Apatite fission track thermochronology of Khibina Massif (Kola Peninsula, Russia): Implications for post-Devonian Tectonics of the NE Fennoscandia

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A B S T R A C T

The thermal history of the Kola Peninsula area of NE Fennoscandia remains almost fully unknown because of the absence of any thermochronological data such as apatite and/or zircon fission track or (U–Th)/He ages. In order to fill this gap and to constrain the post-Devonian erosion and exhumation history of this region, we present the results of apatite fission track (AFT) dating of eleven samples selected from the cores taken from different depths of the northern part of the Khibina intrusive massif. The Rb–Sr isochron age of this alkaline magmatic complex which is located at the center of Kola Peninsula is 368 ± 6 Ma (Kramm and Kogarko, 1994). Samples were analyzed from depths between +520 and −950 m and yielded AFT ages between 290 and 268 Ma with an age uncertainty (1σ) of between ±19 Ma (7%) and ±42 Ma (15%). Mean track lengths (MTL) lie between 12.5 and 14.4 μm. Inverse time–temperature modeling was conducted on the age and track length data from seven samples of the Khibina massif. Thermal histories that best predict the measured data from three samples with the most reliable data show three stages: (1) 290–250 Ma—rapid cooling from >110 °C to 70 °C/50 °C for lower/upper sample correspondingly; (2) 250–50 Ma—a stable temperature stage; (3) 50–0 Ma—slightly increased cooling rates down to modern temperatures. We propose that the first cooling stage is related to late-Hercynian orogenesis; the second cooling stage may be associated with tectonics accompanying with opening of Arctic oceanic basin. The obtained data show that geothermal gradient at the center of Kola Peninsula has remained close to the modern value of 20 °C/km for at least the last 250 Myr. AFT data show that the Khibina massif has been exhumed not more then 5–6 km in the last 250 Myr.

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1. Introduction

Results of thermochronological studies on Precambrian and Phanerozoic rocks within Scandinavian countries (Sweden, Finland, and Norway) have been recently summarized by Hendriks et al. (2007). Their quantity and quality make possible reconstruction of the thermal and tectonic history of western and central Fennoscandia from the Late Precambrian with high reliability and detail. However, such data for NE part of Fennoscandia, including the Kola Peninsula and Karelia, are almost absent. Only a few ages are published in publications with restricted access (Green et al., 1996; Rohrman, 1995). To understanding more fully the tectonic and thermal history of the Precambrian basement or Phanerozoic intrusions in the Kola area, more thermochronologic data are clearly required. Moreover, reliable thermochronological data could provide additional information for understanding of the nature and estimation of the timing of an enigmatic, possibly metachronous natural magnetization component that has been found in many Devonian and, particularly, Proterozoic dykes and Precambrian host rocks over the entire the Kola Peninsula (Veselovskiy and Arzamastsev, 2011; Veselovskiy et al., 2013). These studies have proposed that the metachronous component could be related with previously unknown remagnetization event, that was estimated to be Early Jurassic in age, but based on paleomagnetic data only. According to microprobe and petrographic results, the origin of the metachronous component was connected with changes of magnetic and originally non-magnetic minerals during low-temperature hydrothermal alteration (Veselovskiy et al., 2013).

This hypothetical Early Jurassic hydrothermal event is intriguing in that paleomagnetic and, particularly, petrographic data have established that it occurs on the Devonian dykes mostly and quite rare
on the Precambrian dykes. The K—Ar isotope system in mica, amphibole, and feldspar is the most sensitive to secondary reheating (up to 200 °C and more), but no resetting of K—Ar ages are observed after emplacement of the studied dykes in Devonian (Veselovskiy et al., 2013).

Apatite fission track dating is affected by heating to 60–110 °C and thus offers an alternative, more temperature-sensitive method to test the hypothesis of a Jurassic remagnetization event and, if it really existed, for understanding its nature and timing. Among all of studied Devonian intrusive rocks of the Kola area, the presence of the metachronous magnetization component is observed best in the magnetic record of melanephelinite and phonolite dykes, which cut foyaites of the earliest phases of intrusion on the west and southwest zones of the Khibina massif, as well as in tinguites dykes, which cut Proterozoic schist on the south exocontact zone (Fig. 1b). So, if the Khibina massif, as well as the cross-cutting dykes, were affected by a hypothetical Jurassic remagnetization event, this should be reflected in the fission track age and/or track lengths of apatite grains from these rocks.

