Introduction

The reconstruction of the formation conditions, architecture and mineralogical composition of the early lithosphere is a key problem in modern geology. A number of studies indicates that the geodynamic evolution models of Meso and Neoarchean associations in the various regions of the Earth have both similar features with the Phanerozoic systems, described within the framework of the interaction of lithospheric plate tectonics and mantle plumes [1-3] and principal differences caused by the evolution of the Earth’s thermal regime [4,5].

One of the opportunities to reconstruct the mechanism of Archean craton assembling is analysis of magmatic systems of Green-Stone Belts (GSB), well or partially preserved in the many Archean cratons. The most abundant magmatic systems of Archean are the komatiite-basalt and andesite-dacite-rhyolite systems. It is noteworthy the coexistence of geochemical contract series within the single system. For example, the Archean mafic rocks are represented by the variety of komatiitic, tholeiitic and Island-Arc Tholeiitic (IAT) assemblages [6,7]. The felsic rock series comprise Adakite (A), Basalt-Andesite-Dacite-Rhyolite (BADR), Andesite-Dacite-Rhyolite (ADR), tholeiite (TA), Bajaite (B), and high Nb-basalts (HNB) assemblages [2].

The evolution model of the early crust for the Karelian Craton is based on the estimation of the petrological condition of magma generation and geodynamic regimes of the initiation of magmatic systems. The most suitable area for such studies is the western flank of the Paleorarchean Vodlozero Block (Central Karelia), particularly the Vedlozero-Segozero greenstone belt, where all MesoNeoarchean igneous events are manifested in a local scale [8,9]. This paper presents newly obtained geochemical and U-Pb (SHRIMP II) zircon dating data for the mafic and andesite rocks. The results obtained by using the approach, based on the analysis of the volcanic rocks, combined with intrusive and sedimentary rocks, maintain the model of the initial stage of the assembling of the Karelian Craton.

Geological Setting

The Vedlozero-Segozero greenstone belt GSB is located in the central part of the Karelian Craton and extends in sub-meridian direction over a distance of approximately 300km and has a width of 50-60km (Figure 1). It consists of several local domains including Khatavaara, Koikkary, Palasel’ga, Maselga, Semch, Sovdozero, and Oster [10] in which the series of volcano-sedimentary rocks with the maximum thickness up to 6km occur within the Neoarchean granitoid rocks. The distinctive feature of these domains is the good preservation of the rock texture despite the rocks were affected by greenschist- to epidote amphibolite-facies regional metamorphism of the andalusite-sillimanite type at a pressure of ca. 2-4k bar and temperature of lower than 540 °C [11]. On the contrary, in the Vodlozero Block the tonalite-trondhjemite-granodiorite (TTG) rocks are observed at only few outcrops (Figure 2a).
Figure 1: Geological map of the Vedlozero Segozero greenstone belt [8].

Figure 2: Photographs showing typical features and field occurrence.
Figure 2a: Tonalite-trondhjemite-granodiorite (TTG) from the Vodlozero Block (3.2Ga).
Figure 2b: Komatiitic lava flow with spinifex texture from the Sovdozero domain.
Figure 2c: Lava breccia of komatiite from the Sovdozero domain.
Figure 2d: Pillow lava of komatite from the Koikary domain.
Figure 2e: Agglomerate tuff of andesite from the Chalka domain.
Figure 2f: Pillow lava of andesite porphyrite from the Chalka domain.
Methods

The paper presents the data on the chemical analysis of bulk rock composition conducted in the Analytical Centre of Institute of Geology, Karelian Research Centre, RAS. The concentrations of major oxides were determined by quantitative chemical analysis. Analyses were carried out with uncertainties of 1-5rel.% for elements with concentrations more than 0.5wt% and up to 12rel.% for elements with concentrations less than 0.5wt%. The minor and trace element contents were determined by ICP-MS on a Thermo Scientific X Series 2 instrument, using conventional technique [12]. U-Pb isotopic studies of zircon were carried out using a SHRIMP-II ion microprobe at the Center for Isotopic Research, Karpinskii All-Russia Research Institute of Geology (St. Petersburg) using standard technique [13,14].

