth's crust, thus forming a peculiar mosaic structure of ancient crystalline shields.

As the Earth formation model, we assumed the model first described by Schmidt [1,2] and later modified by Safronov [3]. According to this model, the Earth and other planets of the solar system were formed due to the accretion of cold and homogeneous matter of the protoplanetary cloud. After its birth, the Earth was a relatively cold body, with temperatures in the center of the planet not exceeding 800–1500 K [3–5].

Since the position of the continents on the surface of the rotating Earth markedly distorts the symmetry of its moment of inertia, continent assembling occurs in such a way that its center of gravity is at or near the equator [6,7]. At the same time, in the Archean and Early Proterozoic, the average level of the continents above the rift zones and oceans reached 6 and 5–3 km, respectively [8]. Therefore, despite the hot Archean climate and the significantly cooled, but still warm climate of the Early Proterozoic, high-mountain ice sheets could well have developed on the continents of that time. Indirect evidence suggests that this is the wide distribution of conglomerates in the Early Proterozoic (such as the Witwatersrand Formation in South Africa), which were deposited in abundance at the margins of many ancient cratons [9–11].

It should be noted that at the Archean–Proterozoic transition, a predominantly nitrogen-based atmosphere existed on Earth, with a pressure of approximately 1.5 atm [12,13]. Along with the high elevation level of the continents, this should have led to the extensive high-mountain glaciation in the Early Proterozoic, covering the entire central part of the Monogea supercontinent [8]. Numerous data on tillites and tilloids, dated to 2.5–2.2 billion years ago, support our conclusions and allow us to hypothesize that the first global Early Proterozoic Huron glaciation, in the history of the Earth, covered most of the shields of ancient continental platforms [14].

Reconstruction of the position of ancient continental massifs at the Archean and Early Proterozoic stages of evolution is very difficult. Paleomagnetic methods are often used for the reconstruction of supercontinents [15–18]. The processes of the unique evolution of the Earth, in the Early Precambrian (Gadean and Archean), led to the fact that the differentiation of the planetary material into the core, mantle, and lithosphere occurred only at the Archean–Early Proterozoic transition (about 2.6 billion years ago). That is why in the Archaean, the magnetic (dipole) field familiar to us today could not exist. Instead, there was a toroidal field, due to the absence of an iron–nickel core in the center of the Earth. The mechanism of the Earth's evolution, at the early stages of its development, is described in detail in [12]. Consequently, the obtained paleomagnetic data, on the rocks of the Archean and Early Proterozoic, will be correct only when determining the longitude. An adequate determination of the latitude, in this case, is not possible. As a result, paleomagnetic data related to Precambrian (and in particular, to the Early Proterozoic) are not very reliable, and their linking to age horizons, in many cases, remains uncertain. That is why, for the reconstruction of Precambrian supercontinent positions, as well as positions of the individual continental massifs and continents, we avoided the use of paleomagnetic data, as these might completely distort such reconstructions.

For all the reconstructions, we only employed geological and paleoclimate data linking similarly aged geological structures, formations, and climatic provinces with similar characteristics. For this purpose, we relied on data available from the special literature on Early Precambrian geology [19–24]. In particular, for the Monogea reconstruction, we utilized the data on tillite and tilloid development on Early Proterozoic continents [25]. We used a criterion of compact positioning of known sites of the Early Proterozoic tillites in consideration of possible inheritance of the continents' positions on the Earth's surface during subsequent geological epochs. In such a reconstruction, the "center of gravity" in geographic locations, of the identified tillites and tilloids, approximately defines the mass center of a supercontinent, itself. Moreover, we took into account the structure and strike of the Kenoran belts and associated orogeneses (~2.6 Ga), and also the fact that in the Early Proterozoic, the eastern part of South America (Brazilian Craton) was still merged with the Central and possibly South parts of Africa, but separated from the western part of the South American (Amazon) platform. Additionally, the western part of Africa at that timewas most likely still attached to the Guyana shield of South America [12]. Evidently, at the Archaean–Proterozoic boundary, the other ancient platforms were broken up into parts, and their fragments (Archaean shields) may have occupied different positions than those current. However, there are no reliable geological data about possible displacements of other shields at the end of the Archaean, which is why our Monogea reconstruction (Figure 1) shows other platforms with their present-day configuration and relative positions of their Archaean components.

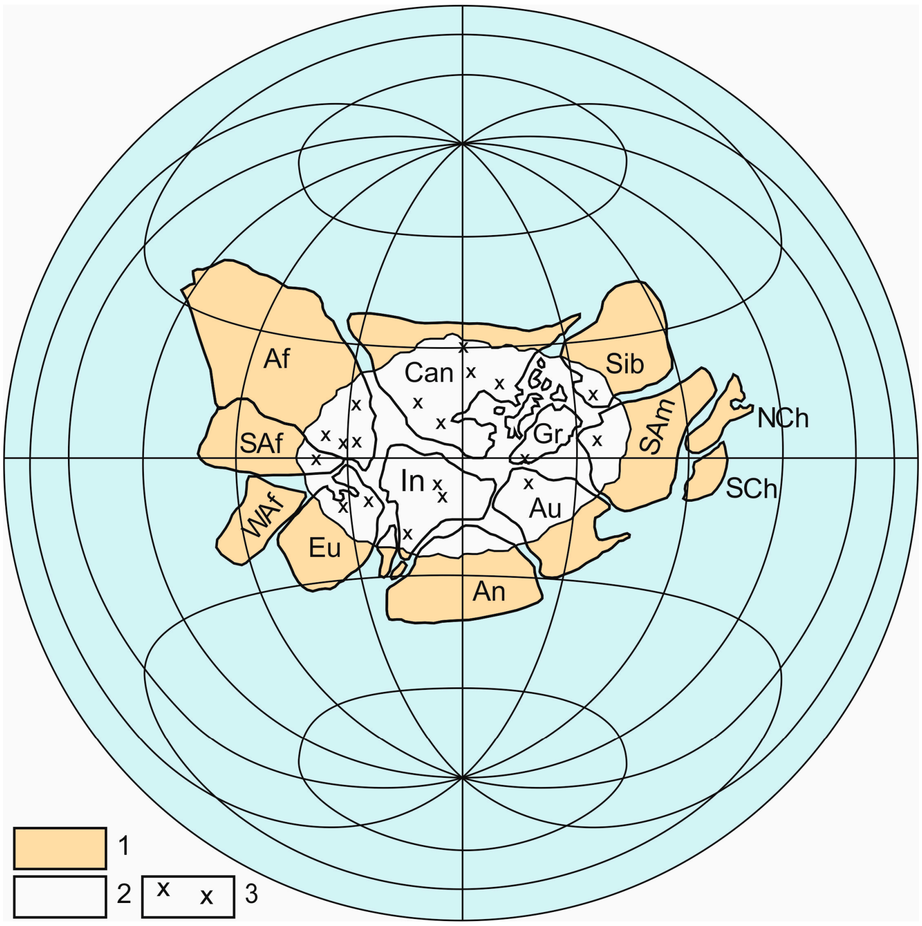

Figure 1. Reconstruction of the Monogea supercontinent (2.5–2.4 Ga) in the Lambert projection. 1—consolidated continental crust free of tillites and tilloides; 2—glaciation areas (may be more extensive); 3—tillites, tilloides, and glacial striation. Au for Australia; NAm and SAm for North and South America, respectively; AN for Antarctic; WAf, CAf, and SAf for West, Central, and South Africa, respectively; EU for Europe; IN for India; KZ for Kazakhstan; NCh and SCh for North and South China, respectively; SIB for Siberia.

2. Geology of the Keivy Median Massif

The Keivy domain is positioned in the central part of the Kola Peninsula (or the western Arctic zone of the Russian Federation). It has boundaries with the Kola–Norwegian domain in the west and on the Murmansk domain in the east. It is confined by the Early Proterozoic formations of the Pechenga-Imandra-Varzuga-Ust-Ponoy greenstone belt in the south (Figure 2). Conventionally, the Keivy median massif includes a marginal zone of the Archean magmatic continental crust formations in its south-western part, which is, according to its characteristics, attributed to the Belomorian mobile belt. It neighbors the Upper Ponoy structure, which was tectonically separated from the Belomorian belt in the Early Proterozoic, when the Imandra–Varzuga segment of the greenstone belt was forming.

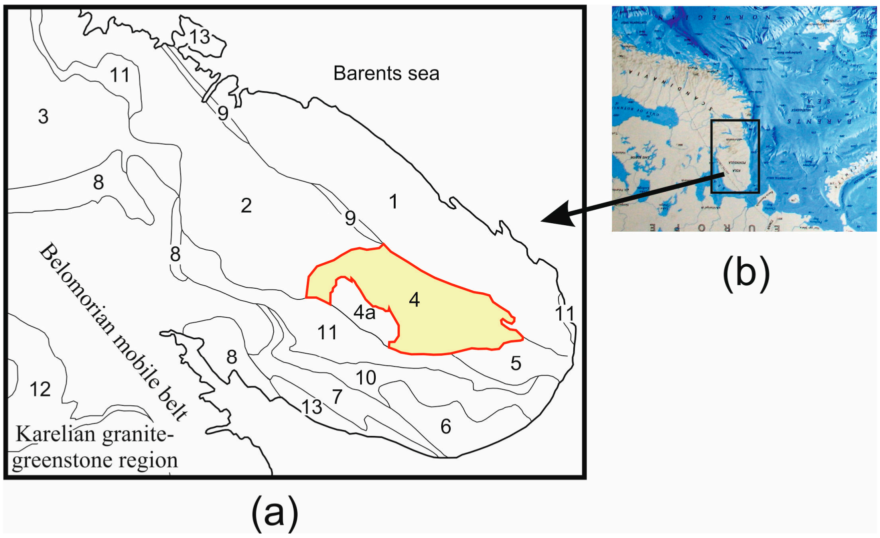

Figure 2. (**a**) sketch map of the Early Precambrian geostructural Earth crust elements in the NE Baltic Shield (after [26], modified); (**b**) the map of the southern part of the Barents Sea with marked area of our study. Crustal domains: 1—Murmansk; 2—Kola-Norwegian; 3—Lotta; 4—Keivy median massif; 4a—Upper Ponoy; 5—East-Kola; 6—Chapoma; and 7—Tersky. Greenstone and granulite belts: 8–10—Archean; 8—Lapland-Kolvitsa; 9—Titovka-Kolmozero (Kolmozero-Voron'ya); 10—Sergozero-Strel'nya; 11, 12—Neoproterozoic: 11—Pechenga-Imandra-Varzuga-Ust-Ponoy; 12—North-Karelian; 13—Riphean rift and continental-margin sediments.