Fig. 1. (a) Kola Devonian Alkaline Province: the Khibina massif and other plutons, alkaline (purple), and tholeiitic (green) dyke swarms within the Kola Peninsula; (b) sketch geological map of the Khibina massif. White stars—the mouths of the boreholes, samples from which were studied in this work; (c) two cross-sections of the northern sector of the Khibina massif. Red polygons—approximate positions of the studied samples taken from the adjacent boreholes with their numbers and depths according to the Table 1.
The Khibina intrusive massif is located in the contact of Archaean gneisses and the Proterozoic Pechenga–Imandra–Varzuga volcanic–sedimentary paleorift complex which forms the Lapland–Kola–Belomorian collisional structure (Fig. 1a). The massif is a concentrically zoned multiphase intrusion composed of agpatic nepheline syenites and to a lesser amount, of ultrabasic alkaline rocks (Fig. 1b). From the oldest to the youngest, the components are as follows.

1. Remnants of the alkaline volcanic complex, which formed the roof of the caldera.
2. Peridotite, pyroxenite, melilite-bearing rocks.
3. Nepheline syenite of the peripheral zone (“Khibinite”).
6. Nepheline syenite of the central part of the massif (foyaite) and pulaskite.
7. Dykes of essexite, alkaline picrite, nephelinite, phonolite, trachyte.
8. Carbonatites.

Numerous geochronological data have been obtained from the rocks of the Khibina massif. The first results of Rb–Sr isochron dating (Kramm and Kogarko, 1994) showed that the massif was formed at ca. 370 Ma. Subsequent age determinations for the different rocks of the massif obtained by U–Pb, Sm–Nd, and 40Ar/39Ar isotope methods (Arzamastsev and Wu, 2014 and references therein) are consistent with these results.

Geological surveying of economic apatite–nepheline deposits has led to the detailed deciphering of the geological structure of the central part of the Khibina massif. Cross-sections based on results of drilling made it possible to trace the apatite ore bodies down to the level of 1 km below sea level. Taking into account mountainous relief of the Khibina area, the interval of vertical investigation of the massif exceeds 1.2 km.

Eleven drill core samples of apatite ores and related alkaline rocks were selected for fission track analysis. Location of investigated drill holes and the position of selected samples is shown in Fig. 1c and Table 1.

### 3. Methods

#### 3.1 Fission track dating

Apatite grains of >0.2 mm size were mounted in epoxy resin, alumina, and diamond polished, and spontaneous fission tracks revealed by etching with 5.5 M HNO3 at 20 °C for 20 seconds. Samples were analyzed by applying the external detector method (Gleadow, 1981) using very low uranium, annealed muscovite mica detectors, and irradiated at the Oregon State University Triga Reactor, Corvallis, USA. The neutron fluence was monitored using European Institute for Reference Materials and Measurements (IRM MM) uranium-dosed glass IRMM 540R. After irradiation, induced tracks in the mica external detectors were revealed by etching with 40–48% HF for 18 minutes. Spontaneous and induced FT densities were counted using an Olympus BX51 microscope at 1250× magnification with automated Kinetek Stage system. Apatite FT lengths and Dpar values were measured using FTStage software, an attached drawing tube, and digitizing tablet supplied by Trevor Dumitru of Stanford University calibrated against a stage micrometer. Central ages (Gabraith, 2005; Gabraith and Laslett, 1993), quoted with 1σ errors, were calculated using the IUGS recommended zeta-calibration approach of Hurford and Green (1983). Theapatite IRMM 540R zeta-calibration factor of 368.1 ± 14.9 was obtained by repeated calibration against a number of internationally agreed age standards including Durango and Fish Canyon apatite according to the recommendations of Hurford (1990).

