UDC 550.42

# Thermochronology of eclogitic rocks of the Kola Peninsula

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**Abstract.** According to the results of U-Pb, Sm-Nd and Rb-Sr dating of metamorphic minerals the chronology of metamorphic events and thermal history of eclogitic rocks of the Wide and Narrow Salma and eclogites of the Chalmozero area (Yona district of the Belomorian Mobile Belt, the Kola Peninsula) have been reconstructed. The conclusion has been made that the studied rocks for more than 700 Ma have been located at depth at high temperature, which lead to a disturbance of U-Pb and Sm-Nd system in minerals at temperature below the closure temperatures, obtained experimentally. Closure temperatures for U-Pb and Sm-Nd isotopic systems in rutile are largely dependent on the grain size and cooling rate of rocks. Closure temperature for U-Pb system in 0.3 mm rutile grains can be 600 °C, higher than usually accepted 400-450 °C. Closure temperature for Sm-Nd system in rutile is about 350 °C, significantly lower than that for U-Pb system. Duration of metamorphic processes and cooling rate of rocks provide constrains on geodynamic models.

**Аннотация.** На основе датирования метаморфических минералов U-Pb, Sm-Nd и Rb-Sr методами определена термальная эволюция эклогитоподобных пород Широкой и Узкой Салмы и эклогитов Чалмозера (Ёнский район Беломорского подвижного пояса, Кольский полуостров). Сделан вывод о вероятном нахождении изученных пород более 700 млн лет на глубине при высокой температуре, что может приводить к нарушению изотопных систем минералов при температурах ниже температур закрытия для этих изотопных систем, определенных экспериментально. Температуры закрытия U-Pb и Sm-Nd изотопных систем в рутиле в значительной степени зависят от размера зерен и скорости остывания пород. При размере зерен рутила больше 300 мкм температура закрытия его U-Pb системы может быть около 600 °C, выше обычно принимаемой 400-450 °C. Температура закрытия Sm-Nd системы рутила составляет около 350 °C, что существенно ниже температуры закрытия его U-Pb системы. Данные о длительности процессов метаморфизма и скорости остывания пород позволяют сделать выводы о вероятной геодинамической обстановке формирования комплексов.

**Key words:** eclogites, isotopic systems, closure temperature, zircon, metamorphism, rutile, garnet
**Ключевые слова:** эклогиты, изотопные системы, температура закрытия, циркон, метаморфизм, рутил, гранат

## 1. Introduction

Findings of eclogites in the Belomorian Mobile Belt: in the Gridino tectonic melange zone (northern Karelia) (*Volodichev et al.*, 2004) and in the Yona district of the Kola Peninsula (*Konilov et al.*, 2005; *Schipansky et al*., 2005; *Schipansky, Konilov*, 2009) (Fig. 1), as well as evidence of their Archaean age by means of isotopic geochronological methods (*Volodichev et al.*, 2004; *Belousova et al.*, 2004; *Natapov et al*., 2005) aroused great interest due to the special significance of eclogites for the reconstruction of the Archaean geodynamics. Although, besides the popular notion on the subduction nature of eclogite, there are other points of view (e.g., *Rusin*, 1998; *Travin, Kozlova*, 2005; *Kozlovsky, Aranovich*, 2008). The latter authors on the example of mafic dykes show that the eclogite mineralization in silica undersaturated systems can be formed at pressures lower than the traditional eclogite facies (≥ 12 kbar) and propose that local manifestations of eclogitization can be considered not as traditional metamorphic rocks, which form the part of the dipping metamorphism zoning but as syn-deformation high temperature metasomatites.

Here we present the results of U-Pb, Sm-Nd and Rb-Sr dating of eclogitic rocks from the Wide and Narrow Salma and Chalmozero areas, located in the Yona district of the Kola Peninsula (the Northern part of the Belomorian Mobile Belt, Fig. 1). Dating of minerals with different closure temperature (Tc) for isotopic systems allowed timing of metamorphic evolution and cooling of rocks and drawing conclusions on the probable geodynamic conditions of the rock formation.