The Upper Ponoy block, which belongs to the frame of the Keivy median massif, is divided into the Efimozero, Upper Ponoy, and Purnacha segments [27,28]. These structures are represented by biotite and amphibole gneisses, bipyroxene crystalline schists, and garnet–biotite gneisses. The Purnacha block is confined by faults, which control the location of gabbro-anorthosite, potassium, and alkaline granite intrusions in the north. Its core is composed of migmatite-granites while the margins consist of plagiogranites and gneisses. The Upper Ponoy block is marked by marginal faults, which define the occurrence of gabbro-anorthosites and alkaline granites. The central part of the block consists of plagiogranites with biotite and amphibole gneisses at the edges (Figure 3).

The Archean complexes beneath the supracrustal formations of the Keivy zone are identified as part of the Kola–Belomor complex and contain biotite, amphibole gneisses, and crystalline schists. They compose the Ponoy block and most of the Efimozero and Purnacha blocks [29]. Rocks of the granodiorite–tonalite–plagiogranite formation were found in pebbles from conglomerates of the lower strata [30].

The inner part of the Keivy massif is composed of the Upper Archean supracrustal rock formations, which were thoroughly examined by the predecessors [28–31]. The crystalline basement of the massif is not exposed anywhere on the surface and its position still remains unclear.

The section of the Keivy median massif includes the following formations (from the bottom up): (1) terrigenous Kolovay and Kinemur formations consisting of amphibole (hornblendite) and biotite gneisses and quartzitic schists with basement conglomerates; (2) Padcherva formation represented by amphibolites, amphibole and sericite plagioschists; (3) Lebyazhka formation of biotite garnet-bearing gneisses and plagiogneisses with relic structural features of volcanics (over-crystallized volcanic glass is found in samples) and their alkaline metasomatic products; (4) the Keivy series that comprises the Chervurt, Vykhchurt, and Pestsovaya Tundra formations comprising kyanite, staurolite, and carboniferous schists, as well as quartzites [28,30].

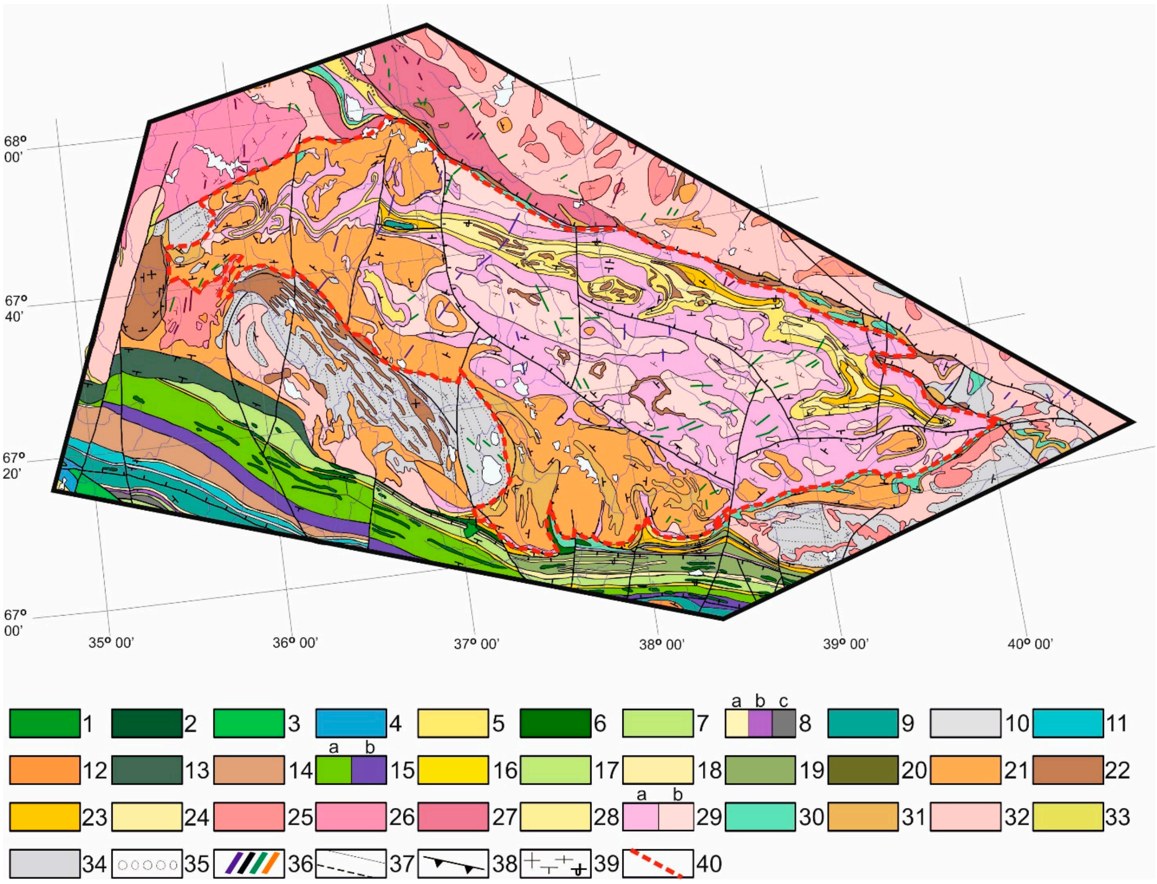

Figure 3. Geological map of the Keivy median massif. 1–19—Lower (Early) Proterozoic: 1–5 Kalevian: 1—peridotites, pyroxenites, gabbro and gabbroic anorthosites; 2—gabbro-diabases, gabbroic amphibolites; 3—basalt porphirites, diabases; 4—interbedding andesite and basalt porphyrites, tuffs, aleuropelitic schists; 5—sandstones, schists with lenses of carbonate rocks and quartzites; 6, Lyudikovian: 6—gabbro, pyroxenites; 7–10—Jatulian: 7—diabases, tuffs, and tuff breccias; 8(a–c): 8a—arkosic sandstones, quartzites; 8b—limestones, dolomites; 8c—siltstone schists, phyllites; 9—diabases, basalt, andesite porphyrites, tuffs, alkaline basalts; 10—limestones, dolomites and carbonate schists; 11–19—Sariolian: 11—picrite, diabase porphyrites and tuffs; 12—alkaline granites and syenites; 13—peridotites, pyroxenites and gabbronorites; 14—rhyolite-dacites, dacites and andesite-dacites; 15(a,b): 15a—basalt porphyrites; 15b—mandelstones, diabases; 16—quartzites, feldspar-quartz metasandstones; 17—diabases, tuff breccias and amphibolites; 18—arkosic metasandstones, limestone sandstones, limestones and conglomerates; 19—andesite-basalts, amphibolites; 20—unstratified complexes of uncertain age: 20—gabbro-amphibolites, metaultrabasites; 21–34—Upper (Late) Archean: 21–32—Lopian: 21—subalkaline granites; 22—gabbro, gabbro-labradorites, mafic dikes d1; 23—metagritstones, metasandstones and arkosites; 24—quartzites, muscovite-quartz and plagio-kyanite-staurolite schists; 25—leucogranites, granodiorites; 26—enderbites, granites, granodiorites and monzodiorites; 27—diorites, granodiorites, plagiogranites, diorites, granodiorites and plagiogranites; 28—mica, garnet-mica paragneisses and schists; 29(a,b): 29a—acid, intermediate metavolcanics; 29b—hastingsite gneisses; 30—mafic metavolcanics, metakomatiites; 31—mica, garnet-mica paragneisses and schists, conglomerates, quartzites; 32—granodiorites, tonalites and plagiogranites; 33—Kola-Belomorian unstratified complex: mica, garnet-mica gneisses with kyanite and (or) sillimanite; 34—basement complex: biotite, amphibolite and pyroxenite-biotite gneisses, migmatites, tonalite gneisses, granodiorite gneisses, and amphibolites; 35—conglomerates; 36—dikes; 37—geological borders and orientation, structural lines; 38—overthrusts; 39—schistosity, gneissic banding, oversteepened; 40—boundary of the Keivy domain.

The rocks referred to the Varzuga series [28] are distributed in the central part of the Keivy domain in small amounts. The series consists of the following three formations: (1) carbonate rocks, phlogopite (muscovite-quartz-feldspar) and diopside–tremolite rocks, and metasandstones; (2) amphibolites, metamandelstones, and metaporphyrites; (3) two-mica, garnet–biotite plagioschists and garnet–biotite plagioschists with amphibole, and quartzite-sandstones.

In the Keivy median massif, alkaline gneiss-granites or granites (in various interpretations) are common. Spatially, they tend to occupy the periphery of the domain, and mark the borders of junctions with other continental crust rocks. There is still no generally accepted view on the nature of these rocks. They have features of typical igneous complexes, but those seem to have formed after rocks of the Lebyazhka series. Some researchers recognize their igneous nature [32], while others attribute them to rock metasomatites [33,34]. Alkaline granites produce dome-like structures and are formed by rheomorphism and remobilization of the volcano–sedimentary complex of the Lebyazhka series, according to M.V. Mints [34]. Zozulya et al. in [35] suggested that alkaline granites had been formed as dike-like or sheet bodies with a thickness of a few hundred meters. The Western Keivy and Ponoy massifs have a subhorizontal geometry, while the Lavrentiyevsky, Belaya Tundra, Pachin and Lower Ponoy massifs are subvertical. There are mostly gneissic granites, but the degree of gneissic banding varies within the same body and between various bodies. The Kulyok and Sakharyok massifs are made up of nepheline and alkaline syenites. Some features of the geochemistry of alkaline granites are considered in [36].

3. Petrographic Rock Description

The detailed description of the petrography is given in publications [26,28,31,37], so here we include only a brief description of the Keivy domain rocks.

3.1. The Kolovay and Kinemur Formations

3.1.1. The Kolovay Sequence

Amphibole and biotite gneisses—fine-grained gneisses of gray and dark-gray coloration with roundish quartz segregations. Sometimes they are very thinly banded due to alternation of thin interbeds, variously enriched in biotite. The structures developed in gneisses are, as a rule, lepidogranoblastic. They are composed of quartz (20–40%), plagioclase (oligoclase, oligoclase-andesine, 30–50%), hornblende (up to 5–10%), microcline (10–30%), biotite (5–7%). As accessories, they are present in allanite, titanite, apatite, magnetite, pyrite, and zircon.

