Low temperature thermochronology of the southern East Greenland continental margin: Evidence from apatite (U–Th)/He and fission track analysis and implications for intermethod calibration

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Abstract

The southern coast of East Greenland is characterized by high topographic relief and deep fjords, but the evolution of the landscape and the low-temperature thermochronology of the region is not well understood. Here we present apatite fission-track and (U–Th)/He ages that suggest several important features of the long-term geomorphic history of this region, but which also illustrate an important discrepancy in the thermal histories derived from each technique. Apatite from bedrock of the southern coast of East Greenland between 62°N and 67°N has fission-track ages ranging from 60 to 840 Ma and (U–Th)/He ages ranging from 21 to 250 Ma. The ages generally increase with elevation and distance from the coast, and fission-track analyses show significant differences in thermal histories for the different regions. In the Kangertittivatsiaq area (c. 66–67°N) apatite fission track data and models suggest two separate periods of slow cooling: prior to c. 200 Ma and between c. 160 Ma and the late Cenozoic (more recently than c. 20 Ma), each of which was followed by a period of rapid cooling and inferred exhumation. Apatite He data in the Kangertittivatsiaq region, including crystal-size–age correlations in low-elevation samples, are most simply interpreted as recording an incision event of at least 1.5 km later than 20 Ma near the coast. This may have been caused by glacial erosion. The (U–Th)/He data also indicate an earlier phase of rapid exhumation at c. 250 Ma. In the Skjoldungen/Kap Mosting area (c. 62–64°N) approximately 200 km south of the Kangertittivatsiaq, apatite fission-track data suggest slow exhumation from c. 200 Ma into the Neogene followed by fast exhumation. The similarity of fission track ages (200 Ma) at sea level in the fjords in the Skjoldungen area (c. 62–64°N) do not suggest tilting in the hinterland related to the breakup of the East Greenland continental margin. Furthermore, the Cenozoic fission track ages and modeling fission track data suggest that pre-breakup basins may have covered the outer coast.

Despite the broadly similar topographic implications of the fission-track and (U–Th)/He data, the thermal histories derived from these systems are inconsistent. Fission-track data require thermal histories that predict He ages younger than observed, and He data require thermal histories that predict fission-track ages older than observed. Similar discrepancies have also been observed in other settings characterized by long-term low-temperature thermal histories, and may reflect changes in annealing or diffusion behavior (or both) that either develop or become more apparent in such cases.

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Keywords: Southern East Greenland; Low temperature history; (U–Th)/He; Fission track; Landscape evolution; Long term cooling

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1. Introduction

The southern East Greenland margin between 67°N and 62°N is characterized by high coastal relief up to c. 800 m, with inland elevations reaching c. 2 km at the Greenland ice shield (Fig. 1). North of Ammassalik there is an alpine topography whereas the topography in some regions to the south suggest the presence of remnants of a gentle mature topography with old peneplain surfaces (Brooks, 1985). Deep valleys shaped by glaciers incise the surfaces in the region. The topographic differences suggest different tectonic evolution between the northern (Kangertittivatsiaq) and southern (Kap Møsting and Skjoldungen) regions. The fjords reach up to c. 60 km inland and continue as glacial valleys under the ice shield. This study addresses the tectonogeomorphic evolution of southern East Greenland using apatite fission-track and (U–Th)/He thermochronology, and in doing so illustrates discrepancies in the thermal histories derived from each technique, which may have important implications for the intercalibration of these systems.

Apatite fission track (AFT) and (U–Th)/He analysis (apatite He dating or AHe) are well suited to estimating low temperature thermal histories of rocks (<120 °C, e.g., Gleadow et al., 1986; Farley, 2002). Here we present five new AFT analyses in the Skjoldungen area and multiple single-grain (U–Th)/He analyses on four samples in the Kangertittivatsiaq profile, for which the AFT analyses were published in Hansen and Brooks (2002).

The southern East Greenland margin (Fig. 1) consists of Archaen to Proterozoic tonalitic and amphibolitic

![Fig. 1. Geology of the East Greenland volcanic margin. Sample locations are shown together with the last three ciphers of sample numbers for new and published AFT and (U–Th)/He analyses (Clift et al., 1996; Hansen and Brooks, 2002). Modified from Hansen and Reiners (2004).](image-url)
gneisses in amphibolite to granulate facies and Precambrian intrusive complexes (e.g., Kalsbeek and Taylor, 1989; Nutman and Rosing, 1994). All the analysed samples are from the Precambrian crystalline basement (gneisses and granites) in southern East Greenland (Fig. 1). The Kangertittivatsiaq profile is located in the northern region characterized by alpine relief. The remaining samples are from the southern region with preserved surfaces of low relief, interpreted as peneplains.

Regional igneous activity related to the Paleogene breakup of the Northeast Atlantic is reported in, e.g., Larsen and Saunders (1998), and includes a dyke close to the Kap Møsting profile. In the Ammassalik area, a Paleogene coastal dike swarm extends northwards onshore from Tugtilik, but is thought to continue offshore southward along the East Greenland margin (Gleadow and Brooks, 1979; Rucklidge et al., 1980; Karson et al., 1998; Klausen and Larsen, 2002). The Paleogene Sulugsut intrusive complex (Brooks et al., 1989) is situated c. 25 km to the northeast of the study area, close to the southern end of the Tugtilik dyke swarm. The study area is landward of the presumed continuation of the dyke swarm (Klausen and Larsen, 2002), and tectonic effects from it are expected to have been minor. Furthermore, no contacts between Paleogene volcanic or intrusive rocks and basement rocks are observed anywhere along our profile in this area and therefore local thermal effects are expected to have been minor (see for example Hansen et al., 2001), although regional heating due to the magmatic activity may have caused regionally elevated geothermal gradients.