## 2. Geology of the studied areas

### *Eclogitic rocks of the Wide and Narrow Salma area*

Outcrops of the eclogitic rocks have been found along the Murmansk – St. Petersburg road near the Straits of the Wide and Narrow Salma of Lake Imandra (Fig. 1). Geologically this area belongs to the northern part of the Belomorian Mobile Belt – the Yona district. The district is composed of tonalite-granodiorite-trondhjemite gneiss with widely developed amphibolite bodies, which originally were regarded as metabasalts of the Yona greenstone belt (*Pozhilenko et al.*, 1995). Amphibolites locally associated with metaultrabasic rocks. At the geological map of the Kola region (*Geological map…*, 1996) there was indicated only single occurrence of eclogites – the Wide Salma area. Since 2004 among the garnet amphibolites of the Narrow Salma area rock fragments with omphacite were discovered that allowed distinguishing several large eclogite bodies here (*Konilov et al*., 2004; 2011; *Schipansky et al*., 2005). According to A. Konilov data the peak metamorphic conditions occurred at 14-15 kbar and ~700-750 °C with the formation of eclogite paragenesis Grt + Omp + Qtz + Rt. Increasing of temperature to the level of granulite facies (780 °C) was fixed at decompression stage in rocks of the Wide Salma area. Further transformations were expressed in the development of clinopyroxene-

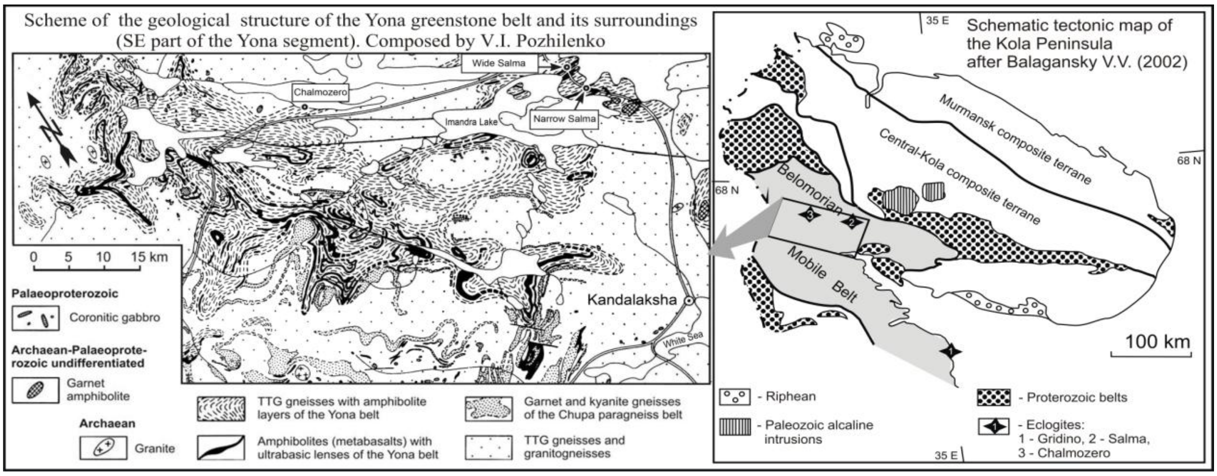


Fig. 1. Location of eclogitic rocks and eclogites within the Belomorian Mobile Belt

