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GEOLOGY

Late Orogenic Granitoids of the Tervu Agmatitic Zone in the Southeastern Part of the Svecofennian Belt (Northern Ladoga Area, Russia)

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Abstract—The Tervu breccia zone was formed at the final stages of the Late Proterozoic magmatic and metamorphic activity (1.86 Ga ago) and healed with granitic material shortly after its formation. The Tervu breccia zone with granitic agmatites has a sublatitudinal orientation, which is discordant in relation to the earlier structures and Kurkijoki enderbite and Lauvatsaar–Impiniem diorite–tonalite complexes in the Svecofennian rocks of the Ladoga region. The largest granitic bodies in this area, the Tervu and Peltola intrusions, are located in the Tervu Zone. The U–Pb age of monazite from granites of the Peltola intrusion is determined as 1859 ± 4 Ma and coincides with the age of the granites of the Tervu intrusion (1859 ± 3 Ma), which indicates that the granites of both intrusions and some surrounding smaller bodies were intruded simultaneously into the tectonically weakened space at the late-orogenic stage while plastic deformations were turning to elastoplastic ones. The results obtained reveal the features of the tectonic development of the junction zone of the two largest blocks of the Fennoscandinavian shield, the Karelian Craton and the Svecofennian Belt.

Keywords: late-orogenic granites, dating, breccia zone, Ladoga region, Svecofennian rocks

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INTRODUCTION

The Tervu Breccia Zone (TBZ) is located on the Tervu Peninsula on the northern coast of Lake Ladoga (Fig. 1) and contains various tectonic breccias, intruded by granitoids. This zone has an apparent thickness of no less than 6–8 km and a sublatitudinal orientation, sharply discordant with the older structures of the region of predominantly northwestern strike. We have identified and traced the Tervu zone for 20 km in the latitudinal direction during research work and detailed mapping of the area [1].

On the regional scale, the time of TBZ formation is associated with overthrust of the Proterozoic Svecofennian block on the Archean Karelian Craton, which is recorded as the Meyer thrust of sublatitudinal strike (Fig. 1, inset) [2, 3]. Formation of the thrust probably gave rise to complementary extension zones, one of which was the Tervu breccia zone. The Meyer thrust zone is in turn the southeastern fragment of a broader (more than 400 km long) Raahe-Ladoga thrust belt which is in fact a juncture between the Archean Karelian Craton and the Proterozoic Svekofennian Belt [3]. The fact that the study undertaken sheds light on late stages of tectonic development of the junction zone of two major blocks of the Fennoscandinavian Shield—the Karelian Craton and the Svekofennian Belt defines its relevance and regional importance.

The Tervu granite intrusion, one of the largest in the region, has been formed in the Tervu Zone. The isochron U–Pb age of the Tervu microcline granites has been determined by the U–Pb ID-TIMS zircon method as 1859 ± 3 Ma (Supplementary Table ESM_1), while the age of its vein facies determined for monazite was 1845 ± 2 Ma [4]. It was suggested [1] that the intrusion occurred in a tectonically weakened zone during the late stages of plutonic–metamorphic activity in the region, so its age also determines the TBZ formation time as ~1.86 Ga [2]. However, the assumption about the time of formation of the tectonic zone required further verification through the study of other granite bodies spatially and structurally related to this zone. Since TBZ has a large length and the dated Tervu intrusion represents only its western coastal part (Fig. 1), it was important to find geochronological evidence of synchronous formation of other granitoids throughout the sublatitudinal tectonic structure. Such verification appeared possible due to