Results

Komatiite-basalt magmatic system

Mesoproterozoic mafic rocks (komatiite-basalt series) from the Vedlozero-Segozero GSB are represented by the rock series with reconstructed thickness up to 2km. Komatiites with MgO content ca. 18-26wt.% form a succession of lava flows ca. 50-600m in thickness.

The komatiite-basalts consist of strata-bound rock sequences, composed of pillowled, massive and variolitic differentiated lavas with spinifex texture, lava breccia (Figure 2b-2d) together with tuff and sedimentary rock beds and intrusive dunite-peridotite and Mg-rich gabbro bodies. The studied sequence in magmatic series is considered to be the result of collage of separate basaltic plates that supposed the idea that the primary series of mafic rocks did not exceed 1.5km.

Tectonic displacement of the basaltic plates is marked by the occurrence of greywacke in the volcanic mafic rock series, which originated from the degradation of komatiitic rocks. The time of mafic rock formation from the Vedlozero-Segozero GSB reasonably assumed to be discrete. The data provided by Arestova et al. [9] indicate, that the age of the gabbroic rocks of Palaselga domain based on U-Pb (SHRIMP II) dating of zircon is 3.02-2.96Ga. The present data show, that the age of mafic complexes from Koikary and Hautavaara domains is slightly younger.

The age of komatiites from Koikary domain based on U-Pb (SHRIMP II) dating of zircons from dacite dykes, which cross-cut the komatiites, is 3.00-2.93Ga. The age of komatiites from Hautavaara domain determined by U-Pb (SHRIMP II) dating of detrital zircons in greywacke interlayered between the komatiitic lava flows is 2.92-2.91. These results argue strongly to multi-stage model of mafic series formation. Regarding chemical composition, the following types of mafic rocks from the Vedlozero-Segozero GSB have been distinguished:

1. Komatiites of Al-depleted uncontaminated type (AUDK-UC) with the contents of SiO$_2$<43wt.% and MgO<18wt.%. It is characterized by the ratios CaO/Al$_2$O$_3$<1 (0.4-1), Al$_2$O$_3$/TiO$_2$≈22 (14-25), (La/Sm)$_n$=0.4-1.1 and (Gd/Yb)$_n$=0.9-1.

2. Komatiites of Al-depleted contaminated type (AUDK-C) with the contents of 43<SiO$_2$<50wt.% and MgO<18wt.%. It is characterized by the ratios CaO/Al$_2$O$_3$<1 (0.4-1.2), Al$_2$O$_3$/TiO$_2$≈22 (19-26), (La/Sm)$_n$=1.1-4.2, and (Gd/Yb)$_n$=0.8-1.3.

3. Komatiitic basalts (KB) with the SiO$_2$ contents from 44 to 52wt.% and MgO content from 6 to 18wt.%. It is characterized by the ratios CaO/Al$_2$O$_3$<1 (ca. 0.5-0.7), Al$_2$O$_3$/TiO$_2$≈20 (ca. 17-25), (La/Sm)$_n$=0.3-0.7, and (Gd/Yb)$_n$=0.7-1.0.

4. Tholeiitic basalts (MORB) with the contents of 46<SiO$_2$<50wt.% and 6<MgO<10wt.%. It is characterized by the ratios CaO/Al$_2$O$_3$<1 (0.5-0.8), Al$_2$O$_3$/TiO$_2$≈40 (30-50), (La/Sm)$_n$=0.1-0.4, and (Gd/Yb)$_n$=0.7-3.0.

5. Island-arc tholeiitic basalts and andesite-basalts (IAT) with 46<SiO$_2$<50wt.%, 2<MgO<10wt.%, CaO/Al$_2$O$_3$<1 (0.5-0.7), Al$_2$O$_3$/TiO$_2$≈25 (18-35), (La/Sm)$_n$=0.1-0.2, and (Gd/Yb)$_n$=2.1-4.0. These rocks are characterized by the content of La=15ppm, Ce=30ppm, Rb=20-80ppm, and Ba=30-200ppm. Their composition is enriched in LREE and depleted in Ti, Nb, and Ta.