plagioclase symplectites after omphacite and clinopyroxene-plagioclase coronas between garnet and quartz. According to the thermobarometry data symplectites and coronas were formed at temperature $T$ = 727 ± 24 °C and $P$ = 10.7 ± 0.7 kbar (*Konilov et al.*, 2011). According to data of V. Yapaskurt omphacite formation is associated with the crystallization of mafic melt rather than with eclogite metamorphism (*Yapaskurt et al.*, 2006). Structures of intragranular transformation of Omp record three episodes of physical and chemical evolution of the mafic rocks of the Wide Salma area: 1) hydration replacement of the initial Omp at eclogite facies ($Jd_{28}$+*Hbl*+$SiO_2$); 2) decompression intragranular recrystallization in the field of subsolidus granulite facies of bipyroxene-plagioclase schists ($Di$+$Hyp$+$Pl_{30\rightarrow77}$±$Hbl$); 3) replacement of Omp relics by $Di$-$Pl_{18}$ symplectites, intensive amphibolization, growth of garnet porphyroblasts at garnet-amphibolite to amphibolite facies of metamorphism (moderate pressure and temperatures 600-700 °C) (*Yapaskurt et al.*, 2006).

***Eclogites of the Chalmozero area***

Chalmozero area is located 35 km west of the Wide and Narrow Salma areas. There in quarry of ceramic pegmatites of the Kuru-Vaara deposit (Fig. 1) tectonic bodies of eclogites, enclosed in TTG gneisses have been revealed. To date, detailed geological, petrologic and geochronological studies of the quarry rocks have been made by A. Schipansky and co-authors (*Schipansky, Konilov*, 2009). On the basis of field observations, they distinguished two types of eclogites: "southern" – coarse-grained retrograde altered rocks, which compose the most of the mapped eclogite bodies and "northern" – fine-grained well-preserved eclogites. The peak metamorphic conditions of eclogite-facies are estimated as 750-780 °C, ~14-14.5 kb for southern eclogites and ~680-720 °C, ~12 kb for the northern (*Schipansky et al.*, 2012, in press).

## 3. Results and discussion

***The Wide and Narrow Salma***

According to isotopic and geochemical zircon data the following stages have been dated in the evolution of rocks of the Wide and Narrow Salma area (*Kaulina et al.*, 2010):

• Crystallization of magmatic mafic protolith of rocks (dating of survived parts of magmatic zircons with high Th/U ratio) – 2.94-2.93 Ga.

• Granulite metamorphism in the Wide Salma area – 2.72 Ga ago (2724±35 Ma – age of zircons, which morphology and chemically corresponds to a typical "granulite" zircons), synchronous with the well-known stage of granulite metamorphism of the Belomorian Belt (2.73-2.71 Ga).

• The beginning of decompression – 2.70 Ga (2703±9 Ma – *Natapov et al.*, 2005). Dating of high-U zircons with oligoclase inclusions (~ 30 % anorthite) in association with monoclinic pyroxene ($Di$ = 73 %, $Hd$ =

16 %, *Jd* <5 %) and clinozoisite ($Fe^{3+}$ = 0,09 f.u.), indicating that the zircon growth occurred at pressure decreasing to 5 kb at the stage of omphacite replacement by *Cpx-Pl-Hbl* symplectites.

• Final metamorphic stages in garnet-amphibolite and amphibolite facies conditions – 1.89 Ga (1891±17 Ma – age of zircons depleted in HREE with positive Eu anomaly, which is interpreted as growth in equilibrium with garnet and at plagioclase breakdown, thus reflecting the time of garnet porphyroblasts growth after Cpx-Pl symplectites).

U-Pb garnet ages for eclogitic rocks of the Wide and Narrow Salma showed the presence of at least two garnet generations of 1.88 and 2.42 Ga. Archaean Pb-Pb ages were also obtained for two garnet abraded fractions, which is likely due to zircon inclusions, because it is the central parts of garnet grains enriched in inclusions. As it was already mentioned there are contradictory petrologic data for Salma eclogites: according to A. Konilov data (*Konilov et al.*, 2011) garnet in rocks was formed in eclogite-facies conditions in association with Omp + Qtz + Rt. According to V. Yapaskurt data (*Yapaskurt et al*., 2006) garnet was formed much later omphacite as a result of metamorphic substitutions in amphibolite-facies conditions. The composition of inclusions in 2.70 Ga zircon meets the decompression stage and formation of Cpx-Pl symplectites. The same set of minerals (oligoclase + clinopyroxene + clinozoisite) of the same compositions were found together with Hbl as inclusions in garnet porphyroblasts, that confirms the assumption about the garnet growth (or at least the most of it) at the late stages of metamorphism under garnet-amphibolite facies. Thus, the formation of garnet in rocks of the Wide and Narrow Salma is limited to an interval 2.70 Ga (the formation of Cpx-Pl symplectites) to 1.89 Ga (growth of zircons depleted in HREE). This is in agreement with the U-Pb garnet ages of 1.88-2.42 Ga, which show that crystallization of garnets, or at least the most of them, occurred at the late Svekofennian stage, which contradicts the data on the Archaean eclogite paragenesis (*Konilov et al*., 2011).