No sedimentary deposits are reported on land in this area. However, drillhole 917 offshore from Kap Møsting (Ocean Drilling program, Leg 152) shows pre-breakup (pre-volcanic) marine shelf sediments of presumably Cretaceous to Paleogene age, which were unconformably overlain by c. 800 m basalts at 61 Ma (Larsen and Saunders, 1998). Thus, in accordance with the suggestion of Ziegler (1982), Site 917 provides evidence for a pre-breakup basin along the southern East Greenland margin that may have originally been several hundred meters thick; this is also supported by seismic investigations (Larsen and Saunders, 1998). Larsen and Saunders (1998) interpreted the results from Leg 152 as requiring deep erosion shortly after breakup at 56 Ma and possibly kilometer-scale margin uplift in the Paleogene (Larsen and Saunders, 1998). Sediments at Site 918 east of Site 917 contain glacial material indicating glaciation beginning in southern East Greenland at c. 7 Ma (Larsen and Saunders, 1998), at a time when volcanic material still remained at the inner shelf. As a consequence Larsen and Saunders (1998) suggests that pre-breakup sediments and basalts, which are now completely removed on land, may have covered the southern East Greenland margin until 7 Ma ago. These units may have been present in the region investigated in this study, though their possible thicknesses are not known.

2. Earlier fission track work in the area

Fission track work in the area was published by Gleadow and Brooks (1979), Clift et al. (1996, 1998), and Hansen and Brooks (2002). Hansen and Brooks (2002) suggested that since the Caledonian orogeny, the Kangertittivatsiaq area experienced c. 3 km more exhumation than the southern area. This was based on the position of the apatite paleo-PAZ (paleo-PAZ is a fossil partial annealing zone for fission tracks, Wagner and Van den Haute, 1992) at Kangertittivatsiaq at c. 2100 m, and the preserved remnants of paleo-peneplain surfaces in the Skjoldungen area, at c. 1000 m elevation. A paleo-PAZ indicates earlier prolonged residence of a crustal section at temperatures in the apatite annealing interval and thus may record the formation of a peneplain 2–3 km above the paleo-PAZ. The suggestion a paleo-PAZ in Kangertittivatsiaq is consistent with formation of a peneplain 2–3 km above the present surface since the Precambrian or Cambrian followed by increased exhumation in post-Caledonian time. Alternatively, the peneplain south of the Kangertittivatsiaq area at Skjoldungen/Kap Møsting may represent a different evolution and thus the peneplains do not yield information about vertical displacement between the two areas. Clift et al. (1996, 1998) showed that the source area in the hinterland (c. 63°N–64°N) for their AFT analyses had not been at elevated temperatures (c. 60 °C) and thus indicate less than c. 2 km of erosion since the Mesozoic. Their samples were sediments from drillholes (Leg 152 Sites 918 and 914, Fig. 1) outside Kap Møsting and north of Skjoldungen and the Singertat intrusion at Skjoldungen.

3. Fission track thermochronology

3.1. Fission track method

The fission track (FT) method is based on tracks formed from spontaneous fission of $^{238}$U in nonconductive materials such as apatite. The observed track density depends on production rate, time and thermal history, and reveals an apparent age for the apatite
Table 1
Apatite FT ages from southern East Greenland