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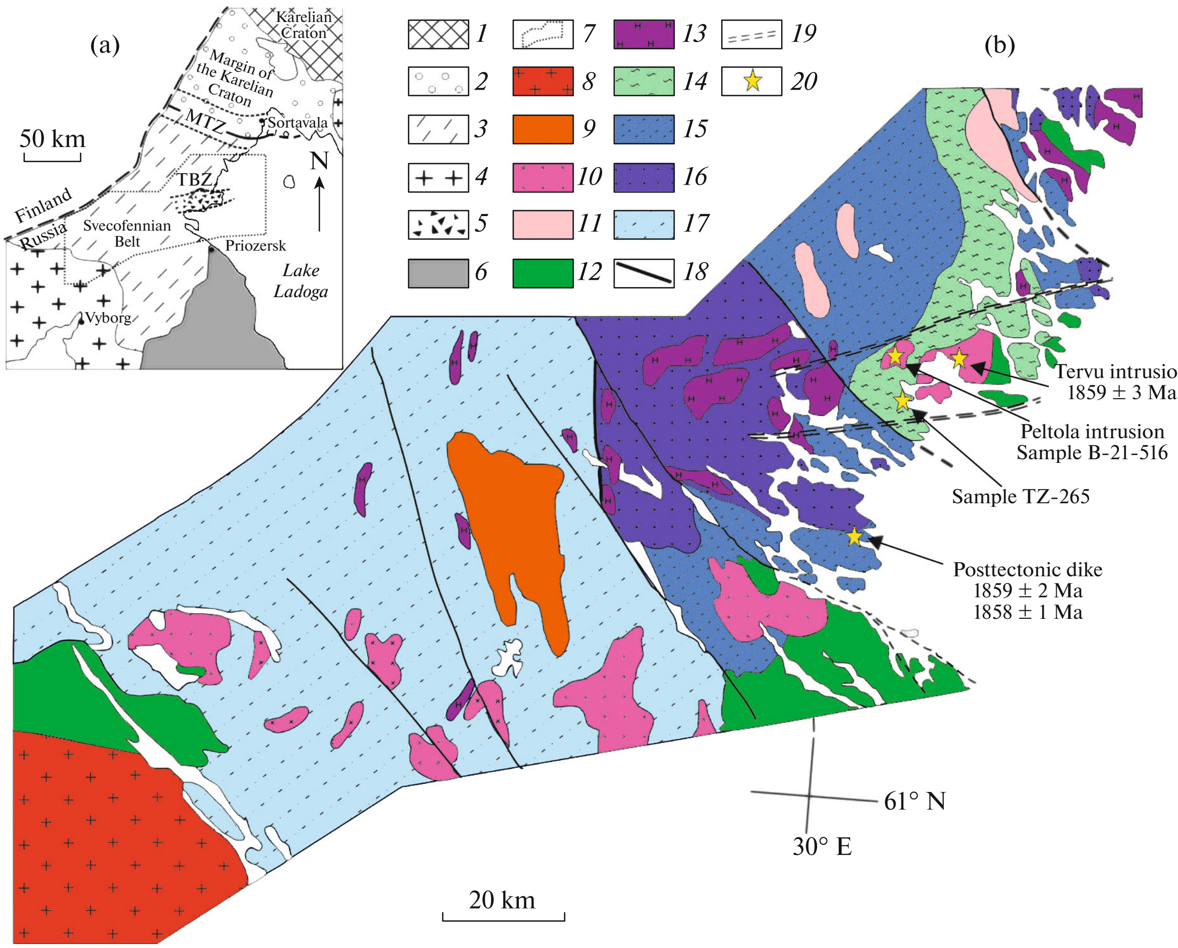