#### Table 1

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample number</th>
<th>Absolute high/depth (m)</th>
<th>No. of crystals</th>
<th>Track density (×106 tracks cm−2)</th>
<th>Mean Dpar (μm)</th>
<th>Age dispersion (P2μ)</th>
<th>Central age (Ma ± 1σ)</th>
<th>Apatite mean track length (μm ± 1σ)</th>
<th>Standard deviation (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1177</td>
<td>520</td>
<td>20</td>
<td>0.5228 (621) 0.2795 (332) 0.8420 (2694)</td>
<td>5.01</td>
<td>-0.01%</td>
<td>283.5 ± 23.1</td>
<td>13.65 ± 0.16</td>
<td>1.59</td>
</tr>
<tr>
<td>2</td>
<td>1221</td>
<td>280</td>
<td>20</td>
<td>0.6517 (714) 0.3413 (374) 0.8344 (2670)</td>
<td>2.30</td>
<td>-0.01%</td>
<td>286.7 ± 22.4</td>
<td>13.67 ± 0.10</td>
<td>1.04</td>
</tr>
<tr>
<td>3</td>
<td>1167</td>
<td>-95</td>
<td>17</td>
<td>0.1321 (129) 0.0737 (72) 0.8496 (2719)</td>
<td>2.94</td>
<td>-0.01%</td>
<td>274.2 ± 42.2</td>
<td>14.40 ± 0.31</td>
<td>0.92</td>
</tr>
<tr>
<td>4</td>
<td>1636</td>
<td>-100</td>
<td>20</td>
<td>0.1819 (220) 0.0976 (118) 0.7965 (2549)</td>
<td>4.32</td>
<td>-0.01%</td>
<td>267.7 ± 32.8</td>
<td>14.04 ± 0.27</td>
<td>1.41</td>
</tr>
<tr>
<td>5</td>
<td>1631</td>
<td>-180</td>
<td>20</td>
<td>0.3874 (466) 0.2009 (466) 0.8117 (2597)</td>
<td>2.67</td>
<td>-0.01%</td>
<td>281.9 ± 25.3</td>
<td>13.89 ± 0.15</td>
<td>1.14</td>
</tr>
<tr>
<td>6</td>
<td>622-1</td>
<td>-380</td>
<td>20</td>
<td>0.2708 (273) 0.1468 (148) 0.8724 (2792)</td>
<td>2.97</td>
<td>-0.01%</td>
<td>289.6 ± 32.3</td>
<td>13.99 ± 0.17</td>
<td>0.90</td>
</tr>
<tr>
<td>7</td>
<td>622-2</td>
<td>-470</td>
<td>20</td>
<td>0.1579 (197) 0.0881 (110) 0.8648 (2767)</td>
<td>3.40</td>
<td>-0.01%</td>
<td>278.9 ± 15.5</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>1632</td>
<td>-500</td>
<td>20</td>
<td>0.2218 (247) 0.1140 (127) 0.8041 (247)</td>
<td>2.97</td>
<td>-0.01%</td>
<td>281.6 ± 33.3</td>
<td>13.82 ± 0.30</td>
<td>0.96</td>
</tr>
<tr>
<td>9</td>
<td>622-3</td>
<td>-530</td>
<td>20</td>
<td>0.1701 (209) 0.0968 (119) 0.8572 (2743)</td>
<td>3.79</td>
<td>-0.01%</td>
<td>271.3 ± 33.4</td>
<td>13.58 ± 0.40</td>
<td>1.28</td>
</tr>
<tr>
<td>10</td>
<td>1630-1</td>
<td>-920</td>
<td>20</td>
<td>0.8190 (933) 0.4529 (516) 0.8269 (2646)</td>
<td>3.40</td>
<td>-0.01%</td>
<td>269.5 ± 19.1</td>
<td>12.49 ± 0.15</td>
<td>1.52</td>
</tr>
<tr>
<td>11</td>
<td>1630-2</td>
<td>-950</td>
<td>20</td>
<td>0.2365 (280) 0.1258 (149) 0.8193 (2622)</td>
<td>3.09</td>
<td>-0.01%</td>
<td>277.3 ± 30.8</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes:
(i) Analyses by external detector method using 0.5 for the 4n/2n geometry correction factor.
(ii) Ages calculated using dosimeter glass: IRMM 540R with \( \chi_s = 368.1 ± 14.9 \) (apatite).
(iii) \( P_2 \) is the probability of obtaining a \( \chi^2 \) value for \( v \) degrees of freedom where \( v = \text{no. of crystals} - 1 \).
(iv) s.e. = standard error of the mean.
3.2. Thermal history modeling

In order to constrain the type of thermal history of the Khibina massif consistent with AFT ages and track lengths distribution, we used HeFTy software version 1.8.3 (Ketcham, 2005). HeFTy is a popular thermal history modeling software, in which formalized statistical hypothesis tests assess the goodness-of-fit between the input data and the thermal model predictions (Vermes and Tian, 2014). The output of the model is two time–Temperature (t-T) envelopes (Fig. 3): the broader envelope being the range within which any thermal history cannot be excluded by the measured data (acceptable fit); the narrower envelope being the range that is supported by the measured data (good fit). For all cases, simulations were run until 100 good-fit paths were found.