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Locality</th>
<th>Elevation (m.a.s.l.)</th>
<th>AFT pooled age (Ma) ±1σ</th>
<th>AFT central age (Ma) ±1σ</th>
<th>Rho0 ( \times 10^5 ) tracks/cm² (no. tracks)</th>
<th>Rho0 ( \times 10^5 ) tracks/cm² (no. tracks)</th>
<th>Rho0 CN1 ( \times 10^5 ) tracks/cm² (no. tracks)</th>
<th>Rho0 CN2 ( \times 10^5 ) tracks/cm² (no. tracks)</th>
<th>Chi² % (no. grains)</th>
<th>Mean track length (μm±1σ)</th>
<th>Std. dev. (μm)</th>
<th>No. tracks measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGU 312073(^a)</td>
<td>SE part of Steenstrup Complex</td>
<td>400</td>
<td>47±5</td>
<td>48±5</td>
<td>2.29 (106)</td>
<td>15.8 (733)</td>
<td>58.90 (2883)</td>
<td>51.67 (2546)</td>
<td>95.1 (30)</td>
<td>13.03±0.25</td>
<td>1.95</td>
<td>62</td>
</tr>
<tr>
<td>GGU 438707(^a)</td>
<td>Kangertittivataq</td>
<td>1280</td>
<td>134±9</td>
<td>134±7</td>
<td>7.97 (525)</td>
<td>18.9 (1243)</td>
<td>56.87 (2803)</td>
<td>52.84 (2604)</td>
<td>34.1 (31)</td>
<td>12.10±0.15</td>
<td>2.01</td>
<td>184</td>
</tr>
<tr>
<td>GGU 438710(^a)</td>
<td>Kangertittivataq</td>
<td>630</td>
<td>63±11</td>
<td>63±11</td>
<td>0.443 (42)</td>
<td>2.24 (212)</td>
<td>56.94 (2806)</td>
<td>52.89 (2597)</td>
<td>60.0 (31)</td>
<td>13.25±0.26</td>
<td>1.83</td>
<td>51</td>
</tr>
<tr>
<td>GGU 438711(^a)</td>
<td>Kangertittivataq</td>
<td>2150</td>
<td>836±57</td>
<td>836±48</td>
<td>17.4 (1302)</td>
<td>6.26 (468)</td>
<td>56.84 (2802)</td>
<td>52.90 (2607)</td>
<td>68.7 (31)</td>
<td>12.35±0.15</td>
<td>2.08</td>
<td>200</td>
</tr>
<tr>
<td>GGU 438712(^a)</td>
<td>Kangertittivataq</td>
<td>1765</td>
<td>296±17</td>
<td>294±13</td>
<td>20.5 (1278)</td>
<td>21.7 (1352)</td>
<td>56.89 (2804)</td>
<td>52.80 (2602)</td>
<td>65.0 (31)</td>
<td>12.55±0.16</td>
<td>2.33</td>
<td>222</td>
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<tr>
<td>GGU 438713(^a)</td>
<td>Kangertittivataq</td>
<td>1140</td>
<td>143±8</td>
<td>143±7</td>
<td>14.6 (837)</td>
<td>32.4 (1860)</td>
<td>56.90 (2805)</td>
<td>52.76 (2600)</td>
<td>49.2 (30)</td>
<td>11.72±0.16</td>
<td>2.29</td>
<td>202</td>
</tr>
<tr>
<td>GGU 438714(^a)</td>
<td>Kap Møsting M1</td>
<td>400</td>
<td>193±12</td>
<td>193±9</td>
<td>19.8 (715)</td>
<td>32.4 (1171)</td>
<td>56.86 (2802)</td>
<td>52.86 (2605)</td>
<td>77.0 (28)</td>
<td>12.70±0.13</td>
<td>1.62</td>
<td>148</td>
</tr>
<tr>
<td>GGU 438715(^a)</td>
<td>Kap Møsting M3</td>
<td>970</td>
<td>238±15</td>
<td>238±12</td>
<td>12.9 (745)</td>
<td>17.0 (987)</td>
<td>56.96 (2807)</td>
<td>52.63 (2594)</td>
<td>93.0 (32)</td>
<td>12.73±0.15</td>
<td>2.13</td>
<td>203</td>
</tr>
<tr>
<td>GGU 438716(^a)</td>
<td>Kap Møsting M5</td>
<td>1050</td>
<td>286±19</td>
<td>286±19</td>
<td>14.3 (757)</td>
<td>15.7 (831)</td>
<td>56.95 (2807)</td>
<td>52.65 (2595)</td>
<td>97.9 (30)</td>
<td>12.51±0.15</td>
<td>2.10</td>
<td>202</td>
</tr>
<tr>
<td>No number(^b)</td>
<td>Kap Møsting, station 6</td>
<td>1381</td>
<td>338±22</td>
<td>338±16</td>
<td>22.86 (1321)</td>
<td>15.99 (924)</td>
<td>46.59 (2296)</td>
<td>42.84 (2112)</td>
<td>93.4 (31)</td>
<td>12.49±0.15</td>
<td>2.14</td>
<td>205</td>
</tr>
<tr>
<td>GGU 940202(^b)</td>
<td>Staerkodder vig Skjoldungen</td>
<td>c. 1000</td>
<td>269±26</td>
<td>271±24</td>
<td>5.748 (318)</td>
<td>4.772 (264)</td>
<td>43.32 (2136)</td>
<td>40.92 (2017)</td>
<td>55.3 (24)</td>
<td>12.78±0.14</td>
<td>1.92</td>
<td>197</td>
</tr>
<tr>
<td>97-508(^b)</td>
<td>Staerkodder vig Skjoldungen</td>
<td>Sea level</td>
<td>211±16</td>
<td>211±13</td>
<td>12.01 (623)</td>
<td>12.65 (656)</td>
<td>42.63 (2103)</td>
<td>40.51 (1997)</td>
<td>65.5 (32)</td>
<td>12.69±0.13</td>
<td>2.05</td>
<td>241</td>
</tr>
<tr>
<td>97-544(^b)</td>
<td>Quitsiqsormuit Skjoldungen outer coast</td>
<td>Sea level</td>
<td>173±21</td>
<td>173±19</td>
<td>1.758 (146)</td>
<td>2.384 (198)</td>
<td>45.38 (2237)</td>
<td>42.13 (2077)</td>
<td>99.8 (28)</td>
<td>12.33±0.23</td>
<td>2.33</td>
<td>102</td>
</tr>
<tr>
<td>GGU 940213(^b)</td>
<td>Island in front of Puisortagaglacier, SE Greenland, c. 0 (lille skær)</td>
<td>59±4</td>
<td>59±3</td>
<td>20.04 (652)</td>
<td>76.74 (2496)</td>
<td>42.97 (2119)</td>
<td>40.71 (2007)</td>
<td>18.5 (26)</td>
<td>12.91±0.15</td>
<td>2.19</td>
<td>202</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) From Hansen and Brooks (2002).

\(^b\) This study; zeta values are 105.3±2.8 for CN1 and 111.8±6.5 for CN2.
sample. Mean track lengths for unannealed tracks are c. 16 μm. They shorten (anneal) in response to temperature and time. The temperature-sensitive annealing interval (PAZ, partial annealing zone) for apatite is often reported to range from 110–140 °C (top) to 50–70 °C (bottom) (e.g., Gleadow et al., 1983, 1986; Green et al., 1989; Wagner and Van den Haute, 1992; Gallagher, 1995). The PAZ shifts towards lower temperatures with time spent at partial annealing temperatures (Gleadow et al., 1983).

Track density, length distribution, U concentration and a model of annealing kinetics allow estimation of thermal history in addition to determination of an apparent AFT age. The annealing behavior of apatite, and its compositional dependence, has been extensively studied (Green et al., 1986; Duddy et al., 1988; Crowley et al., 1991; Green, 1996; Carlson et al., 1999; Donellick et al., 1999). Annealing models (e.g., Laslett et al., 1987, Corrigan, 1991; Crowley et al., 1991; Ketcham et al., 1999; Ketcham, 2005) are based on experimental data (e.g., Green et al., 1986), and are used together with thermal history models to predict track ages and length distributions similar to observed ones in natural samples (e.g., Jensen et al., 1992; Gallagher, 1995; Laslett and Galbraith, 1996; Willett, 1997).