Sm-Nd dating of bulk samples of eclogitic rocks determined the Archaean age of 2.97 Ga, which showed that the Sm-Nd system of the whole rock stores age information of the magmatic protolith, confirming in particular the isochemical nature of metamorphism in the Salma area.

Sm-Nd mineral isochrones for rocks of the Salma area defined ages of 1873-1894 Ma (Fig. 2). The interpretation of this age interval is not clear. According to thermobarometry data and zircon ages 2.72 Ga ago rocks reached the highest temperature of 780 °C in granulite-facies conditions. At 1.89 Ga the temperature was about 700 °C at the amphibolite-facies level. Sm-Nd isochrones for samples of eclogitic rocks combines minerals of different paragenesis (Grt, Cpx, Ilm, Ttn, Ap) and probably with different closure temperature for Sm-Nd system. Most likely, because all minerals lie on the isochron, this ages record the blocking of the Sm-Nd system in dated minerals at cooling below 700 °C. Closure temperature for the Sm-Nd system in Grt is in temperature range between 600-700 °C (*Mezger et al.*, 1991). But Tc for the Sm-Nd system in clinopyroxene (diopside) is above 800 °C (*Sneeringer et al*., 1984) and since the temperature did not rise above 780 °C clinopyroxene might reflect the age of crystallization, because clinopyroxene has already existed in rocks since 2.70 Ga (Cpx inclusions in 2.70 Ga zircons). Therefore, either Tc for the Sm-Nd system in Cpx is lower 800 °C, or rocks for a long time period were at depth at temperature higher 700 °C, and closure of the Sm-Nd system in clinopyroxene occurred only at the exhumation stage, associated with the 1.9 Ga Lapland collision. The fact that re-equilibration of the Sm-Nd system in all minerals happened only 1.9 Ga ago, though there was no increase in temperature at that time, is best explained by the latter assumption. The possibility for metamorphic (e.g. granulites) and magmatic assemblage residence at depth for long time period of 100-2000 Ma are discussed in several papers (*Harley*, 1989; *Levsky et al.*, 2009).

The SM-Nd age of rutile (WR-Rt) yields isochron ages of 1.65-1.66 in all samples of eclogitic rocks. This may be an indication that the closure temperature for the Sm-Nd system in rutile is lower than in all other minerals, and, based on the general cooling history of rocks, probably is below 400 °C (Fig. 2). Cooling to a temperature of 450 °C is fixed by U-Pb system in rutile whose U-Pb age of 1.79 Ga is similar to other U-Pb rutile ages of the Belomorian rocks (*Bibikova et al*., 1999).

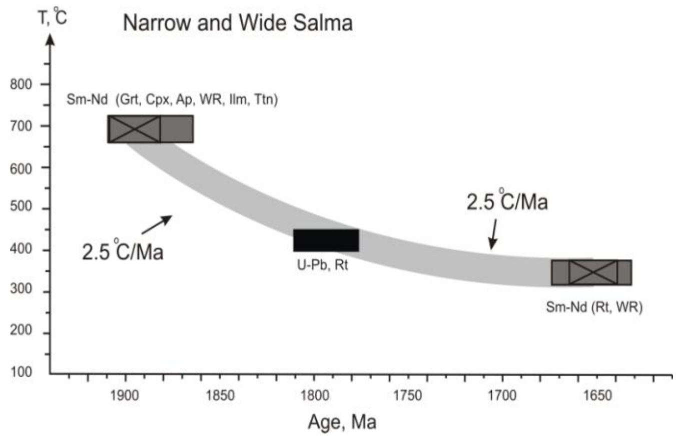


Fig. 2. Scheme of cooling of the Wide and Narrow Salma rocks

***Chalmozero eclogites***

The following events are dated based on U-Pb zircon chronology:

• Crystallization of magmatic protolith – 2.87-2.82 Ga (*Schipansky, Konilov*, 2009).

• Granulite metamorphism – 2.72 Ga (typical "granulite" zircons in morphology and REE pattern – *Schipansky et al.*, 2012, in press).

• Eclogite metamorphism – 1.91 Ga (typical "eclogite" zircons in morphology and composition – *Skublov et al.*, 2010).

Garnets and rutiles from the northern eclogites of the Kuru-Vaara quarry were dated by U-Pb method. Four fractions of garnet define a discordia line with an upper intercept of 2755±32 Ma and lower intercept of 1762±19 Ma. Either garnet in the sample is represented by two generations, or (more likely) this is the contribution of zircon inclusions observed in garnet. The lower intercept is fixed by the concordant point of one garnet faction of 1728±28 Ma, near concordant age of another garnet fraction is 1842±30 Ma. According to K. Mezger and co-authors, the closure temperature for the U-Pb system in garnet of 0.1-1 cm is about 800 °C (*Mezger et al.*, 1989a). The peak metamorphic conditions with $T$ = 700-720 °C (*Schipansky, Konilov*, 2009) occurred at 1907±11 Ma (eclogite zircon age – *Skublov et al.*, 2010). Thus, garnet crystallized at temperatures below its closure temperature for U-Pb system, and the resulting age must meet the time of garnet crystallization, but not blocking of the U-Pb system during cooling. It is not clear why the age of garnet is much less than syn-genetic zircon age. It seems more logical that for garnet grains, smaller than 0.1 cm (as in the sample) Tc for the U-Pb system is significantly less than 800° C and thus different size fractions of garnet would reflect the cooling process, especially in the case of slow cooling (Fig. 3).

U-Pb ages of rutile are 1859±5 and 1678±14 Ma, depending on the grain size (Fig. 3). The first age is likely close to the age of rutile crystallization, since large grains of about 300 microns were used, in which Tc for the U-Pb system is higher than usually accepted 400-450 °C (*Mezger et al.*, 1991). In this case, the closure temperature for the U-Pb system in large grains of rutile is about 600 °C consistent with the experimentally obtained values (*Cherniak*, 2000). Younger rutile age reflects cooling of rocks to 400 °C. It is believed that the age dependence of the grain size (the lager, the older) confirms an action of volume diffusion mechanism. Closure temperature for U-Pb isotopic system in rutile is most sensitive (compared with other minerals) to the grain size and cooling rate of rocks. Tc for the U-Pb system in rutile is 460 ± 50 °C with rapid cooling rate of 20 °C/Ma (*Li et al.*, 2003) and 420 °C to 380 °C with cooling rates of 0,1-0,5 °C/Ma in rutile grains of 0,09-0,21 mm and 0.07-0.09 mm, respectively (*Mezger et al.*, 1989b). The last thermal event in the quarry – the formation of pegmatite veins – occurred at 1841±12 Ma ago at a temperature of 600 °C (*Skublov et al.*, 2010). That is, from the peak of eclogite metamorphism of 700-720 °C at 1907 Ma to a temperature of about 600 °C at 1841 Ma and to 400-450 °C at 1678 Ma the rock cooled to 270 °C per 128 Ma with a rate of 2 °C/Ma (Fig. 3). It is the slow cooling rate which causes the obvious age-size relationship for the studied mineral grains. In general, U-Pb and Sm-Nd ages for rutile obtained from grains of different sizes, even without the use of other minerals, can determine the cooling rate of rocks, confirming the conclusion of *K. Mezger* (1989a,b), that U-Pb ages for rutile provide high-precision ages for evaluating the cooling history of high-grade terranes and can be critical to the quantitative development of thermal models for crustal evolution.