3.1.2. The Kinemur Sequence

The biotite gneisses are of gray and yellow-gray coloration, schistous texture and lepidogranoblast structure. Composed of biotite (10–15%, up to 25%), plagioclase (albite-oligoclase, 15–55%), quartz (15–85%), muscovite (5–15%), chlorite, and sometimes garnet. The accessories are apatite, zircon, titanite, and allanite.

The quartzite-like schists with conglomerates at the base—interbeds with lens-shaped and ellipsoid segregations of quartz and plagio-granite composition.

3.2. The Padcherva Formation

Amphibolites—fine-grained and fine-porphyroblast rocks, with variously oriented porphyroblast inclusions of amphibole, are identified in the fine-grained, substantially plagioclase main mass. Amphibolites are composed of a regular hornblende (up to 80%), plagioclase (oligoclase-andesine, 20–50%) with insignificant amounts of quartz, garnet, epidote, biotite and carbonate (up to 5–10%), and accessories, such as titanite, magnetite, and ilmenite.

Biotite and sericite plagio-schists are plagio-gneisses with relic psammite structure composed of quartz, plagioclase, biotite, and regular hornblende. Sericite plagio-schists are composed of quartz (35%), muscovite (up to 5%) and sericitized plagioclase (oligoclase, 45–55%). The accessories are apatite, titano-magnetite, and zircon.

3.3. The Lebyazhka Formation

Biotite gneisses, *often with garnet* have a fine-grained composition, dark-gray coloration, micro-lepidogranoblast structure with relics of a porphyric one. In amygdaloid varieties, there are recorded ellipsoidal tonsils of quartz and, more rarely, quartz-carbonate, biotite and quartz-feldspar amygdaloid inclusions. It is made up of biotite (15–25% and up to 40%), plagioclase (albite-oligoclase to oligoclase-andesine) (20–60%), quartz (20–35%), microcline (10–35%), muscovite (up to 10%), garnet—almandine (up to 5%), epidote-clinozoisite (up to 5%), chlorite. The accessories are titanite, allanite, leucoxene, and zircon.

3.4. The Chervurt Formation

3.4.1. Lower Subformation

Garnet–staurolite carbonic schists are rocks of black, gray, and, more rarely, light coloration, depending on the content of carbonic matter, with porphyroblast, lepidogranoblast, and granoblast structures. The composition is quartz (25–60%), garnet—almandine (5–10 and up to 50%), staurolite (15–50%), muscovite, biotite, chlorite. The accessories are ilmenite, apatite, titanite, zircon, ore minerals, and carbonic matter.

Garnet–muscovite schists are light- and dark-gray schistous rocks of poikiloporphyroblast and lepidogranoblast structure of the basic fabric. The composition includes garnet—almandine (5–10%), quartz (60%), muscovite (35–25%), and, more rarely, biotite, chlorite, and chloritoid. The accessories are apatite, ilmenite, orthite, and pyrrhotine.

Muscovite–biotite schists and tuff-conglomerates. Tuff-conglomerates and tuff-siltstones are finely laminated rocks, gray and dark-gray in coloration, with fragments of quartz–feldspar rock and irregular-shaped grains (porphyroclasts) of pelitized plagioclase. Fragments in these rocks are varied in size. Muscovite–biotite schists are fine-grained rocks of lepidoblastic structure composed of muscovite, quartz, plagioclase (albite-oligoclase), porphyroblast biotite, ilmenite, and graphite.

3.4.2. Upper Subformation

The kyanite and staurolite–kyanite carboniferous schists are black, gray and light-gray rocks with variously shaped kyanite aggregates and single grains in the fine-grained groundmass. There are schists with porphyroblastic aggregates of fibrous or columnar kyanite, prismatic-granular aggregates, and paramorphic (after chiastolite) aggregates of tabular crystals, depending on the morphological types of kyanite segregation. The rock has a porphyroblastic structure, while the fine-grained matrix is granoblastic, lepidoblastic, or poikiloblastic.

The kyanite schists consist of kyanite (30–60%), quartz, muscovite, rare staurolite, biotite, garnet (almandine), plagioclase, epidote, chlorite, and accessory ilmenite, rutile, allanite, leucoxene, zircon, apatite, and carbonaceous matter.

The staurolite–kyanite schists are made up of kyanite (10–30%), quartz (50–60%), muscovite, staurolite, plagioclase [19], and similar accessory minerals.

The sillimanite schists with sillimanite peramorphoses, as with kyanite, are found in the Western Keivy area.

3.5. The Vykhchurt Formation

3.5.1. Lower Subformation

Quartzites—are rocks of a light-gray color, massive, sometimes with thin gradational lamination, almost monomineral, and with a grain oblast structure.

Muscovite–quartz schists, sometimes with staurolite—rocks of a light-gray color with xenoblasts of staurolite, garnet (almandine), rarely biotite; have granoblast, more rarely blastopsammite structure, are composed of quartz (85–95%), insignificant amounts of muscovite (5–10%), and sometimes plagioclase (5–10%), and microcline. Additionally, the accessories are zircon, apatite, and rutile.

3.5.2. Upper Subformation

The plagioclase–kyanite–staurolite, plagioclase–staurolite and carboniferous schists have a poikiloporphyroblastic structure with a granolepidoblastic groundmass. They are composed of staurolite (1–25%, up to 40% in Malye Keivy), kyanite (5–20%), plagioclase (from oligoclase-andesine to labradorite, 5–15%), quartz (30–50%), muscovite (10–20, up to 50%), biotite, accessory ilmenite, carbonaceous matter, rutile, apatite, zircon, epidote, and allanite. The staurolite idioblasts are predominantly hexagonal, and form twins and trillings. There are kyanite and staurolite with a zonal distribution of carbonaceous matter in cruciform intergrowths. There are also kyanite and staurolite poikiloblasts with a zonal distribution of quartz and carbonaceous inclusions.

3.6. The Pestsovaya Tundra Formation

3.6.1. The Malye Keivy Subformation (the Snezhny Bor Formation)

The muscovite schists with garnet and biotite, feldspar, arkose metasandstones, and polymict conglomerates are represented by silver-gray rocks with rare biotite and garnet (almandine) plates. They also contain gravel and fine quartz pebbles. The tuff conglomerate pebbles include rounded fragments of the Lebyazhka gneisses, melanocratic biotite plagioschists, quartz, quartzites and two-mica schists. Cement is represented by biotite plagioschists in the polymict conglomerates. There are interlayers of sericite–muscovite schists. The biotite plagioschists of the cement are dark-gray rocks with a fine-grained, banded structure caused by alternating garnet–biotite interlayers. The Pestsovaya Tundra schists are silver-light-gray inequigranular rocks that contain 10–30% oligoclase, 10–15% muscovite, and up to 10% biotite at the lower part of the section. The amount of plagioclase decreases to a few grains while that of muscovite increases up to 45%.

3.6.2. The Zolotaya Rechka Subformation

The two-mica schists with garnet and staurolite, or layers of oligomict conglomerates, muscovite-sericite-quartz schists, quartz conglomerates, arkose quartzite-sandstones are often gray-yellow porphyroblastic rocks with coarse bedding. The layers are massive and have a varied content of garnet (almandine) and micas. There are varieties with fragments (from single grains to 10% of the rock volume). Boulders of quartz and quartzite of ellipsoidal shape, and lenses of biotite–chlorite schists are common. Large detrital material was found in the section in the western part of the subformation. The size of quartz and quartzite porphyroblasts and fragments reduces eastwards, but quartzite gravel becomes abundant. The western part of the Malye Keivy subformation is dominated by finely laminated sericite-muscovite-quartz schists with layers of mica and quartz gravel in varying amounts. Interlayers of quartzite-sandstones are rare here.

4. Magmatism, Metamorphism, Petrogeochemistry and Geochronology

4.1. Magmatism

The Keivy median massif was formed as an individual geological structure of the continental lithosphere, at the final stage of the extensive collision zone formation that occurred in the Late Archean, due to the collision of the Murmansk and Karelian granite-greenstone areas [37]. The attenuation of the activity in this geodynamic system (which Khain [38] called a taphrogenic evolutional stage of the collision zones) suggests an intrusion of a series of igneous complexes along the weakened zones. These magmatic formations show a certain spatiotemporal pattern and occur as various lithotectonic formations in the Keivy area. Numerous amphibolite, metagabbro–anorthosite, and mandelstone dike and sill bodies intruded at early stages. Plagiomicrocline, partly aplitoid granite bodies, as well as their ultrametamorphic derivatives (or migmatites) and porphyroblastic granites formed later. Alkaline granites, syenites, and nepheline syenites (or miaskites) erupted even later.

Intrusive diabase, gabbro–diabase, augite and picrite porphyrite bodies emerged at the final stage [31].

4.2. Metamorphism

Metamorphic transformations of the Upper Archean and Lower Proterozoic supracrustal complexes had been occurring in the prevalence of amphibolite and epidote–amphibolite facies. The manifestation time of these processes is not totally studied. It is believed that either, the Upper Archean complexes had not experienced metamorphism, or it had occurred under a substantially lower temperature [39]. On the other hand, the Late Archean age of the tectonic junction of the Keivy domain, with the Murmansk and Upper Ponoy, as well as with the Central Kola segment of the Kola–Norwegian domain, is obvious. As a result, marginal low-gradient metamorphism should have occurred. The rocks of the Lebyazhka complex underwent an amphibolite facies metamorphism, while the rocks of the Keivy series were subject to the disthene–staurolite subfacies of the amphibolite facies metamorphism. This subfacies is replaced with sillimanite–muscovite and sillimanite–microcline subfacies in the Western Keivy area. This is associated with the increased temperature, while the microclinization and muscovitiation were caused by the impact of alkaline granites [40,41].

4.3. Petrogeochemistry

Table 1 provides chemical composition of typical rock varieties.