Apatite concentrates were embedded in Araldite, polished, etched in 1N HNO₃ at room temperature to reveal spontaneous tracks, and irradiated against a mica detector with thermal neutrons at Radiation Center, Oregon State University, Corvallis, USA (Cd rate for Au = 14, Garver, 2000). Detectors were etched in 40% HF at room temperature for about 38 min. Counting to obtain track density was performed on prismatic internal surfaces of the grains and on the mica at c. ×1600 enlargement (transmitted light) to obtain AFT ages. Fluence was monitored by the standard glasses CN1 and CN2 (Corning Glass Works). Fish Canyon tuff apatites were used as age standards, and the AFT ages are calibrated as suggested by Hurford and Green (1983). Track lengths were measured parallel to prismatic surfaces.

3.2. Fission track results

Five new AFT results are presented in Table 1 together with earlier published AFT data for Kangertittivatsiaq and Kap Mosting (Hansen and Brooks, 2002). AFT age-elevation profiles from both this and earlier (Hansen and Brooks, 2002) studies in this area are presented in Fig. 2. In the southern area south of Skjoldungen the AFT age for the sample at the coast (97–544) is c. 60 Ma whereas the ages in the Skjoldungen area at sea level range between 173 and 234 Ma. At Kap Mosting the pattern of ages as a function of elevation does not show evidence for break in slope (Fig. 2). The age–elevation relationship is similar to that for GGU940202 and 97-508 (vertical) from the nearby Skjoldungen profile. In contrast, the Kangertittivatsiaq profile in the northern area (Fig. 2) reveals a break in the age elevation curve between 294 Ma and 143 Ma (GGU438712 and GGU438713) and implies a second break at depth (see below). Length distributions for both northern and southern areas range from skewed through symmetrical to bimodal.

Fig. 2. AFT age elevation profiles for earlier (Clift et al., 1996; Hansen and Brooks, 2002) and present studies in southern East Greenland. From Hansen and Reiners (2004).
distributions (Fig. 3). Mean track lengths are between 12.10 and 13.25 μm (Figs. 3 and 4).

4. (U–Th)/He chronometry

4.1. (U–Th)/He methods

(U–Th)/He dating is based on ⁴He produced by decay of ²³⁸U, ²³⁵U and ²³²Th (and, in some cases, ¹⁴⁷Sm) and their retention or diffusive loss in the analysed material, which is a function of crystal size, time and temperature. The temperature range of the apatite He partial retention zone (PRZ), analogous to the AFT PAZ but referring to partial retention of He, is estimated to be between ~40 and 80 °C (Wolf et al., 1998; Farley, 2000).

Apatite separates left-over from AFT analyses were used for the (U–Th)/He analyses. Most (U–Th)/He measurements were performed on single-grains at Yale University using techniques similar to those of House et al. (2000). Apatite crystals were handpicked from separates under a high power (160×) stereo-zoom
microscope with cross-polarization for screening inclusions (all dated crystals were free of visible inclusions). Selected crystals were measured and digitally photographed in at least 2 different orientations, and loaded into 1-mm Pt foil tubes, which were then loaded into stainless steel sample planchets. Planchets were loaded into a ~10 cm laser cell with sapphire window, connected to the He extraction/measurement line. Once in the laser cell and pumped to <10^{-8} Torr, crystal-bearing foil tubes were individually heated by lasing with about 1–5 W from a Nd:YAG laser for three minutes. Temperatures of heated foil packets were not measured, but from experiments relating luminosity and step-wise degassing of both apatite and zircon, we estimate typical heating temperatures of 950–1000 °C for apatite. 4He blanks (0.05–0.1 femtomol 4He, after correction for 4He in the spike) were estimated using the same procedure on empty Pt tubes. Crystals were checked for degassing of He by sequential reheating and He measurement; in this study no samples exhibited residual gas after the first extraction. Gas liberated from samples was processed by: 1) spiking with ~0.4 pmol of 3He, 2) cryogenic concentration at 16 K on a charcoal trap (condensation time calibrated for no significant 4He/3He fractionation), and purification by release at 37 K, and 3) measurement of 4He/3He ratios (corrected for HD and H3 by monitoring H+) on a quadrupole mass spectrometer next to a cold Zr-alloy getter. All ratios were referenced to multiple same-day measured ratios and known volumes of 4He standards. Linearity of this standard referencing procedure has been confirmed over four orders of magnitude of 3He intensity. 4He standard reproducibility averages 0.2% on a daily and long-term (tank-depletion corrected) basis. Estimated 2σ analytical uncertainty on sample He determinations, including precision and accuracy from original manometric 4He standard calibrations, is 2–3%.

Following degassing, samples were retrieved from the laser cell, spiked with a calibrated 229Th and 233U solution, and dissolved. Apatites were dissolved in situ from Pt tubes in ~30% HNO3 in Teflon vials. Each sample batch was prepared with a series of procedural blanks (including Pt foil blanks for apatite) and spiked normals to check the purity and calibration of the reagents and spikes. Spiked solutions were analyzed as 0.5 ml of ~1–5 ppb U–Th solutions by isotope dilution on a Finnigan Element2 ICP-MS with a Teflon microflow nebulizer and double-pass spray chamber. Procedural U and Th blanks by this method are 1±0.5 pg and 2±1 pg, respectively. Routine in-run precisions and long-term reproducibilities of standard 232Th/229Th and 238U/233U are 0.1–0.4%, and estimated uncertainty on sample U–Th contents are estimated to be 1–2% (2σ). At the time of analysis of the samples in this study, measurement of 147Sm in apatite (U–Th)/He dating in the Yale lab was not routine, and these samples were not analyzed for Sm content. More recently, several hundred (U–Th–Sm)/He dates on apatites from a wide range of locations indicate that in the vast majority of apatites, 147Sm contributes between 0.1% and 2.0% of 4He, and apatites with 147Sm contributions larger than this are typically restricted to those with unusually low U concentrations (e.g., less than ~3–5 ppm U).