Similar ages were obtained for minerals and whole rocks by Sm-Nd and Rb-Sr methods: 1818±21 Ma (Sm-Nd isochron for Grt + Omp + Rt + WR) and 1829±92 Ma (Rb-Sr isochron for Grt + Ap + WR). Minerals belong to eclogite paragenesis, while the obtained age is younger than U-Pb age of eclogite zircon. As noted above, the temperature range for Sm-Nd closure system in garnet is within 600-700 °C (*Mezger et al.*, 1991). But in dry mafic rocks closure temperature for the Sm-Nd system in garnet of 1 mm can be above 700-760 °C (*Vance, O'Nions*, 1990). On the other hand, Tc for Nd isotope diffusion in slowly cooling garnet is ~200 °C lower than in high-Ca pyroxene and is about 600 °C (*Van Orman et al.*, 2002). In the present case, the obtained ages, although they fit into the overall scheme of slow cooling (Fig. 3), do not exclude the possibility of fluid influence, associated with the intrusion of pegmatite veins (1.84 Ga), which is also confirmed by similar Rb-Sr age. Rb-Sr system often re-equilibrates when fluid affects, because Rb and Sr (due to low ionic potential) are more soluble in aqueous fluids.

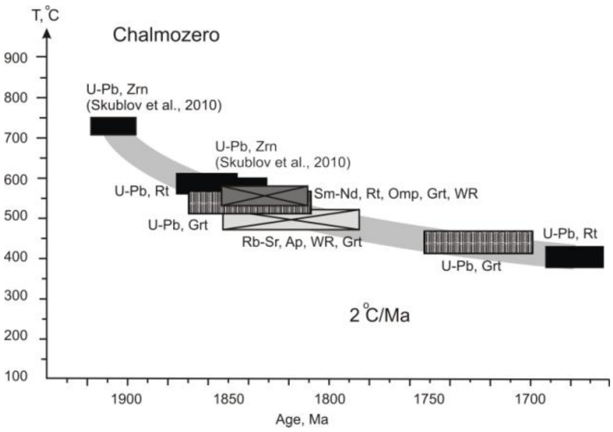


Fig. 3. Scheme of cooling of the Chalmozero rocks

It should be noted that commonly the low cooling rate is not characteristic of subduction processes in which the subduction-exhumation take rather short time span of 10-12 Ma (e.g. *Kaneko et al.*, 2003). Slow cooling of the Chalmozera rocks suggests the formation of eclogite paragenesis

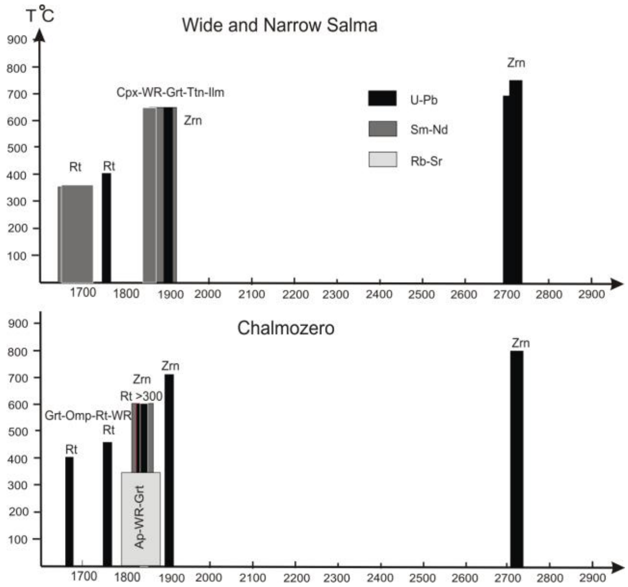


Fig. 4. Scheme of metamorphic history of rocks of the Wide and Narrow Salma and Chalmozero

rather as a result of syn-deformation metasomatic process similar to that described for mafic dykes (*Kozlovsky, Aranovich*, 2008), rather than related to the subduction metamorphism during subduction-collision.