The study of the mineral composition of the entire spectrum of metamorphites of the Keivy domain, carried out on the basis of the existing database of 1116 complete silicate analyses, shows the maximum diversity of rocks for the Archean of the Kola region, as in the case of the Kola–Norwegian domain [26,37]. There are 18 varieties, which belong to different groups of the petrochemical systematics, made by A.A. Predovsky [42], in terms of their primary nature. These are metapicrobasalts (0.3%), alumina, ferriferous, and magnesian metabasites (10.8%, 3.4% and 4.5%, respectively), metaandesobasalts (9.8%), metaandesites (3.9%), metadacites (0.7%), metarhyodacites (1.1%), metarhyolites (1%), as well as such metaclastogenic rocks, as metatuffites (5.8%), metaplagioquartzites (0.1%), metaarkoses (15.7%), metasubgraywackes (8.3%), metagraywackes (5%), metamelanowackes (2.1%), and metapellites (9.1%). A significant part (18.3%) of samples could not be deciphered as in the other Archean structures. However, the rather even composition of these rocks is similar to metatuffite and metamagmatite superimposition (9.3%), or the mixture of the metamagmatites and metasedimentary rocks (9%).

Disregarding unidentified varieties by protolithogenesis, it should be noted that sedimentary and volcanic-sedimentary rocks predominate in the spectrum of metamorphites, comprising 56.5% in total, as in the Kola–Norwegian domain. Among metamagmatites, varieties with different compositions predominate, comprising 23.3% to 43.5%, accounting for the proportion of primarily igneous rocks. Compared to the rocks of the Kola–Norwegian domain, the grained metasedimentary and volcanic-sedimentary rocks are primarily comprised of, not metagraywackes and metatuffites, but metaarkoses (19.2%), metapelites (11.1%), and metasubgraywackes (10.2%), i.e., rocks more typical for platform areas (Table 2).

Reconstruction of the probable geodynamic regime of the protolith formation, based on granitoid analysis using the diagrams of J. Pearce et al. [43], suggests some similarity between the rocks of the Keivy domain and the rock series of island arcs [26,37]. Meanwhile, the reconstructions, using original methods for mafic rocks [44], imply close compositions of metabasites and trap formations. The authors believe this approach to reconstructions is the most reliable.

The position of felsic metamorphite material reconstructed as grained metasedimentary rocks, according to the diagrams by M. Bhatia [45] and Maynard et al. [46], also falls within the passive margins and intracratonic rifts [26,37]. In general, the Keivy rocks principally differ from all the other Archean structures of the Kola region in terms of chemical composition.

Table 1. Chemical analyses of the main rock types in the Keivy domain.

#	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
1	69.50	0.45	14.10	0.68	2.99	0.05	0.91	2.11	3.72	2.00
2	53.22	1.46	15.71	2.88	8.84	0.20	3.54	8.72	3.30	0.26
3	54.46	1.28	14.24	3.84	10.2	0.24	2.50	7.53	3.19	1.41
4	60.22	1.27	13.13	3.03	9.05	0.15	2.28	4.70	3.00	4.00
5	68.78	0.49	12.69	1.65	6.17	0.14	014	1.03	3.75	3.88
6	76.40	0.23	10.43	0.31	3.66	0.06	0.07	0.55	2.31	4.95
7	71.20	0.61	14.28	1.80	7.56	0.09	0.55	0.29	0.30	2.10
8	74.30	0.51	12.18	2.80	5.20	0.08	0.00	0.23	0.28	2.26
9	67.22	0.60	17.00	2.06	3.06	0.03	0.70	1.72	2.48	3.78
10	90.76	0.05	4.82	0.37	0.43	0.01	0.18	0.10	0.25	1.03
11	92.60	0.05	3.23	0.44	1.82	0.02	0.12	0.10	0.08	1.26
12	64.37	0.66	28.83	0.87	0.56	0.00	0.18	0.62	0.11	0.82
13	62.23	1.18	30.72	1.75	0.83	0.01	0.00	0.28	0.37	1.33
14	67.75	1.56	24.04	0.84	0.72	0.01	0.29	0.38	0.62	1.25
15	82.06	0.79	10.06	1.14	1.13	0.01	0.00	1.35	0.73	0.87
16	85.84	0.54	8.82	1.27	1.22	0.01	0.00	0.78	0.30	1.04
17	68.00	1.46	21.06	1.03	0.02	0.55	0.66	1.55	2.16	0.13
18	62.92	1.60	23.59	2.96	0.82	Traces	0.78	1.22	2.37	1.75
19	75.10	0.36	13.29	1.71	1.71	0.03	1.10	1.14	1.80	3.00
20	78.18	0.30	10.82	0.50	2.40	0.03	1.29	0.50	3.85	1.86
21	66.04	1.20	17.33	3.23	3.03	0.06	1.75	1.58	2.65	2.07
22	81.80	0.25	10.80	0.36	0.81	0.02	0.27	0.43	0.31	3.72
23	83.14	0.19	8.34	0.30	1.62	0.03	0.30	0.86	1.02	3.58

The Kolovay formation: 1—biotite gneiss, Ponoy River below the Ryaboga River mouth (241); the Patcherv formation; 2—porphyroblastic amphibolite, Malye Keivy (R-7225-6); 3—biotite-bearing plagioamphibolite, midstream of the Achi River (2997); 4—biotite–amphibolite plagioschist, Lebyazhka and Kofta rivers interstream (541/1); the Lebyazhka formation: 5, 6—garnet–biotite gneiss and muscovite–biotite gneiss, midstream of the Achi River (3528; 4053); the Chervurt formation (Lower subformation): 7—staurolite–garnet–micaceous schist, Keivy (401/2); 8—garnet–muscovite schist, Mt. Tyapshmanyuk (344); 9—two-mica gneiss, Keivy (2614/1); 10, 11—muscovite quartzites, Mt. Pestsovaya (433; 434); the Chervurt formation (Upper subformation): 12—paramorphic kyanite schist, Mt. Vorgel'urta (60/51); 13—medium-grained staurolite-kyanite schist, Mt. Shuururta (326); 14—staurolite-kyanite schist, Mt. Shuururta, (9/68); 15, 16—muscovite–quartz schists with staurolite and kyanite, Mt. Nussa (741, 743); the Vykhchurt formation: 17—porphyroblastic plagioclase-kyanite–staurolite schists, Mt. Shuururta (7/68); 18—porphyroblastic plagioclase–staurolite schist, Mt. Vorgel'urta (12/28); the Pestsovaya Tundra formation, Malye Keivy subformation: 19—biotite–muscovite schist (conglomerate cement), Kolmozero (3034/2); 20—arkose metasandstone, Malye Keivy (860/12); 21—two-mica schist with garnet and staurolite, north of Kanevka village (130/1); the Pestsovaya Tundra formation, Zolotaya Rechka subformation: 22—muscovite–quartz schist, Malye Keivy (K–376); 23—quartzite-sandstone, Malye Keivy (5148/7); from [16].

Table 2. Comparison of the Archean protoliths composition in the Kola region.

Sites	Metamagmatite Content, %	Predominant Types of the Sedimentary Protoliths
Murmansk domain	75.7	Greywackes, subgraywackes
Ingozero structure	73.4	Greywackes, subgraywackes
Kola–Norwegian domain	47.2	Greywackes, tuffites
Keivy domain	43.5	Arkoses, subgraywackes, clays
Belomorian domain	68.8	Tuffites, graywackes

The compositional correlation of the Keivy domain rock assemblages and other Archean complexes from the NE Baltic Shield, Canada, and Greenland, based on 4800 complete silicate tests using the methods described in the previous publications [26,37,44], justifies interpolation within the "intermediate" regions, but not the granite–greenstone or granulite–gneiss zones. In general, there is a similarity to the rocks of the Kola region (Table 3).

Table 3. Degree of the Keivy metamorphites and Archean complexes similarity in the Baltic Shield and North-Atlantic craton.

Target	GGSA							Intermediate			GGA			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
$F_{dif.}$	**3.9**	5.2	5.5	9.7	6.4	7.4	5.4	6.2	**<u>3.4</u>**	4.4	**4.8**	**5.7**	**6.0**	**4.1**

GGSA for typical granite-greenstone areas; intermediate for intermediate types of areas; GGA for typical granulite–gneiss areas. Numbers label the block structures: 1—the Murmansk domain; 2—West Greenland and East Labrador; 3-7—block structures of the Karelian craton: 3—Voknavolokskaya; 4—Tulosskaya; 5—Vodlozero; 6—North Finland; 7—Tavayarvi; 8—Central Belomorian; 9—Tersky domain; 10—West Belomorian; 11—Allarechka structure; 12—Notozero block; 13—Priimandra structure; 14—Central-Kola segment of the Kola-Norwegian domain. Bold font marks the structures of the Kola region. $F_{dif.}$ means difference factor of the correlated targets. The minimum value of $F_{dif.}$ is underlined.

Notably, the Keivy metasedimentary rocks may be clearly divided into two groups, one of which is anomalously rich in TiO_2 [26]. Such a compositional feature of the Keivy rocks was defined by regionally manifested metasomatic processes [47].

The geological and petrogeochemical data examined using the original author's methods, have allowed the complementing of the depiction of the supracrustal complexes formed in the Keivy structure [48]. It is evident that the formational processes of the Kola orogen had a certain spatiotemporal zoning and a pulse pattern. The maximum intensity of orogen activity was experienced by the rock associations of the Murmansk domain, as a result of which, the terrigenous material removed from its mountain slopes prevailed in the metasedimentary complexes of the Keivy median massif. The obtained data provide evidence against the recent viewpoint [49] on the coevality of the formation of the Lebyazhka alkaline granites and felsic metavolcanics. It is most likely that the rocks used for the above studies, and dated at 2678 ± 7 Ma, are not typical of the supracrustal section of the Lebyazhka metavolcanics and are most probably represented by metasomatites.

The reconstruction of the formational settings for the Keivy supracrustal complexes is extended in Kozlov et al. [50]. It was shown that the metasedimentary rocks of the Chervurt and Vykhchurt formations were mainly formed by the material from the underlying strata. Besides, the rocks of the domains surrounding the Keivy median massif become involved in the generation of the Vykhchurt formation from the top. The upper part of the Keivy structure cross-section (the Pestsovaya Tundra formation) is dominated by the material of the Murmansk domain. Moreover, the Pestsovaya Tundra formation demonstrates the least similarity to the rocks of the Lebyazhka formation compared to all the other sites analyzed. This contradicts the earlier conclusion [29] that it was formed due to the erosion of the Lebyazhka formation. It should be emphasized that the obtained data do not exclude the possible correlation of the Snezhny Bor and Pestsovaya Tundra rocks. As stated above, this needs further investigation.