Alpha ejection was corrected using the method of Farley (2002). Replicate analyses of Durango apatite during the period of these analyses yielded a mean age
of 32.0 Ma, with two standard deviations of 2.0 Ma. On the basis of reproducibility of these and other interlaboratory standards (e.g., 97MR22, 8500-15), we estimate an analytical uncertainty of 6% (2σ) for apatite age determinations in this study.

4.2. (U–Th)/He results

Inclusion-free apatites from one sample (GGU438710) were too small (radii of 31–34 μm) and contained too little U and Th (<1–2 ppm) to obtain reliable apatite (U–Th)/He (AHe) ages. Table 2 shows results from each of the four to nine aliquots from the remaining samples, most of which were single-grain analyses. The ages range from 21 to 250 Ma (Table 2). Fig. 5 shows the (U–Th)/He age data plotted versus elevation, along with the AFT data. Most AHe ages are significantly younger than the AFT ages on the same sample, especially the highest elevation sample (GGU438711), with an AFT-AHe age difference of more than 600 Myr. The lowest elevation sample (GGU438713) with both AHe and AFT analyses, however, has several single-grain analyses whose AHe ages overlap those of AFT age within error.

Multiple replicates from the highest elevation sample (GGU438711) show good reproducibility, with an average age of 229±12 Ma. The next highest elevation

<table>
<thead>
<tr>
<th>GGU sample</th>
<th># of grains</th>
<th>Corrected age (Ma)</th>
<th>2σ±(Ma)</th>
<th>Radius (μm)</th>
<th>Mass (μg)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Th/He at STP</th>
<th>AFT age (Ma)</th>
<th>1σ±(Ma)</th>
<th>Elevation (m.a.s.l.)</th>
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<tbody>
<tr>
<td>438710</td>
<td>n/a</td>
<td>64</td>
<td>11</td>
<td>630</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>229±12 Ma</td>
</tr>
<tr>
<td>438707A</td>
<td>9</td>
<td>0.74</td>
<td>55.5</td>
<td>3.3</td>
<td>50.1</td>
<td>53.5</td>
<td>28.8</td>
<td>14.7</td>
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<td>438707B</td>
<td>1</td>
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<td>49.8</td>
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Table 2 (U–Th)/He analyses from Kangertittivatsiaq

a FT is α-ejection correction (Farley, 2002).

b Radius is c-axis perpendicular half-width for single grains and mass-weighted average (MWAR) of these for multiple-grain aliquots (Reiners and Farley, 2001).

c Rs is equivalent sphere radius of the crystal (see text).
sample also shows a good reproducibility with six single-crystal ages averaging $235 \pm 13$ Ma (GGU438712), indistinguishable from GGU438711. The two lowest elevation samples, GGU438707 and GGU438713, both have average ages much younger than the higher samples, but single-grain ages in each show large variations ($21-102$ Ma, and $102-170$ Ma, respectively). These two samples also show an atypical pattern (Fig. 5) in which the average age ($54 \pm 30$ Ma) of the higher elevation sample (GGU438707) is younger than the average age ($136 \pm 21$ Ma) of lower elevation one (GGU438713). This pattern is also seen in the AFT ages, however, and the lower elevation sample is displaced c. 25 km inland from the higher one, suggesting that this age–elevation relationship is real. If the two oldest ages for sample GGU438707, closest to the coast are removed, the ages cluster more tightly at a younger age ($39 \pm 13$ Ma), but are still highly dispersed.

5. Interpretation and discussion

5.1. Apatite fission-track data

AFT ages versus elevation and AFT length distributions (Figs. 2 and 3) for this and earlier studies in the area between c. 67°N and 62°N suggest different thermal histories for the northern and southern regions. Mean track length versus AFT age shown in Fig. 4 does not reveal simple boomerang trends. A boomerang trend is characteristic of AFT analyses in an inverted sediment basin, but a similar trend may also be expected for a section across a paleo-PAZ. Track length distributions in a paleo-PAZ show mean track lengths that are shortest (and often complex) in the middle part of the zone, and longer in both the upper and lower parts, associated with the older and younger ages, respectively. Trends of track length distributions for the Kangertittivatsiaq, Kap Møsting, and Skjoldungen areas are different (Figs. 3 and 4), suggesting different thermal evolutions for each area. Hansen and Brooks (2002) pointed out that the age–elevation trend in the upper part (GGU438711 and GGU438712) of the Kangertittivatsiaq profile may represent the bottom of an apatite paleo-PAZ. This is supported by complex track length distributions in these samples. The two lower-elevation samples in the Kangertittivatsiaq profile (GGU438707 and GGU438713) show length distributions dominated by significantly shortened, partly annealed tracks, suggesting that these samples were exhumed relatively recently, with little time to grow in longer, unannealed tracks. The lowermost sample in this profile, GGU438710, shows dominantly long, unannealed tracks and a young AFT age, suggesting recent cooling from relatively high temperatures (compared to the other samples).