Thus, the obtained ages of 1.8-1.9 Ga with cooling rates of 2-2.5 °C/Ma reflects the time of uplift of tectonic plates of the Belomorian Mobile Belt from the middle to the upper levels of the crust during the collision stage of the Lapland-Kola orogen development (*Daly et al.*, 2001).

Summary diagram for the metamorphic evolution of the Wide and Narrow Salma and Chalmozera areas shows that the isotopic systems of minerals did not reflect metamorphic events between 2.7 and 1.9 Ga (Fig. 4). That is, as noted above, either Sm-Nd isotopic system was blocked at 1.9 Ga, or all dated minerals were formed 1.9 Ga ago. The second assumption can be partially implemented for the Chalmozero rocks. However, petrological data for the Salma rocks show that dating mineral were crystallized before 1.9 Ga. Nevertheless, the Sm-Nd system has fixed the age frontier of 1.8-1.9 Ga, when the temperature dropped to 650-600 °C.

In addition to this, an interesting picture is observed for zircons from the surrounding TTG gneisses, which have an Archaean age of 2.93 Ga (*Mintz et al.*, 2010). There is a significant difference (70 Ma) between SIMS and TIMS data (2.93 and 2.86 Ga, respectively). Furthermore, both methods show strong discordance of ages. All zircon crystals show clear magmatic zoning in cathodoluminescence and the absence of secondary alteration within the grains. Normally, discordant ages are related to the lead loss from disturbed zircon domains (fractured, marginal zones, etc.). Our data were obtained by mass spectrometer SHRIMP-II from the central parts of zircon crystals with clear primary magmatic zoning. Closure temperature for the U-Pb system in zircon is above 900 °C, so radiogenic lead usually is not lost from undamaged crystal structure, especially from the centre of grains. In this case, the lost of radiogenic lead can be explained in term of diffusion induced by the thermal effect of long duration up to 1.9 Ga, when the rocks were uplifted to the cold levels of the crust. Although the results are not consistent with Pb diffusion parameters, calculated on the basis of experimental data (e.g. *Cherniak, Watson*, 2003).

Based on the foregoing, it can be concluded that prolonged (more than 700 Ma) mineral residence in high-temperature conditions, at temperatures close or even below the blocking temperatures obtained experimentally, the diffusion of radiogenic elements is fast enough for partial resetting of the U-Pb and Sm-Nd system. Could this be due to dislocations or plastic deformation in crystals, which significantly accelerate the process of volume diffusion (e.g. *Reddy et al*., 2007)? This question requires further special study.

## 4. Conclusions

1. Closure temperatures for U-Pb and Sm-Nd isotopic systems in rutile are largely dependent on the grain size and cooling rate of rocks. For rutile grains of above 300 µm closure temperature for its U-Pb system can be 600 °C, higher than usually accepted 400-450 °C. Closure temperature for Sm-Nd rutile system for grains of 100-150 microns is about 350 °C, which is significantly lower than the closure temperature for U-Pb rutile system in grains of the same size.

2. The studied rocks of the Salma and Chalmozero area for a long time (several hundred Ma) were at depth at high temperature.

3. Long duration of high-temperature process over 700 Ma leads to disturbance of the U-Pb and Sm-Nd system in minerals at temperature below the closure temperature obtained experimentally (perhaps, because of plastic deformation in crystals of minerals-geochronometers).

4. Data on duration of metamorphic processes and cooling rate of rocks provide constrains on probable geodynamic conditions of rock formation.

The work is supported with RFBR grant N 11-05-00817.

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