It may be inferred that at least the middle part of the Keivy section (the Chervurt and Vykhchurt formations) were formed by weathering and redeposition of the material of the structure, itself. It also supports the conclusions that (i) the Keivy massif contains redeposited weathering crust, and (ii) the Keivy structure was formed under the conditions, which were most typical for the median massifs. It explains, to a certain extent, the generation of a large alumina deposit within the Keivy massif.

4.4. Geochronology

The U-Pb zircon age for the metamorphosed rhyodacites of the Lebyazhka formation is 2871 ± 15 Ma [51]. The alkaline–granite magmatism within the domain started at 2751 ± 41 Ma (Ponoy massif) [35] and ended at 2670–2650 Ma (Western Keivy and Belye Tundras massif). The recrystallization of alkaline granites occurred in the interval of 2500–2400 Ma. The gabbro–anorthosite magmatism is dated at 2678 ± 16 Ma (Achinsky massif) and 2659 ± 3 Ma (Tsaga massif) [35], 2664 ± 9 (Shchuch'e Ozero massif) [52]. The initial anorthosite magmas are supposed to have an enriched mantle source with low values of Y/Nb ratios. On the basis of geological and geochemical data, the initial magma for the Keivy anorthosites belongs to the alkaline type and was formed in an intraplate setting [53]. Sm-Nd model ages for alkaline granites vary in a range of 2.6 to 3.1 Ga. As mentioned above, earlier data [48] reject the recent viewpoint on the formational coevality of the Lebyazhka formation alkaline granites and felsic metavolcanites. We can state that the rocks used to derive this conclusion (2678 ± 7 Ma, [49]) are not typical of the supracrustal section of the Lebyazhka formation metavolcanites, and are most probably metasomatites.

5. Geodynamics

Detailed geological and petrogeochemical research on the metamorphic rocks from the Keivy median massif allowed the authors [26,37] to show that this structure could be considered as a distinct domain located inside the Early Precambrian Kola deep-seated collision. No clear proximity of the Keivy formations to any geodynamic type of framing (granite-greenstone or granulite-gneiss) structures was found. As well, it is worth noting that the Archean evolutionary stage of the Keivy median massif sharply differs from all the surrounding continental crust formations of the eastern Baltic Shield, in terms of its nature. The earliest compositional complexes within the massif are represented by cover-type volcano–sedimentary formations. The available data are indicative of their discontinuous accumulation in the cratonization regime. This development of Keivy is indicated by data on the extensive formation of anomalously light carbon within this structure [54].

The near-border interaction of the Keivy median massif with other surrounding continental-crust formations is poorly studied. For example, the Late Archean metamorphism within the domain has not yet been revealed, although its collision relationships with the other crustal domains could definitely have induced a low-grade contact metamorphism in the peripheral regions.

In addition to the volcano–sedimentary formations, alkaline granites with an origination age varying within 2630–2760 Ma [32,35,55] are common in the Keivy median massif. The zircon age for porphyroblastic granites of the Kolovay massif, cutting through the rocks of the Lebyazhka series, corresponds to a value of 2620 ± 30 Ma [56]. The syntectonic gabbro-anorthosites in the zone of the Upper Ponoy block, contacting the Keivy domain, emplaced ca. 2760 ± 80 million years ago according to some researchers [56], or 2659 ± 3 million years ago according to Bayanova et al. [55].

The geodynamic and petrogeochemical research executed for the Keivy microcontinent has demonstrated that it was buried by overthrusted adjacent continental crust domains of the Kola region in the Late Archean. As a result, a unique sedimentary basin, where terrigenous material drifted during the destruction of the orogenic structures of the adjacent continental massifs, formed. It should be kept in mind that the emplacement of the Keivy median massif coincided with the formation of the Earth's first supercontinent, (Monogea), and took place under the conditions of a highland glaciation. Thus, a closed shallow basin surrounded by mountain systems was overlain by a thick ice cover, within which the products of the rewashed tonalite–trondhjemite and amphibolite–komatiite continental crust rock assemblages were deposited in the Kola region.

The study of the geological and geodynamic mechanisms of the evolution, of lithotectonic formations of the Keivy microcontinent, allows us to conclude that this is the oldest median massif of the continental crust within the collision zones of the world (Figure 4). Younger analogues of such structures may include, for example, the South-Chinese or

Chinese–Korean lithospheric plates. In accordance with the currently available geological and geophysical data, the dip azimuths of all the tectonic boundaries in the Keivy median massif are oriented towards its junction with the other crustal areas.

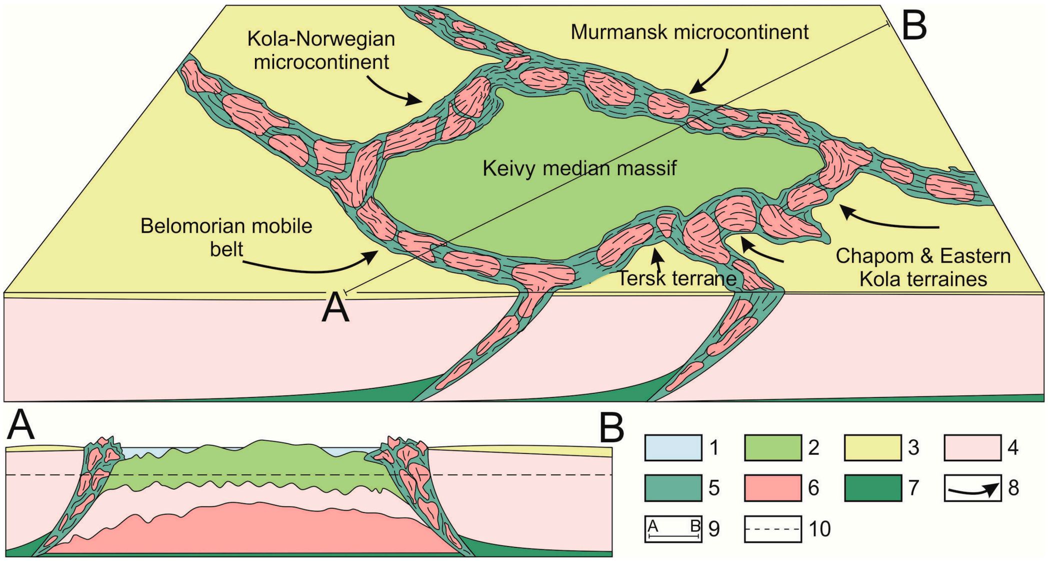

Figure 4. Formation mechanisms of the Keivy median massif at the initial collision stage in the Late Archean (after [37]). 1—water basin; 2—sedimentary cover of the Keivy median massif; 3—sedimentary cover of adjacent terranes and microcontinents; 4—continental crust; 5—greenstone-type folded formations; 6—synorogenic tonalite-trondhjemites, granodiorites, migmatite-granites and remobilized crust of the Keivy median massif; 7—subcrustal mantle; 8—orientation of the collisional thrusting of microcontinents and terranes on the Keivy median massif; 9—section line; 10—modern level of the erosional truncation.

The intracontinental sedimentary basin, which began to form in the late Archean, was covered by a glacier and, as a result, was cold and freshwater. The rewashing and chemical decomposition of the predominantly tonalite–trondhjemite rock assemblages, in such climatic settings, should have led to the formation of alumina-oversaturated and carbonate-undersaturated sedimentary formations. Due to this, in our opinion, unique conditions were created in the Keivy median massif for further formation of large deposits of aluminum raw materials.

The intensive accumulation of the sedimentary cover of the Keivy median massif was due to geodynamic conditions. Submerged rocks within the continental crust underwent a process of partial melting and remobilization under the high temperature gradient observed in the Late Archean. Due to this process, numerous intrusions of alkaline granites were formed, which penetrated through zones of weakening into the sedimentary complexes of the Keivy domain. The time of their emplacement corresponds to the regime of the system cratonization and initiation of the conditions for the tectonic relief of the whole collision zone in the NE Baltic Shield. It was mainly possible due to the reduction in the geothermal gradient and significant cooling of the regional lithosphere. The extinction of the collision system consistently triggered the development of numerous faults in the peripheral part of the Keivy massif and corresponding intrusion of fluid-saturated magmas, which were remobilizates of the lower crustal material. In terms of composition, these were alkaline granites and syenites, which exposed the volcano–sedimentary framing rock formations to profound metasomatic changes, which formed wide fields of potassic metasomatosis, developed after terrigenous sediments. Under the conditions of a cold climate, calcium chloride may form a mineral called antarcticite ($CaCl_2 \cdot 6H_2O$). Additionally, interacting calcium chloride and sodium orthophosphate frequently form calcium orthophosphate, which composes apatite.

It is necessary to consider a number of basic reactions in order to trace the process of chemical transformations within the Keivy sedimentary cover. During the denudation of the orogenic complexes in adjacent domains of the continental crust, main rock-forming minerals of the trondhjemites, tonalities, and granodiorites are mainly represented by orthoclase ($K(AlSi_3O_8)$), albite ($Na(AlSi_3O_8)$), anorthite ($Ca(AlSi_2O_8)$), and microcline (polymorphic orthoclase modification). They decompose in the presence of water through the following types of reactions:

$$\underset{\text{orthoclase}}{K(AlSi_3O_8)} + nH_2O + CO_2 \rightarrow \underset{\text{kaolinite}}{Al_4\,[Si_4O_{10}](OH)_8} + \underset{\text{potash}}{K_2CO_3} + \underset{\text{opal}}{SiO_2{\cdot}nH_2O}, \tag{1}$$

or:

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

and

$$\underset{\text{albite}}{Na(AlSi_3O_8)} + 2H_2O \rightarrow \underset{\text{kaolinite}}{Al_4[Si_4O_{10}](OH)_8} + 4NaOH + \underset{\text{hydrated silica}}{8H_4SiO_4} \tag{3}$$

Orthosilicic acid dissolves in water saturating it with silica.