The mean track lengths below the break in slope in the Kangertittivatsiaq profile decrease slightly with decreasing age, and then rise again with younger ages, similar to the pattern for the Skjoldungen area (Fig. 4). The Kap Møsting profile shows a similar pattern, but more complex length distributions and only slightly rising mean track lengths at young ages compared with the other two profiles (Fig. 4). These differences may be due to exhumation from different sections of a paleo-PAZ.

An extrapolation of the age elevation relation for the two profiles reveals that the Kangertittivatsiaq profile requires an increase in exhumation rate later than c.
65 Ma (the age of GGU438710, Fig. 2). Gleadow and Brooks (1979) showed that a dyke at Tugtilik (approximately 20 km from the Kangertittivatsiaq profile) has a cooling age of c. 20 Ma. Extrapolation of AFT ages below the break in slope for Kangertittivatsiaq including Tugtilik yields zero ages at less than 500 m depth below sea level (or at 15 °C, for a geothermal gradient of 30 °C/km), compared with an expected depth of ~4–5 km (for a zero-age intercept at a temperature of 120 °C). Therefore the combined AFT data for Kangertittivatsiaq and Tugtilik require an increase in cooling rate later than c. 20 Ma. The extrapolation of the age elevation profile at Kap Møsting intersects zero age at c. 1500 m depth, suggesting that the recent exhumation rate change was either less extreme or occurred later at Kap Møsting than at Kangertittivatsiaq. Sea-level samples along the Skjoldungen Fjord system, about 20 km to the south of Kap Møsting, reveal similar AFT ages, consistent with erosion to similar crustal levels in the inner part of the fjord. Southwards from the Skjoldungen area, AFT ages at sea-level decrease from 173±21 Ma at Quitsigssorumit, to 59.0±3.9 Ma at Puisortoq (over c. 125 km, Figs. 1 and 2). The skewed track-length distribution at Puisortoq are consistent with Paleogene exhumation from below the PAZ (Fig. 3).

We used fission track modelling (Jensen et al., 1992, 1993) to test a range of thermal histories that could potentially explain the AFT data. Although different thermal histories may result in similar track length distributions, performing this modelling in a geological framework allows us to test the thermal histories associated with different geological scenarios. The AFT modelling program uses an annealing model that describes track shortening in response to temperature and time. Gallagher (1995) has shown that thermal histories derived from AFT data depend on the annealing model(s) used. The annealing model of Laslett et al. (1987) is used in these calculations. We note here that other annealing models, such as the fanning curvilinear model of Ketcham et al. (1999) [also used in the HeFTy program of Ketcham (2005)], which includes effects of annealing at low-temperatures over long durations (Vrolijk et al., 1992), may predict lower-temperature thermal histories. We discuss this further in a subsequent section.

Following the method of Jensen et al. (1993), in the first step of the modelling we calculate a histogram from a specific thermal history where all tracks in a column belong to the same time interval. In the second step the histogram is convolved (each column from the first calculation step is changed to a length distribution using the measured track length distribution for the Fish Canyon apatite and then the distributions from each column are combined). We further use length distributions for different annealing steps (Green et al., 1986) as filters for the convolution of individual columns to consider the continuous broadening of length distributions in annealing. In this way the initial track length distribution at the time of retention is taken into account. This combined convolved histogram is then compared to the measured histogram. The thermal history is repeatedly altered within the constraints provided by the geological framework to minimize the difference between the calculated convolved histogram and the observed histogram.

The geological framework used in the forward modelling is based on information about the regional and local geology as described above. Potentially important points in the geological framework include that the basement surface after c. 150 Ma may have been superposed by a pre-breakup basin (with an assumed maximum depth at c. 62 Ma), a basaltic cover (continental magmatism from c. 61 Ma), a post-breakup basin (from c. 53 Ma), and glacial erosion (from c. 7 Ma), which could cause incision of fjords in the area. Included in the modelling are also surface temperature, heat flow, rock-types and their physical parameters (porosity and heat conductivity). Thus many free parameters (and degrees of freedom) are allowed. In the modelling, surface temperature, heat flow and physical parameters are set in accordance with the presumed lithology such as basement rocks, clastic sediments and basalts. Only depths and timing of specific events in the geological framework are changed during the modelling. Fig. 6 illustrates two versions of likely combined solutions for the Kangertittivatsiaq, Kap Møsting profiles and Skjoldungen areas, based on the above approach. We do not claim that these model thermal histories are the only ones capable of explaining the main features of the fission-track ages and the track-length distributions, as there are too many free parameters to obtain a unique thermal history, especially given the old ages and complex track length distributions. Nevertheless, these models illustrate several important points and general features of the geologic history required by the AFT data.

We have tested possible thermal histories within two broad geologic scenarios. The thermal histories presented in Fig. 6 result from the best coherent solutions within a transect/region to each of the two model scenarios:

**a:** Samples are assumed to have been exhumed to the surface prior to burial due to formation of 1: pre-
breakup basins, 2: possible later burial due to volcanic and 3: post-breakup basin formation, and final exhumation probably due to glacial erosion.

**b:** Samples are exhumed mainly by continuous erosion of overlying basement, with minimal thermal effects from any pre-basin, volcanic and post-basin burial.

In **a**, samples in the Skjoldungen and Kap Møsting areas are exhumed to the surface (exposing the present landscape except for GGU940213) and then reburied due to pre-breakup basin formation, volcanic deposits and post-breakup basin formation. In this model (**a**), burial and exhumation are required for all three events followed by glacial exhumation and exposure to the present surface. The samples 97-544 and GGU940213 closest to the continental margin, however, require an additional 300–500 m burial in a pre-breakup basin compared to the other samples. In the Kangertittivatsiaq model the two uppermost samples (GGU348711 and GGU348712) are exhumed to the surface at c. 200 Ma and the lower lying samples (GGU348707 and GGU348713) are exhumed at higher rates to the surface at c. 155 Ma followed by multiple burial events and final exhumation after the onset of glacialiation. Compared to GGU348707 and GGU348713, an additional c. 500-m pre-breakup burial is required for sample GGU348710. The success of these complex thermal histories in explaining the AFT data means that we cannot rule out complex histories involving pre-breakup basin formation, volcanism and post-breakup basin formation in the histories of most of these samples. However, even these models require a late stage of rapid cooling since 7 Ma for all samples except GGU438711, which is situated farthest inland and at the highest elevation.