Fig. 1. Geological map of the study area showing the sampling sites and sample ages. (*1–7*) (inset a): *1*, margin of the Archean Karelian Craton; *2*, Paleoproterozoic rocks of the craton margin; *3*, Paleoproterozoic rocks of the Svecofennian Belt; *4*, rapakivi granites; *5*, breccia zone; *6*, Riphean cover of the East European platform; *7*, contour of the study area; (*8–20*) (in the map b): *8*, rapakivi granites; *9–13*, Svecofennian intrusions: *9*, post-orogenic monzonites, quartz syenites, and granites of 1.80 Ga; *10*, late-orogenic potassic granites of 1.87–1.80 Ga.; *11–13*, synorogenic intrusions: *11*, *12*, Lauvatsaar–Impiniem complex of 1.88–1.88 Ga (*11*, late phase: tonalites, *12*, early phases: gabbro, diorites, quartz diorites); *13*, synorogenic Kurkijoki complex of 1.89–1.88 Ga (norites, enderbites); *14–17*, Early Proterozoic supracrustal series of the Lahdenpohja metamorphic series with the following petroformations: *14*, biotite gneiss; *15*, garnet gneiss; *16*, hypersten–garnet gneiss; *17*, cordierite gneiss; *18*, faults; *19*, boundaries of the breccia zone; *20*, sampling sites. MTZ, Meyer tectonic zone; TBZ, Tervu breccia zone. TZ-265, number and location of chloritized garnet–amphibole–plagioclase schist.

the presence of numerous granitoid bodies within the TBZ, the Peltola intrusion being the largest of them. The results of isotopic dating of this intrusion are the subject of this publication.

MATERIALS AND METHODS

U–Pb monazite isotopic study. Mineral separates, in particular monazite, were extracted from a sample of microcline granite (sample B-21-516, weight 3 kg). Monazite of the sample is represented by light yellow transparent or translucent flattened crystals and by large dark-brown grains with traces of corrosion. The U–Pb isotopic analysis was carried out for all monazite varieties (four samples) after being picked out under a binocular microscope; some grains were subjected to additional screening with an scanning electron microscope. Pb and U were separated by elution with HCl on BioRad AG 1-X8 ion-exchange resin. A ^{235}U–^{208}Pb tracer was used for isotope studies. Isotope analyses were performed on a Triton TI multicollector mass spectrometer in the static mode using Re cathodes pre-annealed for 30 min at 2000 ± 50°C. A silicate emitter mixed with H_3PO_4 was used for the measurements. Pb fractionation coefficient measured in the NBS standard SRM-982 and the U fractionation coefficients determined from a natural sample were 0.1 and 0.08% per amu, respectively. The accuracy of both the U and Pb contents and the U/Pb ratios was 0.5%. Blanks were within 25 pg Pb and 5 pg U. All analyses were carried out at the Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, St. Petersburg.

Microprobe mineral analysis in polished thin sections were carried out on a JSM-6510LA scanning electron microscope equipped with a JED-2200 JEOL energy dispersive spectrometer (Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences). The analysis conditions were the following: accelerating voltage 20 kV, current 1 nA, ZAF-method for correction of the matrix effects. Natural minerals, pure oxides, and metals were used as standard samples. The detection limit of the elements to be determined was 0.1 wt %.

The content of chemical elements in rocks was determined using X-ray fluorescence analysis (XRF, Russian Geological Research Institute, St. Petersburg). The powdered sample and flux (50% lithium metaborate and 50% lithium tetraborate) in a ratio of 1 : 9 were melted in gold–platinum crucibles and then pressed with a force of 20 t to produce tablets 40 mm in diameter and 4 g in weight. The detection limit for major oxides and minor elements was 0.01–0.03 wt % and 2–5 ppm, respectively.

Thermobarometric assessments of metamorphic mineral parageneses were carried out by multi-equilibrium geothermobarometry using the THERMOCALC software [5] and the thermodynamic database of minerals and DS55 solid-solution models (updated in 2004).

BRIEF OVERVIEW OF THE GEOLOGICAL SETTING OF THE PELTOLA INTRUSION

Igneous rocks of the orogenic stage in the southeastern part of the Svecofennian mobile belt are grouped into three complexes: the Kurkijoki, Lauvatsaar–Impiniem, and Tervu [1, 4, 6]. These complexes were successively formed during the main stage of plutonic–metamorphic activity ~1.89–1.86 Ga ago and closely correlate with deformations and metamorphism of that time [1]. The formation of the Kurkijoki enderbite and Lauvatsaar–Impiniem diorite–tonalite complexes along with the formation of compressed and isoclinal folds took place during the early and main orogenic stages. The late orogenic stage was characterized by the development of plicative and mainly discontinuous dislocations and the formation of intrusions and dikes of the Tervu granitoid complex. The deformational structures formed roughly at the same time as rocks of the Tervu Complex are of mainly north-northeasterly orientation; they are superimposed onto the structures of the early stage, which have a meridional and northwesterly strike in modern coordinates [1].