4. AFT results

Eleven samples were analyzed, AFT central ages range from 289.6 ± 32.3 Ma to 267.7 ± 32.8 Ma (Table 1 and Fig. 2). The central ages show an apparent decrease in age with depth (Fig. 2a), although this is statistically insignificant because of the large 1σ age uncertainties. Mean track length in studied samples change depending on the depth (Fig. 2b) increasing from 12.5 μm in the deepest sample to 14.4 μm on the middle depths, and decreases to 13.6 μm in the upper part of the vertical profile. Unfortunately, as far as the middle part of this plot is based mostly on the samples with low numbers of measurable horizontal confined track lengths (n ≤ 29), this part of the approximation curve can be considered as a preliminary result only. In general, decreasing of the mean track length with depth is consistent with the thermal history of the Khibina massif (see below). The track lengths distribution in each sample (Fig. 2c) are all unimodal with a slight negative skew and higher standard deviation in the lowermost samples. The mean track lengths are reasonably long consistent with long-time residence at low annealing temperatures.

5. Discussion

5.1. Thermal history from AFT analysis

Seven samples were selected for inverse time–temperature modeling of the thermal history of the Khibina massif, because only samples with track lengths data could be modeled. Samples no. 1177 and no. 1636 have unusually high Dpar values (large track size) likely owing to unusual apatite chemistry—these are outside of the limits of the Ketcham annealing model used in HeFTy software, thus could not be used in modeling.

Samples no. 1221, no. 1630–1 (both with 100 track lengths), and sample no. 1631 (with 61 measured track lengths) show the best constrained t-T paths; the age uncertainties for these samples are also much better (Fig. 3a–c). The data obtained from other samples (nos. 622-1, 622-3, 1167, and 1632) are not so reliable with low number of tracks and poor age uncertainty resulting in less well-constrained models, as many more t-T histories are allowed that predict the poorer data, but these still fit the general conclusions within the broad range of acceptable t-T paths (Fig. 3d–g).

According to our best-fit t-T paths (Fig. 3), the rocks at the sampled depths of the Khibina massif (±280 and −920 m) cooled from temperatures N110 °C to 40 °C (sample 1221) and 60 °C (sample 1630–1), respectively, between about 320 and 280 Ma. For about 200 Myr, the temperatures of these rocks were quite stable, but, taking into account

Fig. 2. AFT dating results: (a) distribution of the AFT ages with depth with sample numbers on the right of the age error bars; (b) distribution of the mean track length with depth (n—number of tracks used in statistics); (c) the most representative mean track length distributions in four samples.
Results of t-T modeling for seven samples are shown as path envelopes encompassing the thermal histories that generated good fits (purple shading) and acceptable fits (green shading) to the data. Insets: mean track length distributions (red) and the best-fit curves (green). In d–g, the larger spread in acceptable t-T histories is a result of the low number of measurable horizontal confined track lengths in these samples (see text and Table 1 for details).
the confidence level of the model, could vary within ±10°. Close to 50–40 Ma, the rocks show a slight increase in cooling rates, cooling down to their modern temperatures (0 °C and 25 °C, respectively). It is important to note that the difference in depths between samples no. 1221 and no. 1620–1 is 1200 m—thus making it possible to estimate the geothermal gradient over the long geological cooling history of these samples.

Described time–temperature model of the Khibina massif can be interpreted in tectonic terms, like this:

1) The difference in temperature of the t-T paths from the two samples at significantly different depths indicate that the geothermal gradient of the Khibina massif did not vary much from ~20 °C over the last 250 Myr.

2) From the time of the last alkaline magma injection ~362 Ma (Arzamastsev and Wu, 2014) to ~320 Ma, the Khibina massif was located at temperatures higher than the 110 °C isotherm, equivalent to depths about 6 km and deeper.

3) The sampled levels of the massif were exhumed up to depths about 2–3 km within about 40 Myr and cooling associated with this exhumation ceased at about 280 Ma. The average rate of this exhumation can be estimated as 0.1 km/Myr.

4) From Triassic to Eocene, the Khibina massif remained at close to constant temperatures, implying little vertical movement or erosion, except for possible quasioscillatory movements within the model accuracy ±500 m.