In **b** (**Fig. 6**), for most samples at Kap Møsting and Skjoldungen, exhumation occurs at c. 150 Ma or earlier and samples are held at nearly constant temperatures close to the top of the PAZ until the onset of glaciation followed by fast cooling. The exceptions to this are samples 97-544 (Skjoldungen) for which final exhumation began earlier (**Fig. 6, b**) and GGU940213 (Skjoldungen), which was exhumed to isothermal temperatures as late as c. 60 Ma (**Fig. 6, b**). The modelling for Kangertittivatsiaq (**Fig. 6, b**) requires slow cooling since Precambrian time at temperatures below or within the upper part of the paleo-PAZ for samples GGU438711 and GGU438712 until c. 200 Ma.

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**Fig. 6.** Forward modelled thermal history based on the Laslett et al. (1987) AFT annealing model using Jensen et al. (1992, 1993). **a** (left panel) represent models exhumed to the surface in Mesozoic time and reburied, and **b** (right panel) models based mainly on time dependent erosion of basement. Surface temperatures (long stitched lines) are mainly from Frakes et al. (1992). Calculation is performed in 1 Ma steps.
or earlier. 200 Ma is the approximate extrapolated time for the break-in-slope (Fig. 2) situated between GGU438712 (294 Ma) and GGU438713 (143 Ma). Before c. 160 Ma, higher cooling rates are required for GGU438713 and GGU438707. Between c. 160 and 7 Ma (Fig. 6, b) the samples are held at relatively constant temperature implying extremely low cooling rates again until c. 7 Ma, when the models for the four lowermost samples require rapid cooling to surface temperatures. However, for sample GGU438710 it is very difficult to find a good match between predicted track length distributions obtained from modelled thermal histories and measured length distributions and ages, but a very fast cooling is necessary before c. 61 Ma.

Regardless of the model scenario (a or b), these results require different thermal histories for the Kangertittivatsiaq and Skjoldungen areas (Fig. 6). Kap Mosting may represent a transition between the areas but its model thermal history more closely resembles that of the Skjoldungen area. At Skjoldungen, model a indicates exposure of the present topography at c. 150 Ma and since then, reburial and final exhumation since glaciation. Model b indicates holding at similar depths (and temperatures) below the surface between c. 160 and 7 Myr, followed by exhumation to the surface at the time of glaciation, however, probably earlier at the coast (sample 97-544). This implies a period with slow erosion and probably a mature landscape eroded in the latest Cenozoic. The southernmost sample GGU940213 (Puisortoq) requires exhumation that begins at c. 62 Ma and is consistent with an extension of the pre-breakup basin found in drillhole 917 (Ocean Drilling program, Leg 152) to the present coast as already suggested by Larsen and Saunders (1998) and Ziegler (1982). For Kangertittivatsiaq, model scenario a suggests exposure between 200 and 160 Ma and reburial due to basin formation and volcanic activity between c. 160 Ma and 7 Ma for the samples GGU438712, GGU438713 and GGU438707. Model b for Kangertittivatsiaq requires a transition from slow to fast exhumation probably before 200 Ma, followed by a stable landscape since 160 Ma with little or no exhumation until the onset of glaciation, when all samples were exhumed to the surface. This result is supported by Klausen and Larsen (2002) who pointed out that the basement inland north of our study area was unaffected by Paleocene tilting, rotation and dilatation. The modelling of sample GGU438710 may indicate either the existence of a pre-breakup basin that did not affect the higher elevation sample GGU438707, or creation of coastal relief at c. 62 Ma, in accordance to the suggestions of Larsen and Saunders (1998), which was further incised during the glaciation since 7 Ma ago. All the samples from Kangertittivatsiaq are exhumed from different temperatures and depths, an indication of formation of the alpine relief during the last c. 7 Myr A similar, but less obvious pattern is seen in Kap Mosting as well.

In summary, the AFT data and our modeling, taking into account geologic constraints, are consistent with two stages of slow or no exhumation, which may be peneplanation periods, in the Kangertittivatsiaq area: prior to 200 Ma, and between ~160 and 7 Ma. The last period ended with an episode of rapid exhumation that may have created the present topography. Only the second stage of slow-to-no erosion (and possible peneplanation) appears to be recorded in the Skjoldungen area. Hence the thermal history of the Kangertittivatsiaq region and the Skjoldungen area to the south appear to be distinct.

5.2. (U–Th)/He data

The (U–Th)/He data for Kangertittivatsiaq show a 600 Myr difference in AFT and AHe ages for the highest elevation sample (Fig. 5), which requires either very slow cooling during the Paleozoic between the closure temperatures of the two systems, or a reheating event before ~250 Ma that only reset the AHe ages (Fig. 5 and Tables 1 and 2). Other samples have much more similar AFT and AHe ages, reflecting more rapid cooling after 250 Ma. The ~60 Myr AFT-AHe age difference for sample GGU438712 suggests an average (assumed monotonic) cooling rate of about 2 °C/Myr during much of the Triassic. It is difficult to constrain the post-250-Ma cooling history from AHe ages or AHe-AFT age pairs of the two lower samples, however, because these samples show a wide range of single-grain AHe ages.