To estimate the time of TBZ formation, we studied the Peltola granite intrusion, the second largest intrusion after the Tervu pluton, located in the central part of the TBZ (Fig. 1). The structural position of the Peltola intrusion indicates that its formation was synchronous with the formation of the tectonic zone: there are signs of weakly deformed healed granites. The Peltola intrusion has a complex structure, numerous inclusions of framing rocks, and an abundance of shadow textures.

The Peltola intrusion with an area of approximately 20 km^2 is not the only intrusion in this area: there are numerous small unnamed intrusions and vein bodies, injecting the Lahdenpohja metamorphic series and older intrusions of the Kurkijoki and Lauvatsaar-Impiniem magmatic complexes. The granites considered to be a part of the Tervu Complex are characterized by a significant homogeneity, essentially the crustal (S-type) geochemical parameters, probably due to their formation mainly from sedimentary rocks (Figs. 2a–2d).

The composition of rocks of the Peltola intrusion and smaller bodies apparently composed of the same material varies from leucocratic biotite and two-mica plagiogranites to two-feldspar granites. The margins of granitoid massifs under consideration have gradual transitions to migmatite fields, forming bodies of banded migmatites and agmatites. The petrochemical characteristics of rocks (Figs. 2a–2d, Supplementary Table ESM_2) indicate the highly aluminous composition of granitoids of two intrusions and small bodies, and their intermediate position between calc–alkaline and alkaline–calcareous series (Figs. 2b, 2c).

The Peltola and Tervu granitoids are not the latest magmatic formations within the TBZ and its immediate surroundings. The most recent igneous rocks here are represented by a dyke complex with a composition of rocks ranging from diorites to granodiorites and granites (Fig. 2a). Although these dikes have a relatively limited distribution, they are important for understanding the history of endogenic events in the area. Some of the dikes are deformed and folded, while others do not bear any traces of deformation. The U–Pb ages of monazite samples from one of the undeformed dikes, 1859 ± 2 Ma and 1858 ± 1 Ma [11], almost coincide with the age of the Tervu intrusion. These dikes intersect metamorphic, strongly migmatized rocks and, in turn, are metamorphosed and turned into amphibolites, biotite–rhombic–plagioclase and biotite–plagioclase schists, often migmatized. The schistosity in the rocks of the dikes is parallel to their contacts, intersecting the schistosity of the host rocks. The TBZ also contains boudinaged and reoriented fragments of dikes of basic composition. In general, their orientation coincides with the northwestern orientation of the axial planes of earlier folds, which is dominant in the region. There are reasons to think that prior to brittle deformation, there were plastic shear deformations of this direction in the Tervu Zone [1].

Metamorphic and igneous rocks of basic composition surrounding the Peltola intrusion were subjected to intense biotitization, which resulted in the formation of pale green hornblende and chlorite. Acidic