It should be kept in mind that the Keivy sedimentary complexes were formed in a cold climate with an atmosphere undersaturated with oxygen and carbon dioxide [12]. In such conditions, anorthite turns into kaolin and gypsum under the action of sulfated fluid:

$$\underset{\text{anorthite}}{Ca(Al_2Si_2O_8)} + 2H_2O + H_2SO_4 \rightarrow \underset{\text{kaolin}}{Al_2Si_2O_5(OH)_4} + \underset{\text{gypsum}}{CaSO_4{\cdot}H_2O} \tag{4}$$

Under the action of hydrochloride-mineralized fluid, gypsum may decompose into sodium sulfate and calcium chloride:

$$CaSO_4H_2O + 2NaCl \rightarrow H_2O + CaCl_2 + Na_2SO_4 \tag{5}$$

Under the conditions of a cold climate, calcium chloride may form a mineral called antarcticite ($CaCl_2{\cdot}6H_2O$). Calcium chloride and sodium orthophosphate frequently form calcium orthophosphate, which composes apatite.

$$3CaCl_2 + 2Na_3PO_4 \rightarrow Ca_3(PO_4)_2 + 6NaCl \tag{6}$$

Moreover, under the conditions of hypergenesis and in a cold humid climate, orthoclase may decompose into hydromicaceous minerals, which further form kaolinite. For example:

$$6K(AlSi_3O_8) + 2CO_2 + 2H_2O \rightarrow 2KAl_2[AlSi_3O_{10}](OH)_2 + 2K_2CO_3 + 12SiO_2 \tag{7}$$

In the presence of carbon dioxide and water, muscovite may turn into kaolinite and potassium carbonate by the following reaction:

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

Further hydrolysis processes, manifested in the Keivy median massif at the Archean–Proterozoic transition, could lead to the formation of laterite (red clay mineral) and silicon oxide (opal):

$$Al_4[Si_4O10](OH)_8 \rightarrow H_2Al_2O_4 + SiO_2{\cdot}nH_2O \tag{9}$$

or hydrargillite and opal:

$$Al_4[Si_4O10](OH)_8 \rightarrow Al(OH)_3 + SiO_2{\cdot}nH_2O \tag{10}$$

Moreover, hydrargillite contains more than 65% of alumina (Al_2O_3).

The physical and chemical transformations of the terrigenous material of the surrounding highland systems led to the formation of abundant kaolin material with little or no carbonates. It became possible at the stage of catagenesis and the slow burial of the sedimentary cover to a depth, due to its successive overlapping with younger rocks. The formation of kaolinite was mainly facilitated not by temperature and pressure, but by mineralized infiltration of underground waters. The geochemical conditions of the kaolinite formation were close to the conditions of weathering (or hypergenesis), for which generation of this mineral is a typical phenomenon.

Very interesting processes accompany the transformation of micaceous minerals in the setting of lithogenesis. According to O.V. Yapaskurt [57], this is a multistage process. It begins at a stage of diagenesis and continues in the catagenesis. Transformational processes strongly affect biotite, which at the stage of initial catagenesis, is subject to hydration and mechanical corrosion. In this setting, it frequently turns into vermiculite and kaolinite in the medium of excessive acidity. The further evolution of catagenetic transformations may result in the metasomatic replacement of biotite with chlorite (chloritization). Additionally, biotite may be replaced with muscovite (muscovitization). Such changes may lead to the formation of hydromuscovite and sericite. This process is most widely developed in the terrigenous sediments enriched with feldspars. The process of biotite replacement with muscovite is proceeeded by the following reaction [57]:

$$\underset{\text{biotite}}{K(Fe,Mg)_3[AlSi_3O_{10}](OH)_2} + 2Al^{3+} = \underset{\text{muscovite}}{KAl_2[AlSi_3O_{10}](OH)_2} + Fe^{2+} + Mg^{2+} \tag{11}$$

Progressive catagenetic changes may also result in the biotite's replacement with quartz, to yield pyrite and iron oxides.

The further history of the geodynamic evolution of the Keivy median massif was accompanied by the manifestation of intensive metamorphic processes for the formed sedimentary cover. It most probably occurred at a stage of maximum orogenesis in the NE Baltic Shield associated with the collision of the Archean continental massifs and emplacement of the Earth's first supercontinent (Monogea). As a result, the thick sedimentary cover of the Keivy median massif at the Archean–Proterozoic transition was overlain by tectonic thrust plates of the framing orogenic structures in the Kola region (Central Kola, Murmansk, Ust–Ponoy domains and Belomorian mobile belt (Figure 2). These processes entailed progressive metamorphic changes, heating, and dehydration of the sedimentary cover. Thus, unique deposits of kyanite schists were formed and this process may tentatively be described by a simple endothermic reaction:

$$\underset{\text{kaolinite}}{Al_4[Si_4O10](OH)_8} \rightarrow \underset{\text{kyanite}}{Al_2OSiO_4} + 2H_2O \tag{12}$$

It may also be written in an easier and more understandable way:

$$Al_2O_3{\cdot}2SiO_2{\cdot}2H_2O \rightarrow Al_2O_3{\cdot}2SiO_2 + 2H_2O \tag{13}$$

Kyanite may also be crystallized directly at the modification of anorthite under the conditions of an amphibolite–facies metamorphism by the following reaction:

$$CaAl_2Si_2O_8 \rightarrow CaO + Al_2O(SiO_4) + SiO_2 \tag{14}$$

The polycyclic manifestation of the physicochemical material transformation processes assumes that the reactions proceed in the same way and with a change in the conditions for the predominance of exothermic and endothermic reactions. During the development of the continental crust, lithotectonic units are formed under conditions of high temperatures and pressures, which allows both endothermic and exothermic chemical reactions. During the destruction of rocks and their transformation into sediments, exothermic reactions predominate, since this is most favorable in the context of energy balance. Endothermic reactions of the progressive metamorphism branch can proceed only with the accumulation of powerful sedimentary masses at their base. This is related to the lithostatic pressure and influence of mineralized hydrothermal solutions on the rocks. The recurrent process of metamorphism and heating of the geological system allows reverse chemical reactions, carried into effect at the second stage.

The progressive metamorphism from greenschist to epidote–amphibolite facies may result in the recrystallization of albite, chlorite, and epidote in the sediments to form alkaline amphibole and hydrous anorthite by the following reaction:

$$\begin{array}{l} \underset{\text{albite}}{10NaAlSi_3O_8} + \underset{\text{chlorite}}{3Mg_5Al_2Si_3O_{10}(OH)_8} + \underset{\text{epidote}}{6Ca_2Al_3Si_3O_{12}(OH)} + 7SiO_2 + 2H_2O \rightarrow \\ \underset{\text{alkaline amphibole}}{5Na_2Mg_3Al_2Si_8O_{22}(OH)_2} + \underset{\text{hydrous anorthite}}{12CaAl_2Si_2O_8H_2O} \end{array} \quad (15)$$

Garnet (almandine) may form in the sedimentary rock during the recrystallization of iron epidote in the presence of aqueous fluid by the following reaction:

$$\underset{\text{iron epidote}}{9Ca_2FeAl_2(Si_2O_7)(SiO_4)O(OH)} + 2H_2O \rightarrow \underset{\text{almandine}}{3Fe_3Al_2(SiO_4)_3} + 10CaO + 6SiO_2 + 9OH + \underset{\text{epidote}}{4Ca_2Al_3(Si_2O_7)(SiO_4)O(OH)} \quad (16)$$

As well, at a greenschist facies metamorphism, and in the presence of alkaline hydrothermal solutions containing potassium hydrate (KOH), kaolinite turns into sericite, which ultimately forms muscovite:

$$\underset{\text{kaolinite}}{3Al_2Si_2O_5(OH)_4} + 2KOH \rightarrow \underset{\text{sericite}}{2KAl_2(AlSi_3O_{10})(OH)_2} + 5H_2O \rightarrow \underset{\text{muscovite}}{2KAl_2(AlSi_3O_{10})(OH)_2} + 5H_2O \quad (17)$$

Metamorphic rock transformations are always related to the changes in their mineral composition and chemical modification. It is contingent on the fact that the physicochemical transformation necessarily occurs under the conditions of allochemical metamorphism, during which metasomatic processes are intensive.

The dehydration of the volcano–sedimentary rock formations is discussed in detail in [44,58]. Under the conditions of high degrees of amphibolite facies metamorphism, muscovite is also replaced with sillimanite and orthoclase, due to the substrate oversaturation with alumina:

$$\underset{\text{muscovite}}{KAl_2(AlSi_3O_{10})(OH)_2} + \underset{\text{quartz}}{SiO_2} = \underset{\text{sillimanite}}{K(AlSi_3O_8)} + \underset{\text{orthoclase}}{Al_2SiO_5} + H_2O \quad (18)$$

Similarly, under such conditions, reactions to form kyanite after kaolinite may occur:

$$Al_2(Si_4O_{10})(OH)_2 \rightarrow Al_2SiO_5 + 3SiO_2 + H_2O \quad (19)$$

and corundum after kaolinite:

$$2KAl_2(AlSi_3O_{10})(OH)_2 \rightarrow K_2O + 3Al_2O_3 + 6SiO_2 + 2H_2O, \quad (20)$$

$$2KAl_2(AlSi_3O_{10})(OH)_2 + 11H_2O \rightarrow 2KOH + 3Al_2O_3 + 6H_4SiO_4 \quad (21)$$

The both reactions (20) and (21) are endothermic, and the first reaction runs without aqueous fluid, while the second one with it.

In the volcano–sedimentary rocks of the Keivy median massif, there is a series of accessory minerals, which are indicative of the transformation of their substance at a stage of regional Late-Archean–Early Proterozoic metamorphism. Such minerals include cordierite, apatite, leucoxene, hawleyite, and carbon.