Intrusive rocks, that are comagmatic to the mafic volcanic rocks from the Vedlozero-Segozero GSB, are represented by dunite-peridotite (chemical analogues of komatiite of AUDK-C type) and Mg-rich gabbro (chemical analogues of the IAT type) rocks. The sedimentary rocks associated with the studied Mesoproterozoic mafic complexes have the litho-geochemical characteristics similar to the sedimentary sequences from Phanerozoic ophiolite complexes [15,16]. They are represented by mafic tuffs and tuffites, silicites and siltstones, which are enriched in clay, organic matter, silica, iron and sulphur, and associated with exhalative-hydrothermal removals.

Andesite-dacite-rhyolite magmatic system

Andesites are the most dominant volcanic rocks within the Vedlozero-Segozero GSB. The most common rocks are massive, amygdaloidal, porphyritic, brecciated, pillow lavas together with agglomerate and peptitic tuffs (Figure 2e & 2f). The andesite lava flows vary in thickness from 1-25m and are interbedded with tuffs and lava breccia formed the rock sequence with the thickness of 300-2000m. The time of andesite rock formation from the Hautavaara domain was determined by U-Pb (SHRIMP II) dating of zircons from andesite as 3.05-2.92Ga. The age of andesite from the Koikary, Semch, and Hautavaara domains based on U-Pb (SHRIMP II) dating of zircons from dacite lavas and dykes, is 2.90-2.84Ga. The probable age of andesite from the Masela area of Hautavaara domain is estimates as 2.79-2.74 using U-Pb (SHRIMP II) dating of single zircons from andesitic tuffs formed coeval with sanukitoids of the same age [17]. These results argue strongly to multi-stage model of BADR formation as in the case of mafic magmatic systems. The andesites comprise of the following series:

Adakite series (HSA and LSA): In the volcanic and subvolcanic rocks of this type the SiO$_2$ content varies from 53 to 
76wt.%, so they can be identified as High Silica (HSA) and Low-Silica (LSA) varieties. The first one is dominant in the series. The rocks are characterized by Na₂O content ca. 2.5-5.6wt.%, MgO<4wt.%, 200<Si<100ppm, Ba>350ppm, Zr ca. 115-140ppm, U ca. 1.1-1.7ppm and Sr/Y=20-123. They have depleted HREE patterns and pronounced negative anomalies of the Nd and Ti.

**Nb-enriched series (BADR):** Regarding composition of SiO₂ and alkali, the rocks are identified as andesitic basaltic and rhyolites with normal alkalinity. The K₂O/Na₂O varies from 0.3 to 0.5wt.%. The BADR type rocks have evaluated content of Al₂O₃ (ca. 16-18 wt.%), Cr (20-200ppm), Ni (12-140ppm), Nb (7-11ppm), and are characterized by Zr/Y=5.4-8.8, (La/Yb) pm=8-19, and Nb/Ta=8-19. They have enriched LREE patterns with weakly fractionated HREE.

**High Nb basalts, andesite basalts and andesite (HNB):**
This type is distinguished by the abnormally high Nb content in the andesite rocks. The HNB rocks are characterized by low-Mg number (Mg#=100*MgO/(MgO+FeO) ) Mg#=45-52 and low SiO₂ content (50-53wt.%). These rocks have high Cr (220-620ppm) and Ni (150-650ppm) content at low Nb content (6-9ppm). They are characterized by Zr/Y=4.8-5.6, (La/Yb) pm=4.9-6.2, and Nb/Ta=18-23.

**High Mg andesite basalts and andesite (High-Mg-BADR):**
This are distinguished on the base of composition similarity to the Phanerozoic reference pattern of Mg-high andesite from Baja California, Mexico [18]. The principal difference from the above mentioned rock series is the high Mg-number (Mg#=100*MgO/(MgO+FeO) ) Mg#=53-64 with SiO₂ content ca. 53-64wt.%. These rocks have high Cr (220-620ppm) and Ni (150-650ppm) content at low Nb content (6-9ppm). They are characterized by Zr/Y=3.5-5.9, (La/Yb) pm=1.9-4.5 and Nb/Ta=17-19 ratios.

**Tholeiitic andesites (TA):**
This are represented by lava and dyke facies. They have from low to moderate - Mg number (Mg#=35-53) and SiO₂ content (58-65wt.%) typical to andesites. The tholeiitic andesites are enriched in Cr (270-800ppm) and Ni (100-300ppm) at low Nb (<4ppm) concentration. They are characterized by Zr/Y=5.0-7.5, (La/Yb) pm=0.9-1.9 and Nb/Ta=12-26 ratios. The distinctive feature of the tholeiitic andesites is weakly fractionated REE pattern.