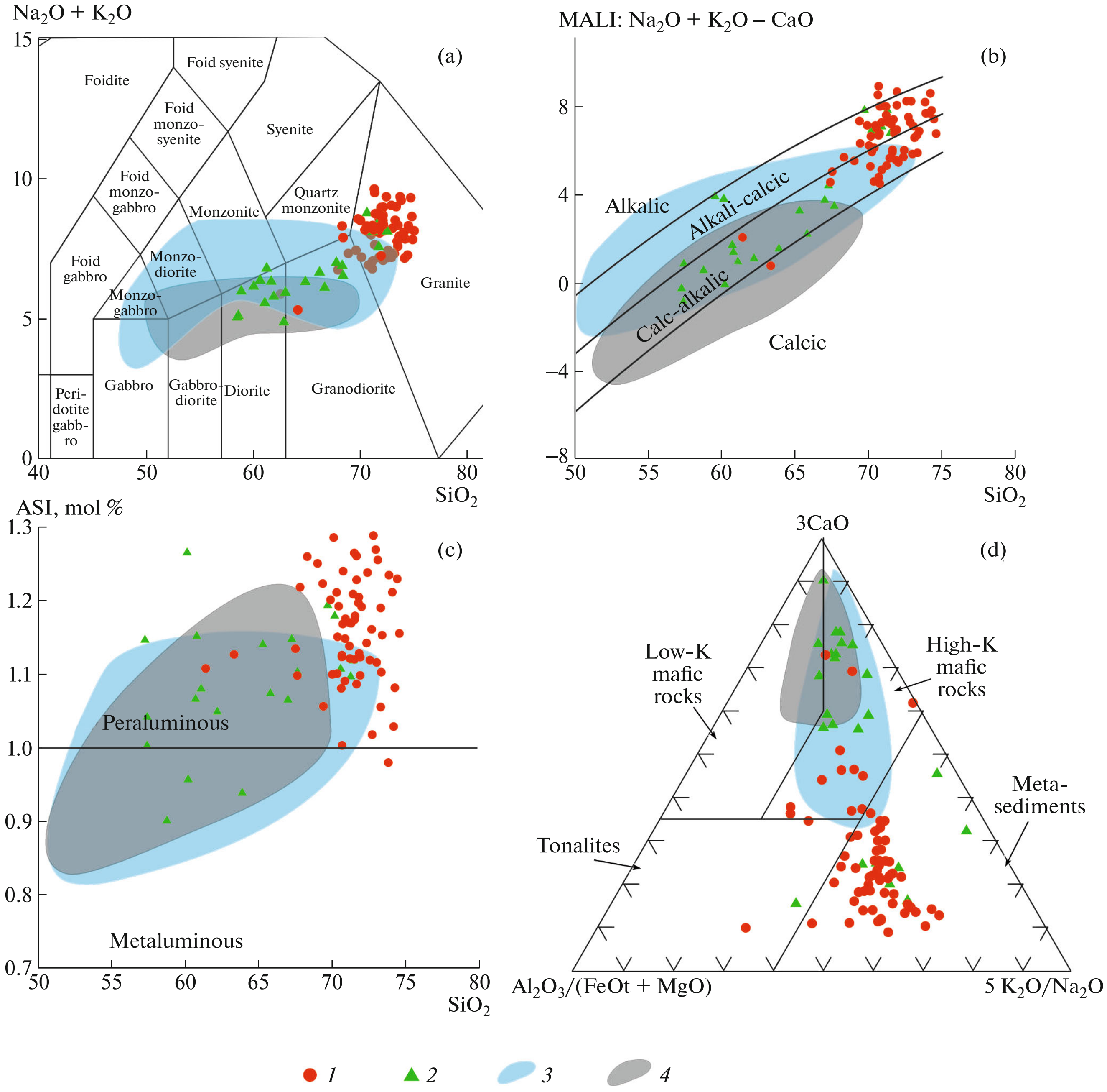

Fig. 2. Petrochemical diagrams for granitoids of the Tervu and dyke complexes of Northern Ladoga. (a) $SiO_2 - (Na_2O + K_2O)$ [7]; (b) SiO_2 – index MALI, (c) ASI = Al/(Ca – 1.67P + Na + K) [8]; (d) $Al_2O_3/(FeOt + MgO)–3CaO–K_2O/Na_2O$ diagram characterizing the sources [9]. Compositions of the rocks shown in the diagrams are given in the appendix to this paper (Supplementary Table ESM_2), part of them related to the Tervu complex were borrowed from [10]. (*1*) Rocks of the Tervu Complex, (*2*) dyke complex, (*3*) composition field of rocks of the Kurkijoki complex, (*4*) composition field of rocks of the Lauvarsaari–Impiniemi. Fields of rock compositions of magmatic complexes are mapped using published data [6].