5) From the early Paleogene and up to now, the rocks of the Khibina massif cooled by about 20–40 °C.

Following Carminati et al. (2009), we infer that the first cooling stage is related to late Hercynian orogenesis and was connected with extensive uplift and erosion of the continental landmasses. The nature of the second cooling stage could be a result of Cenozoic cooling of global surface temperatures (Zachos et al., 2001, 2008). Similar Cenozoic cooling recorded by thermochronometers in northern Alaska has also been attributed to changes in paleosurface temperature (O’Sullivan, 1999). Obvious coincidence of the modeled t-T paths and Cenozoic cooling curve (Fig. 3) is in agreement with this suggestion. As well as cooling of paleosurface temperatures, part of the Cenozoic cooling stage could be related to uplift and erosion associated with tectonics accompanying with opening of Arctic oceanic basin and/or with a drift of Fennoscandia above the Icelandic plume (Carminati et al., 2009). Cenozoic cooling recorded by thermochronometers is also observed in other parts of Fennoscandia, particularly Norway (Hendriks et al., 2007), where it has been related to vertical movement along the Norwegian Atlantic margin.

5.2. Time–temperature constrains from numerical modeling of the Khibina massif cooling

The higher temperature thermal and tectonic history of the Khibina massif directly after its emplacement 360 Ma is not recorded by our AFT data. However, Ar/Ar analyses from minerals the lowest temperature sensitivity, e.g. feldspars (250 °C), yield Late Devonian ages. This implies that the Khibina massif cooled rapidly following emplacement owing to intrusion at a shallow depth of ~12.5 km (taking into account the value of geothermal gradient 20 °C/km, calculated above). However, owing to the relatively large spread in best-fit cooling paths following Late Devonian intrusion, it is difficult to distinguish whether cooling of the large Khibina massif down to 110 °C was controlled by post-magmatic process of heat dissipation, and/or was connected to late Hercynian uplift and erosion.

In order to answer this question, we have done numerical modeling which describes post-magmatic cooling of the Khibina pluton. The massif has been described as a cylindrical body with vertical axis ~15 km and diameter ~40 km, that correlates with a real shape of the massif, which is known from geophysical data (Arzamastsev et al., 2013), as a first approximation. Thermal evolution of the Khibina massif was modeled as it was described in Pechersky et al. (2004) taking into account crystallization of the magma. Modeling has been made for different depths from the top of the massif, which varied from 1 to 15 km.

For numerical simulation, we used following thermophysical parameters. Host rocks: temperature conductivity \( k = 2.51 \text{ W/(m} \cdot \text{K)} \), heat capacity \( C_p = 1050 \text{ J/(kg} \cdot \text{K)} \), density \( \rho = 2650 \text{ kg/m}^3 \). For the Khibina massif:

\[ k = 3.52 \text{ W/(m} \cdot \text{K)}, C_p = 1110 \text{ J/(kg} \cdot \text{K)}, \rho = 3220 \text{ kg/m}^3, \lambda \text{ latent heat} = 550 \text{ kJ/kg}. \]

We also assume that the intrusion process of the Khibina massif took place over an insignificantly short time relative to the duration of its cooling. This makes it possible to neglect heat exchange during emplacement of pluton and to suppose that the temperature of host rocks at the upper and lower boundary of the massif at the time of emplacement was controlled by an "undisturbed" geotherm. We used 20 °C/km as geothermal gradient value. For modeling, we used parameter \( T_{in} = 1100 \text{ °C} \), which represents the magma initial temperature, and \( T_{sol} = 700 \text{ °C} \) as a solidus temperature.

The main result of the numerical simulations is that in 15–17 Myr after the emplacement, the Khibina massif had to cool down to the temperature of the surrounding rocks, so the final temperature of the rocks on the different depths depends on geothermal gradient value only. The initial depth of the roof of the massif has almost no influence on the cooling duration. The solidus temperature play a significant role during the first few millions of years of the cooling. Thus, the results of the modeling indicate that cooling of the Khibina massif down to 110 °C could not have been related with post-magmatic heat exchange process, but instead was related to exhumation processes. The latter is suggested to be the result of doming above the plume head which initiated the alkaline magmatism in the Kola part of Fennoscandian Shield (Marty et al., 1998). The best-fit t-T paths (and weighted mean of those paths) in both modeled samples do in fact imply a second stage of post-intrusion cooling between about 320 and 280 Ma (Fig. 3).