It is noteworthy that the identified volcanic rock series have their intrusive analogues occurred as subvolcanic bodies and dyke systems of various scale. Sedimentary assemblage within the Vedlozero-Segozero GSB are represented by psammitic andesite tuffs, tuffites, silica tuffites, siltstones, quartz arenites, the terrigenous components of which reflect the local removal provenance.

**Discussion and Main Conclusion**
 Petrologic and geochemical studies of the magmatic systems and the calculation of formation conditions supposed that the formation of the komatiitic melts with the maximum MgO content ca. 25-30wt.% is the consequence of high degree partial melting of mantle lherzolite at temperatures near 1750 to 1820 °C and pressures near 5 to 7Gpa, associated with the formation of olivine-orthopyroxene restite phases, caused by the rising of thermal plume. The discontinuity of the initial melt compositions, obtained during the komatite-basalt forming reactions, depends on the mineral composition of the restite phases, appeared during melting, and further magma fractionation. The formation of Mg- high assemblages probably took place in back-arc basins. The back-arc basin environments are indicated by the eruption conditions, types of sediments and the appearance of IAT-type basalts at the top of the sequence. This process is multi-stage including the oceanic stage with the formation of AUDK-UC+KB+MORB rocks, convergent stage associated with formation of AUDK-C rocks and back-arc basin closing with the IAT-type rock formation.

The initial formation of andesite magmatic systems, which are also characterized by geochemical heterogeneity, was almost synchronous with the formation of mafic magmatic systems. The observed typical assemblage comprises adakites (HSA and LSA) and Nb-rich andesite (High-Nb BARD), Mg-rich andesites (HNB) and in some cases tholeiitic andesites (TA) is the signature of their subduction origin. Besides, it is the adakites that indicated the direct melting of the subducted plate. Model calculations show, that the observed compositions of adakites (HSA and LSA) can be formed during melting of the 10-15% amphibolite, resulting in the formation of restite phase composed of Cpx (60%) +Gar (10%) +Pl (25%) +Hbl (5%). The further melt evolution developed in the processes of Pl+Cpx fractionation. The other andesite rock series (HNB, High-Nb BARD, TA) formed during the processes of metasomatic mantle wedge melting and assimilation of initial adalite melts with the mantle melts.

The results obtained by using the «triad» approach, based on the analysis of the volcanic rocks, combined with intrusive and sedimentary rocks, maintain the model of the initial stage of the assembling of the Karelian Craton, corresponding to the evolution of consistent convergent system. Chronological scheme of the system evolution (Figure 3) was established using the U-Pb (SHRIMP II) dating of zircon from the representative volcanic and intrusive rocks and sediments from the Vedlozero-Segozero GSB. A chronological evolution scheme of the region is described by a sequence of events at the Paleoarchean block margin, represented by TTG (3.2-3.1Ga):

A. The formation of an initial subduction-accretion system (3.05-2.94Ga) and the simultaneous formation of mafic series in back-arc basins;

B. A collision stage with the obduction of oceanic plates on a continental basement (2.94-2.90Ga);

C. The evolution of a volcanic belt and a collision stage with the formation of sanukitoids, intermediate-felsic volcanic and granitoids (2.88-2.84Ga);

D. The formation of pull-apart basins (2.64-2.61Ga).
Thus, the mafic and andesite magmatic systems at the western flank of the Vodlozero Block were forming in several cycles throughout 0.40-0.45Ga. It reflects the interaction of plume, subduction, accretion and collision processes. Concluding the results, we note as well that the key magmatic systems including the komatiite-basalt and andesite ones play an important role in the Archean crust-forming processes, particularly in the accretion collision processes. The mafic rocks formed large allochthon complexes on the continental margin that resulted in the increasing of the continental crust thickness. Subduction of separate plates caused the formation of adakite and bajaitic assemblages during its melting and BADR and TTG complexes in the processes of mixing with mantle wedge.

The conclusions of the study indicate that the assembling of Archean cratons, including Canadian, Australian, Karelian and Indian cratons, probably, was controlled by the similar factors with the key role of interaction between the mantle plumes and subduction processes, which determined not only the composition, but also the architecture of ancient continental crust.

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