rocks are muscovitized, in some places andalusitized. Alteration of the host rocks of the Peltola intrusion is reflected in the development of medium-temperature metamorphic associations, replacing the high-temperature metamorphic minerals. The most common form of alteration is garnet replaced by biotite and a biotite–plagioclase aggregate. The chemical zoning of garnet is regressive, which is expressed in an increase in the FeO and MnO concentrations and a decrease in MgO towards the edges of grains of this mineral [1, 6]. The zoning is caused by adaptation of the equilibrium garnet composition with surrounding minerals to decreasing temperature and pressure. The nature of mineral alterations indicates a drop in temperature

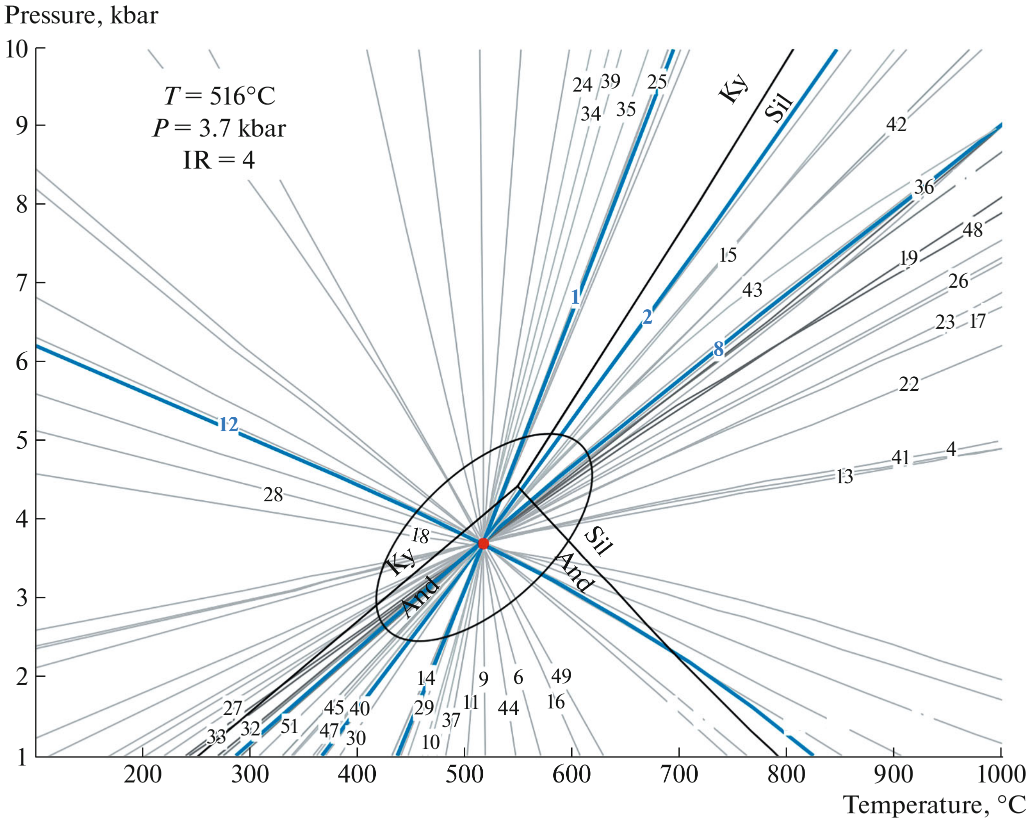

Fig. 3. *PT* parameters of the of rocks of the late metamorphic stage of the migmatite–gneiss complex in the Tervu breccia zone according to THERMOCALC calculations [16]. Linearly independent mineral reactions (IR) are highlighted in blue; the size of the ellipse corresponds to the error in the *P* and *T* estimates due to the error in determining the minals . The positions of reaction lines and ternary points of Al_2SiO_5 aluminosilicates were calculated using the *ds55* database of the THERMOCALC software. The list of reactions and their numbers are given in Appendix 3 (Supplementary Table ESM_3). Sample TZ-265 is chloritized garnet–amphibole–plagioclase schist.