5.3. Estimation of the post-Devonian erosion volume

As shown above, the depth of the Khibina massif emplacement is constrained by both feldspar K—Ar isotope system and AFT ages to an interval between 12 and 6 km. This value is in good agreement with other available independent estimations. Comparative analysis of 3D models of the Kola intrusions has shown that the estimated thickness of rocks eroded from the paleosurface to the modern erosion level of the Khibina caldera does not exceed 5–9 km (Arzamastsev et al., 2000). Moreover, the value of post-Phanerozoic denudation of the whole Kola Peninsula area was previously estimated as ~12 km based on the volume of terrigenous rocks in the adjacent sedimentary basins (Sim, 2012). Finally, Hendriks et al. (2007) have estimated the erosion volume in southern Norway as 13 km for the last 390 Myr based on mainly thermochronological data.

The proximity of the Khibina massif to adjacent areas of the central Kola Peninsula suggests that both regions have had a similar thermal and tectonic history since the Devonian. Moreover, similarity of AFT ages from the Khibina massif (~287 Ma, sample no. 1221, close to the present-day surface) and Precambrian rocks at the mouth of the Kola Super Deep Borehole (~300 Ma, Hendriks et al., 2007), let us to suppose similar thermal and tectonic history for a large area within the Kola Peninsula.

5.4. Significance for paleomagnetic data

Obtained AFT data play an important role for interpretation of the paleomagnetic data from the Kola part of the Fennoscandian shield (Veselovskiy and Arzamastsev, 2011; Veselovskiy et al., 2013). In particular, AFT ages show that the Khibina massif and the central part of the Kola Peninsula have not been reheated up to temperatures more than 110 °C from 280 Ma until now. Taking into account the absence of the K—Ar system disturbance even in plagioclase in some of the Devonian
dykes (Veselovskyi et al., 2013), we conclude that described area of the Kola Peninsula has not been affected by reheating of more than 150–250 °C after the formation of the Kola magmatic province at 390–360 Ma. If so, the presence of the enigmatic component of the natural remanence magnetization in the Devonian dykes from different parts of the Kola Peninsula (Veselovskyi and Arzamastsev, 2011; Veselovskyi et al., 2013) and, possibly, within the whole Fennoscandia, cannot be connected with thermal remagnetization. Also, it appears unlikely that the enigmatic component in Devonian dykes has a thermoviscous nature. According to Pullaiah et al. (1975), it is likely that the enigmatic component in Devonian dykes has a thermal unblocking temperature should be not more than 250 °C. This estimation is in disagreement with observed unblocking temperatures for enigmatic component, which reach 500 °C and even more (Veselovskyi et al., 2013).

6. Conclusions

1) Eleven new AFT ages, which vary from 268 to 290 Ma, were obtained from apatite samples from different depths of the Devonian Khibina alkaline intrusive massif.

2) Best-fit t-T models of the Khibina massif were constructed based on inverse modeling of AFT ages and mean track length distributions from three samples taken from the depths +280, −180, and −920 m. According to this modeling, two stages of accelerated cooling—320–280 Ma and 50–0 Ma are recognized, separated by a long ~200 Myr time interval of thermal stability, when the present-day levels of the massif would have been situated at depths about 2–3 km.

3) Thermal numerical modeling of the Khibina massif, as well as feldspar Ar/Ar data from the surrounding Devonian dykes, show that the massif was formed ~370 Ma at a depth of not more than 12 km. Its cooling down to <110 °C can be explained by tectonic uplift with an average rate ~0.1 km/Myr and erosion of the massif to depths of ~2–3 km by around 280 Ma.

4) Parallel best-fit t-T paths from three samples with vertical separation of about 1 km show that the geothermal gradient value in the central part of the Kola Peninsula was quite stable for the last 250 Myr and can be estimated as ~20 °C/km. This estimation is similar to the present value ~15–20 °C/km (Popov et al., 1999).

5) There is no sufficient evidence from the results of AFT dating to believe that the Khibina massif and adjacent territories of the Kola Peninsula could have been reheated to temperatures higher 110 °C during the last ~280 Myr, and to temperatures higher than 250 °C from 390 to 280 Ma.

6) Our estimation of the post-Devonian erosion for the central part of the Kola Peninsula, based on the AFT and Ar/Ar data, does not exceed 12 km; maximum post-Mesozoic erosion is estimated as 5–6 km.

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