Cordierite often forms during the metamorphic transformations of garnet (pyrope) and diopside, which are abundant in the greenstone assemblages of the continental crust of the regions adjacent to the Keivy massif. The reaction of its formation may be as follows [59]:

$$\underset{\text{pyrope}}{Mg_3Al_2Si_3O_{12}} + \underset{\text{diopside}}{CaMgSi_2O_6} \rightarrow \underset{\text{cordierite}}{CaMg_4Al_2Si_5O_{18}} \tag{22}$$

Under the conditions of increased pressure, the magnesium content of garnet and cordierite increases. In this case, it can be formed by the following reactions:

$$\underset{\text{albite}}{4NaAlSi_3O_8} + \underset{\text{pyroxene}}{2MgSiO_3} + \underset{\text{olivine}}{3Fe_2SiO_4} \rightarrow \underset{\text{cordierite}}{Mg_2Al_4Si_5O_{18}} + \underset{\text{quartz}}{12SiO_2} + 4Na + \underset{\text{magnetite}}{2Fe_3O_4} \tag{23}$$

Cordierite is a typical mineral of metamorphosed sedimentary rocks, which is poor in calcium oxide (CaO) and rich in oxides of aluminum (Al_2O_3), iron (FeO), and magnesium (MgO). It is also a barophobian mineral, which is replaced by assemblages of denser iron–magnesium minerals such as garnet, orthopyroxene, or sapphyrine at high pressures. This mineral is typical of lower degrees of the amphibolite facies metamorphism, and forms stable assemblages with chlorite, kyanite, and muscovite. There are also pseudomorphs of kyanite and staurolite after cordierite, muscovite after chiastolite, and sillimanite after cordierite [60]. In this case, cordierite may turn into garnet (almandine), kyanite, and quartz by the following reactions:

$$\underset{\text{cordierite}}{3(Mg,Fe)_2Al_4Si_5O_{18}} \rightarrow \underset{\text{garnet}}{(Mg,Fe)_3Al_2(SiO_4)_3} + \underset{\text{kyanite}}{4Al_2SiO_5} + \underset{\text{quartz}}{5SiO_2} \tag{24}$$

In other cases, cordierite and garnet (pyrope) change into clinopyroxene and kyanite:

$$\underset{\text{cordierite}}{2Mg_2Al_4Si_5O_{18}} + \underset{\text{garnet}}{2Mg_3Al_2(SiO_4)_3} \rightarrow \underset{\text{enstatite}}{5Mg_2Si_2O_6} + \underset{\text{kyanite}}{6Al_2SiO_5} \tag{25}$$

In the presence of spinel, cordierite forms kyanite and garnet:

$$\underset{\text{cordierite}}{Mg_2Al_4Si_5O_{18}} + \underset{\text{spinel}}{MgAl_2O_4} \rightarrow \underset{\text{kyanite}}{2Al_2SiO_5} + \underset{\text{garnet}}{Mg_3Al_2(SiO_4)_3} \tag{26}$$

Under the conditions of the amphibolite–facies metamorphism, between cordierite and garnet, iron and magnesium exchange reactions proceed easily:

$$2Fe_3Al_2Si_3O_{12} + 3Mg_2Al_4Si_5O_{18} \rightarrow 3Fe_2Al_4Si_5O_{18} + 2Mg_3Al_2Si_3O_{12} \tag{27}$$

The garnet-group minerals are frequently found in the rocks of the Keivy complex, being predominantly represented by almandine. However, garnets from the garnet–two-mica schists, with microcline, show a significantly increased share of the grossular and spessartine minal [61]. It most probably happens when the metamorphic changes affect rocks oversaturated with calcium and manganese, but undersaturated with iron. In this case, grossular ($Ca_3Al_2[SiO_4]_3$) or spessartine ($Mn_3Al_2[SiO_4]_3$) crystallizes instead of almandine ($Fe_3Al_2(SiO_4)_3$). The reaction to form grossular under the conditions of an amphibolite-facies metamorphism, due to the recrystallization of anorthite and melilite-group mineral (gelenite), can be written as follows:

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + \underset{\text{gelenite}}{Ca_2Al_2SiO_7} + \underset{\text{wollastonite}}{3CaSiO_3} \rightarrow \underset{\text{grossular}}{2Ca_3Al_2(SiO_4)_3} \tag{28}$$

In the Keivy volcano–sedimentary complexes, there is such an accessory mineral as cadmium sulfide (CdS, or hawleyite), which marks sedimentation settings in the region. The cadmium content in the Earth's crust is $1.6{\cdot}10^{-5}\%$, which is sufficiently close to antimony ($2{\cdot}10^{-5}\%$), in terms of abundance. This mineral typically demonstrates a high mobility in the hydrothermal systems and joint migration with some chalcophyle metals, e.g., with zinc, which tend to form natural sulfides. In clays, which concentrate cadmium, its content may reach a value of 0.3 ppm. It belongs to rare, scattered elements and is frequently contained in zinc minerals in the form of an isomorph admixture [62].

In the hydrothermal solutions, cadmium may be present in the sulfate form and settle out as an admixture with the segregation of oxygen and sulfated solution:

$$2CdSO_4 + 2H_2O \rightarrow 2Cd + O_2 + 2H_2SO_4 \quad (29)$$

When interacting with sulfur, cadmium quickly takes the sulfide form to yield hawleyite by the following reaction:

$$8Cd + S_8 \rightarrow 8CdS \quad (30)$$

Cadmium sulfide (or hawleyite) may also form by the following reaction:

$$Cd(NH_3)_4(OH)_2 + Na_2S + 4H_2O \rightarrow CdS\downarrow + 4NH_3{\cdot}H_2O + 2NaOH \quad (31)$$

Since hawleyite associates with zinc in the fluid and sphalerite may settle out at the excess of Na from the solution by the following reaction:

$$Na_2Zn(OH)_4 + Na_2S \rightarrow ZnS\downarrow + 4NaOH \quad (32)$$

or

$$Na_2Zn(OH)_4 + 3H_2S \rightarrow ZnS\downarrow + 2NaHS + 4H_2O \quad (33)$$

As mentioned above, due to the cold climate in the Late Archean, the sediments of the Keivy massif were formed under conditions of carbonate undersaturation with the generation of CdS (hawleyite) instead of $CdCO_3$ (otavite). If the climate were warm and there were a lot of carbonates, the reaction would most probably be as follows:

$$\underset{\text{cadmium sulfate}}{CdSO_4{\cdot}8H_2O} + CO_2 \rightarrow \underset{\text{otavite}}{CdCO_3} + H_2SO_4 + 7H_2O \quad (34)$$

However, this mineral (otavite) was not observed in the Keivy volcanic–sedimentary rocks, which indicates the existence of a cold climate in the described epoch.

The biotite recrystallization processes (see Reaction (11)) is accompanied by the removal of iron, titanium, and other chemical elements. Hence, its alteration (recrystallization) is genetically and spatially associated with the catagenetic, newly formed pyrite, iron oxides, leucoxene, and anatase. These minerals create the accessory impregnation after biotite. The leucoxene generation reactions may be as follows:

$$\underset{\text{ilmenite}}{4FeTiO_2} + 2TiO_2 + 3CO_2 \rightarrow \underset{\text{leucoxene}}{2Fe_2Ti_3O_9} + 3C \quad (35)$$

It does not suggest that free carbon may form as a result of such reactions. Since this reaction proceeds at high temperatures, and in the presence of carbonated fluid composed of CO_2 and CO, carbon should immediately oxidize.

The Keivy sedimentary basin was formed in the cold climate of the Huronin glaciation and, apparently, was covered by a thick glacial sheet in the Late Archean (Figure 5). In the current era, such a setting could be observed in the Antarctica. The only difference lies in the fact that the Late-Archean Huronian glaciation was global and covered the most of the Earth's continents [12,25]. As in modern Antarctica, a shallow, closed basin most likely formed under the ice cover of the Keivy median massif in the Late Archean. Under the conditions of high volcanic and hydrothermal activity related to the intensive orogenesis, it was too warm for organic life to develop. It is implied by the available scattered carbon, which is abundant in volcano–sedimentary rocks of the described region. Graphite is present in a dispersed accessory form in numerous samples and rarely forms monomineral segregations. This indirectly suggests that the amount of organics was not very large at that time. Compounds of nitrogen, phosphorus, and carbon were in an aqueous solution, concentrating in organic matter.

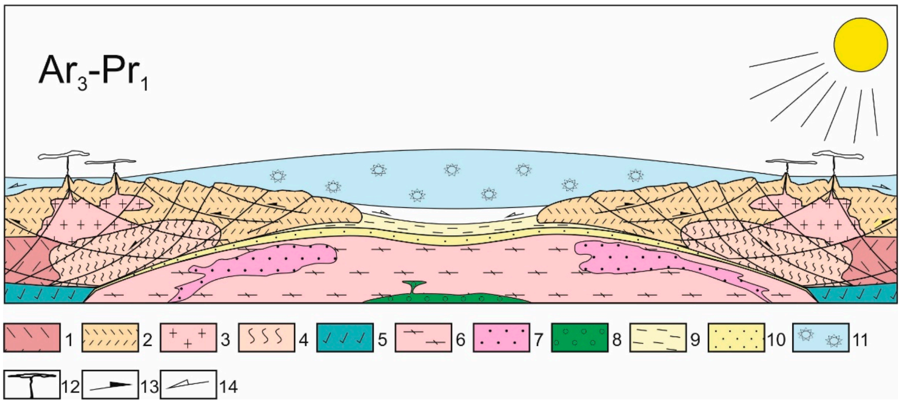

Figure 5. Paleogeodynamic reconstruction of the Keivy median massif during the Huronian glaciation at the stage of formation of the Monogea supercontinent in the Late Archean—Early Proterozoic (2.7–2.5 Ga). 1—Middle Archean continental crust (Ar2); 2—Late Archean orogenic continental-crust assemblages (Ar3); 3—Late Archean tonalite-trondhjemite ultrametamorphic eliquations (Ar3); 4—potassium microcline granites and gabbro-norites remobilized complexes of the continental lithosphere (Ar3); 5—supracrustal mafic and ultramafic lithosphere; 6—continental crust of the Keivy median massif: 7—remobilized Keivy alkaline granites and syenites; 8—remobilized mafic and ultramafic magmatites; 9—volcano-sedimentary complexes of the Keivy series; 10—terrigenous complexes of the Kolovay, Kinemur, Padcherva, and Lebyazhka formations; 11—ice mass of the Huronian glaciation; 12—volcanic structures; 13—strike-slip elements of the continental lithosphere; 14—drifting direction of the terrigenous material.

Such compounds may cover, for example, carbon dioxide (CO_2), orthophosphoric acid (H_3PO_4), ammonia (NH_3), methane (CH_4), and some others.