and an increase in the alkalinity and water content; the replacement of garnet by biotite and plagioclase shows that the new thermodynamic conditions of mineral formation correspond to the andalusite stability field and the adjacent part of the sillimanite field. The estimated *PT* parameters (T = 516°C and P = 3.7 kbar, Fig. 3, Supplementary Table ESM_3) obtained for the mineral association of TBZ rocks, in particular chloritized garnet–amphibole–plagioclase schist (sample TZ-265, Fig. 1), confirm the above regression transformations and corresponding features of the chemical composition of minerals. Similar *PT* parameters, T = ~450–600°C and P = 2–4 kbar [1, 12], are typical metamorphism in the entire region.

U–Pb DATING

Monazite used for isotope–geochronological studies was selected from biotite granite (sample B-21-516) of the central part of the Peltola intrusion (Fig. 1). This rock is characterized by a massive structure and granitic texture. It is pinkish gray, coarse- to giant-grained. It contains biotite, two feldspars, and quartz. Plagioclase is represented by albite and oligoclase (An_{24} to 9%) often altered, microcline with perthitic ingrowths. Sometimes, such granites contain muscovite; biotite may be replaced by chlorite chlorite.

The plotted isotopic compositions of the four monazite samples (Fig. 4) lie below the concordia, although close enough to it. The isochron calculated for all four points allows the ages of the upper and lower intersections of discordia and concordia to be estimated as 1859.1 ± 3.7 Ma, and 252 ± 340 Ma, respectively, MSWD = 1.2 (Fig. 4, Table 1). The age determined by the upper intersection of discordia and concordia appears to correspond to the time of granite formation. The age of the lower intersection, given that it is determined with a large error apparently has no geological sense.

DISCUSSION

The isochron age of the Peltola granites (1859 ± 4 Ma) coincided exactly with the age of the microcline granites of the Tervu intrusion (1859 ± 3 Ma). This is a convincing argument in favor of the TBZ formation

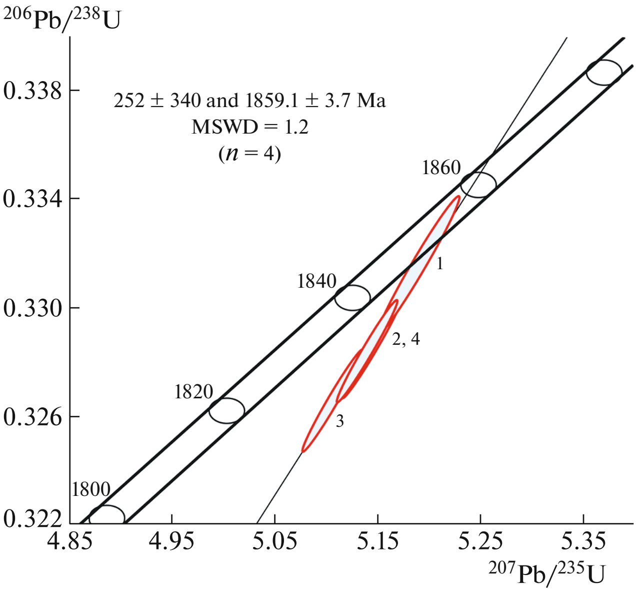

Fig. 4. Concordia diagram for monazite from the Peltola granite intrusion. Number of ellipses corresponds to the number of the sample (see Table 1).

at a late stage of plutonic–metamorphic activity in in the northern Ladoga area. Taking into account the close age of the above-mentioned undeformed dikes (1859 ± 2 Ma and 1858 ± 1 Ma), the TBZ forming and the sequence of intrusive and dike complexes should have been formed within a very short time interval on the geological scale.

During the late stage of Svecofennian orogeny, the newly formed consolidated Proterozoic crust started interacting with the marginal parts of the Archean Karelian Craton. At time, both tectonic and magmatic processes in the junction zone between the Svecofennian mobile belt and the Karelian Craton were quite intense.

The relationship between magmatic activity and the formation of tectonic zones was noted in many works. For example, it has been shown that reactivation of ancient shear zones in Avalonia Terrane of the Canadian Appalachians led to the formation of mylonites and the intrusion of dykes [13]. The dike systems subsequently form plutons with different geochemical characteristics. It is believed [14] that composite plutons may contain gabbroids, formed as a result of partial melting of the mantle, and acidic rocks formed due to partial melting of the lower crust.

The mutual relation of tectonic processes and granite formation is also indicated, e.g., by the confinement of granitoid massifs to the shear zone in the province of Borborema in northeastern Brazil. It is considered that the rheologically heterogeneous and incompletely crystallized magmatic bodies could cause localization of deformation and origination of shear zones [15, 16].

The rocks of granitoid intrusions developed in shear zones are characterized by schistosity, mineral streaking, interpreted as a result of syntectonic intrusion of magma. Based on the observations of linear schistosity in some granite massifs and concentric schistosity in others, researchers [17] came to the conclusion that these granite massifs could have one source, but formed and evolved in different tectonic settings: parallel schistosity was developed as a result of overprinting regional deformations, while concentric schistosity was due to magmatic flow.

It is likely that the observed diversity of structural and textural features of late orogenic granitoids of the Northern Ladoga area is also determined primarily by local tectonic factors. It is especially likely, considering the fact that formation of the granitoids coincided with the change in rheological properties of the framing rocks and the transition from plastic deformations to elastoplastic deformations followed by formation of brittle deformation zones, one of which was the TBZ.

The endogenic activity at the late stage of the Svecofennian orogeny in the Northern Ladoga area was marked by magmatic activity and metamorphism, overprinting on rocks of early and mid-orogenic magmatic complexes (enderbites, diorites, tonalites). The late-orogenic stage of magmatism included dikes of basic and intermediate composition and granites of the Tervu complex, including rocks of the dated Peltola intrusion. Late orogenic magmatism was accompanied by mid-temperature metamorphism, in some places superimposed on Tervu granitoids and older magmatic rocks of the early- and mid-orogenic stages. At the same time, metamorphism was accompanied by the formation of secondary crystallization schistosity and blastocataclastic textures due to a decrease in plasticity of rocks under moderate temperature, in which the Tervu breccia zone was formed. This zone also served as a supply channel for granitoids, which healed the breccia zone and were themselves deformed as a result of continuing tectonic movements. The latter is evidenced by pronounced blastocataclasis, gneiss and trachytoid textures of granitoids, which coincide in orientation with the structural and textural elements in the host gneisses and migmatites [1, 18].

The petrochemical parameters of of late-orogenic granitoids show that the latter differ from the preceding magmatic rocks of the region by more acidic and alkaline magmas. Such features, along with the increased alumina content in these granitoids and lower eNd(*t*) values as compared to enderbites and tonalites [19], indicate that their origin was mainly due to melting of crustal sedimentary material. Such granitoids are widely manifested in neighboring Finland where their formation marks a long stage of crustal magmatism from 1.86 to 1.81 Ga [20].

CONCLUSIONS

Based on the age data, the kinematic features of the intrusions, and the accompanying series of dykes and veins, we can conclude that formation of the Tervu and Peltola intrusions occurred synchronously during the late stages of metamorphic transformations and deformations of the Svecofennian rocks of the Northern Ladoga area. The structural position of granitoids and the host migmatite–gneiss complex indicates a gradual loss of plasticity of the environment during the formation of a series of granitoids from the earlier to later, which is manifested in the replacement of weak plicate deformations by disjunctive. This assumption is not contradicted by the available geological evidence, including the newly presented isotopic data on the age of granitic intrusions marking the time of formation of the sublatitudinal breccia zone.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

SUPPLEMENTARY INFORMATION

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OPEN ACCESS

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