The occurrence of greenschist, and amphibolite metamorphic facies metamorphic processes in the Keiv sedimentary complexes, led to the fact that these compounds were transformed into metamorphic minerals. For example, phosphorus compounds formed orthophosphates of various metals, which were present in hydrothermal solutions. It was possible through the following endothermic reactions:

$$2H_3PO_4 + 3Ca(OH)_2 \rightarrow Ca_3(PO_4)_2 + 6H_2O, \quad (36)$$

$$2H_3PO_4 + 3Mg(OH)_2 \rightarrow Mg_3(PO_4)_2 + 6H_2O, \quad (37)$$

$$H_3PO_4 + 3NaOH \rightarrow Na_3PO_4 + 3H_2O \quad (38)$$

Calcium orthophosphate may also form as the thermal effect of high amphibolite facies grades on wollastonite in the presence of phosphorus and CO by the following reaction:

$$3CaSiO_3 + 2P + 5CO \rightarrow Ca_3(PO_4)_2 + 3SiO_2 + 5C \quad (39)$$

The resulting carbon should quickly oxidize to CO_2. The calcium orthophosphate obtained in this way composes a wide range of minerals, which includes apatite ($Ca_5[PO_4]_3$(F, Cl, OH) and hydroxyapatite ($Ca_{10}(PO_4)_6(OH)_2$).

The metamorphogenic apatite, in particular fluoroapatite, may also form during the transformation of wollastonite in the presence of phosphorus, calcium fluoride, and carbonated fluid:

$$18CaSiO_3 + 3P_4 + 2CaF_2 + 30CO \rightarrow 4Ca_5(PO_4)_3F + 30C + 18SiO_2 \quad (40)$$

Chloroapatite forms in a similar way.

Near Mt. Ploskaya in the western Keivy, there is a hydrothermal yttrium phosphate, or xenotime, in the amazonite pegmatites, which may also crystallize from phosphorus and yttrium oxides by the following reaction:

$$Y_2O_3 + P_2O_5 \rightarrow 2YPO_4 \quad (41)$$

Increasing temperature and pressure, under the conditions of fluid saturation of the volcano–sedimentary complexes within the Keivy median massif, resulted in alteration of rocks and their transformation into metamorphic formations of various facies and grades. The enhanced action of these factors could ultimately lead to the discriminatory manifestation of ultrametamorphic processes.

The study of the Keivy geology has shown that gneisses and crystalline schists of the Keivy formation include numerous intrusive sills and dikes of ultramafic and metamorphosed rocks. They are represented by tremolite, feldspar, garnet–feldspar amphibolites, metaanorthosites, and metagabbro-anorthosites. Less metamorphosed bodies are represented by amphibolites, plagioportphyrites, and mandelstones. These rock assemblages cut through the volcano–sedimentary formations of the Keivy formation. Shortly afterwards, the Keivy sedimentary cover was penetrated by plagiomicrocline granites, syenites, nepheline syenites, and alkaline granites.

It is noteworthy that mafic and ultramafic magmatites and anorthosites intruded mainly into the central parts of the described structure, while alkaline granites and syenites penetrated into its periphery.

The research of the geodynamic mechanisms of the formation of collision systems demonstrates that the stage of their extinction, depression processes of the common stress field and regional compression conditions are replaced by a tectonic dormant state. The ambient temperature generally reduces to decrease the rock expansion coefficient. At the background of the isostatic continental surface adjustment, the processes of denudation and tectonic fracturing of the lithosphere intensify in areas of collisional crowding. In these circumstances, melts of remobilized rocks, and mantle eliquations preserved in the lower parts of the continental crust, stream up to the surface (Figure 4).

Thus, the deepest magmatism should be manifested where the continental crust is warped to the maximum. The central part of the Keivy median massif is considered as such. This zone, exactly, shows intrusions of higher-temperature, deep, and differentiated mafic and ultramafic magmas. These complexes reflect the settings for the magma generation in the upper mantle and lower crust of that time.

Igneous melts from the shallower levels of the continental crust of that time intruded along the periphery of the Keivy massif. These rock assemblages are represented by alkaline granites, and almost completely frame the marginal parts of this region. Since magmas of alkaline granites and syenites formed in a fluid-saturated medium, their metasomatic potential was rather high. That is why it is most often impossible to divide magmatogene and metasomatic formations of this type within the Keivy median massif.

Mafic plagioclase (or labradorite) is the main rock-forming mineral of the anorthosites that penetrated the sedimentary cover. Under the conditions of postmagmatic transformation of anorthosites, by hydrothermal solutions and metasomatic re-crystallization of plagioclase in the presence of clinochlore and zoisite, alkaline amphibole and anorthosite could form:

$$\underset{\text{albite}}{10NaAlSi_3O_8} + \underset{\text{clinochlore}}{3Mg_5Al_2Si_3O_{10}(OH)_8} + \underset{\text{zoisite}}{6Ca_2Al_3Si_3O_{12}(OH)} + 7SiO_2 + 2H_2O \rightarrow \rightarrow \underset{\text{alkaline amphibole}}{5Na_2Mg_3Al_2Si_8O_{22}(OH)_2} + \underset{\text{anorthite}}{12CaAl_2Si_2O_8H_2O} \quad (42)$$

At a retrograde metamorphism stage, anorthite hydrolysis in the presence of CO_2, in turn, caused the formation of kaolinite rims and the saturation of fluids with Ca and HCO_3. In this case, the following reaction could proceed:

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + 3H_2O + 2CO_2 \rightarrow \underset{\text{kaolinite}}{Al_2Si_2O_5(OH)_4} + Ca^{2+} + 2HCO_3 \quad (43)$$

During the subsequent progressive amphibolite facies metamorphism, garnet with a high grossular minal could crystalize (see Reaction (28)).

At the final stage of the collision system evolution in the NE Baltic Shield, large dike- and sill-like mafic and ultramafic massifs intruded into the sedimentary cover of the Keivy median massif. Due to metamorphism, these rocks were recrystallized to amphibolites of various compositions, and their primary igneous mineral assemblages are now absent. There is a certain spatial rule in the distribution of the described amphibolites [31]. So, tremolite amphibolites are only developed on the flanges of the Keivy synclinorium, predominantly in its western and eastern parts. In its central part, tremolite amphibolites are absent, fading to abundant feldspar amphibolites, which compose the thickest bodies. The Late Archean denudation and hydrolysis of mafic and ultramafic rocks most probably resulted in the formation of tremolite amphibolites. Their subsequent metamorphism, in the presence of chlorite and corundum, could produce subalkaline-series amphibole schists, epidote, and quartz. Under the high-pressure and temperature conditions, this process could proceed as follows:

$$\underset{\text{labradorite}}{10NaAlSi_3O_8} + \underset{\text{tremolite}}{2Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\text{chlorite}}{Mg_5Al_2Si_3O_{10}(OH)_8} + \underset{\text{corundum}}{2Al_2O_3} \rightarrow \rightarrow \underset{\text{alkaline amphibole}}{5Na_2Mg_3Al_2Si_8O_{22}(OH)_2} + \underset{\text{epidote}}{2Ca_2Al_3Si_3O_{12}(OH)} + 3SiO_2 \quad (44)$$

Tremolite is a typical metamorphogenic mineral. Therefore, tremolite amphibolites could presumably be formed due to the hydrolysis of pyroxene (enstatite and diopside) under the conditions of metamorphism of the amphibolite facies, according to the following reaction:

$$\underset{\text{diopside}}{4CaMgSi_2O_6} + \underset{\text{enstatite}}{5Mg_2Si_2O_6} + 2H_2O \rightarrow \underset{\text{tremolite}}{2Ca_2Mg_5Si_8O_{22}(OH)_2} + \underset{\text{forsterite}}{2Mg_2SiO_4} \quad (45)$$

Under the same conditions, reactions of olivine serpentinization and brucite formation could proceed and brucite could pass into a hydrothermal solution:

$$\underset{\text{forsterite}}{2Mg_2SiO_4} + 3H_2O \rightarrow \underset{\text{brucite}}{Mg(OH)_2} + \underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4} \quad (46)$$

In addition to the above described processes, we should consider that the destruction and resedimentation of tonalite–trondhjemite and granodiorite series rocks were accompanied by the formation of abundant potassium salts (K_2CO_3). These salts are highly water-soluble and, thus, could most probably mineralize water-saturated sedimentary formations of the Keivy domain of that time. Later, in the course of their metamorphic transformations, potassium served as a building material for the generation of metasomatic microcline (alkaline) granites, which were widespread along the periphery of the domain (Figure 3).

6. Conclusions

The study of the processes of the generation of the Meso- and Neoarchean structural–material complexes of the Baltic Shield showed that a mosaic pattern of formations of different ages represents the continental lithosphere of that time. The collision of domains of the continental crust occurred at the Archean–Proterozoic transition (~2.6 Ga), due to the formation of the first supercontinent in the history of the Earth (Monogea). At the same time, the Keivy domain experienced subsidence due to the thrusting of adjacent continental massifs. Geological and geophysical surveys have shown that the studied landscape of that time was a typical environment for the median massif, in which a sedimentary basin, surrounded by mountain systems, was formed. This basin developed under the conditions of the cold climate of the Huronian glaciation, and was apparently covered by a thick glacier layer in the Late Archean. Most likely, a shallow enclosed basin was formed under the ice cap of the Keivy median massif at that time. This basin was warm enough to develop organic life in high volcanic and hydrothermal activity conditions in the peripheral zones. This is evidenced by the presence of dispersed carbon, which is abundant in the sedimentary–volcanogenic strata of the region. The mountain systems surrounding the closed, shallow water basin led to the sedimentation of erosion products of the tonalite–trondhjemite and amphibolite–komatiite rocks of the continental crust of the Kola region. Predominantly undersaturated carbonate deposits were formed in the Keivy region in the Late Archean, due to the cold climate, as evidenced by the indicator mineral howlite (reactions (30) and (31)). In addition, the Keivy sedimentary complexes were formed under atmospheric conditions undersaturated with oxygen and carbon dioxide. As a result, typical for the Neoarchean reactions of decomposition of anorthite under the action of sulfuric acid, fluid and its transformation into kaolin and gypsum proceeded. Gypsum, under the influence of hydrochloric acid mineralized fluid, decomposed into sodium sulfate and calcium chloride, which formed a mineral—antarcticite. All physicochemical transformations of the sedimentary cover of the Keivy median massif occurred under conditions of greenschist and amphibolite facies of metamorphism. The destruction and chemical transformation of tonalite–trondhjemite rock complexes led to an anomalous enrichment of the sedimentary cover, with alumina under the above conditions. Vast deposits of aluminum raw materials, represented by kyanite substrates, emerged due to metamorphism. Further evolution of the Keivy median massif, at the Archean–Proterozoic transition, led to the cessation of collisional processes, the emergence of deep faults along the region's periphery, and the intrusion of large masses of alkaline granites. It should be noted that the unique mineral deposits of the Keivy median massif are associated with the features of its geodynamic evolution.

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