The large variation of single-grain ages (Table 2) for the two lowest elevation samples may have several possible origins, including close proximity of apatites to (within 20 μm) of high-U phases within these rocks, unusually large contributions from $^{147}$Sm decay, or heterogeneous He retentivity for some unknown reason. We also note, however, that poor He age reproducibility is common for apatites that have experienced very slow cooling through, prolonged residence at temperatures within, or, in some cases, reheating to, the AHe partial retention zone (PRZ $\sim$40–80 °C, analogous to the AFT partial annealing zone, PAZ), where fractional He retentivity in apatite changes most rapidly as a function of temperature (House et al., 2001; Reiners and Farley,
Because the lengthscale of the diffusion domain forapatite scales with the physical grain size (Farley, 2000), prolonged residence in this temperature range can produce correlations between apparent age and crystal size, the details of which can be used to constrain models of thermal histories in or below the temperature range of the AHe PRZ (Reiners and Farley, 2001).

Diffusion of He fromapatite is typically modeled as thermally activated volume diffusion from crystals with idealized spherical geometry, following conventional noble gas approaches, and consistent with the assumption of spherical geometry used in experimental derivation of diffusion parameters (Wolf et al., 1996; Farley, 2000). Meesters and Dunai (2002a) showed that He diffusion models forapatite using spherical diffusion domains with surface-area-to-volume ratios equivalent to those of the actual cylindrical crystals provide reasonably accurate predictions of more realistic geometries. For this reason, rather than examining AHe ages in our samples as a function of measured grain radii, we have converted these radii to those of spheres (c-axis parallel lengths) and widths [c-axis perpendicular lengths = two times the “radius” or “mass-weighted average radius” (MWAR) in multiple crystal aliquots; see Table 2] of the crystals, using the equation $R_s = \frac{3}{\beta}$, where $\beta$ is the surface-area-to-volume ratio of the apatite crystal with a hexagonal cylinder morphology and assumed pinacoidal terminations. For crystals that were broken perpendicular to the c-axis (presumably after cooling, e.g., during sample preparation), we have used measured widths and assumed lengths based aspect ratios of whole crystals in the same population (typical aspect ratios are 1.7–2.0). Calculated $R_s$ is much more sensitive to measured width than assumed length.

Fig. 7 shows AHe ages plotted as a function of $R_s$ for individual aliquots from all four samples. The two highest elevation samples (GGU438711 and GGU438712) — also those with relatively good single-grain age reproducibility — show no correlation between these parameters. The sample collected closest to the coast (GGU438707), however, shows a good positive correlation between age and $R_s$, with the smallest grain ($R_s = 36 \, \mu m$) having an age of 20.8 Ma and the largest ($R_s = 65 \, \mu m$) an age of 102 Ma. For the other low elevation sample (GGU438713), there is a reasonable correlation for crystals with $R_s$ between 38 and 52 $\mu m$, with ages ranging from 102 to 170 Ma, but the three largest crystals, with $R_s$ of 61 to 65 $\mu m$, fall off this trend to lower ages (124–150 Ma). A possible reason for this, though it is not possible to test at this point, is that the largest crystals contained internal structures such as cracks that reduced the effective diffusion domain size of the grains.

In order to constrain the types of thermal histories consistent with the AHe ages observed in the Kangerittivatsiaq section, we used the (U–Th)/He-AFT program (HeFTy) for modeling He production–diffusion (as well as AFT ages and length distributions) of Ketcham (2005), combined with He diffusion parameters forapatite from Farley (2000). There are at least three essential features of any model thermal history capable of explaining these AHe data. First, the reproducible and crystal-size–invariant AHe ages in the highest elevation samples record a final episode of relatively rapid cooling through the AHe closure temperature (and even lower, through the lower temperature limit of the AHe PRZ) at around 220–250 Ma at least for these samples. Second, assuming that the poor reproducibility in the two lower samples does not reflect heterogeneous diffusivity, “excess” He, or some other unrecognized control on AHe ages, then the crystal-size–age correlations in these samples reflect either prolonged residence in the He PRZ (~40–80 °C), or a reheating event that has partially reset the AHe ages. Third, the minimum age of 21 Ma for the smallest crystal analyzed in sample GGU438707 provides a maximum age for final cooling through the AHe closure temperature for these samples with relatively young ages.

Although an infinite number of thermal histories for each sample could be reconciled with these constraints, two endmember models are useful for illustrating the basic implications of the AHe data. In any model, the relatively reproducible and size-invariant AHe ages of the high-elevation samples require a period of rapid cooling through the low-temperature portion of the AHe PRZ at approximately 250–225 Ma. Much younger ages and crystal-size–age correlations of samples at lower elevation, however, require a model with final cooling through these temperatures much later; at ~20 Ma or younger. Prior to this, the lower elevation samples resided at temperatures either within the AHe PRZ or at lower temperatures since ~250–225 Ma. If they sat in the AHe PRZ for ~250–225 Myr, they could grow in He while partially open, developing crystal-size–age correlations over a long period of time. Alternatively, the crystal-size–age correlations may have been produced by a reheating event following long-term (~250–225 Myr) residence at very low (i.e., near-surface) temperatures, partially resetting smaller
grains to greater extents. Multiple cooling and reheating episodes would be intermediate between these endmember scenarios, as would slow cooling, although by itself slow cooling cannot produce pronounced crystal-size–age correlations over this timescale, or the appropriate AHe ages.

The cessation of the rapid cooling episode at \( \sim 250\)–\(225\) Ma required by the high-elevation AHe ages is within the range required from the AFT data, though the AFT models allow for a shift to lower cooling rates as late as \( \sim 160\) Ma. The resolution on the timing of the end of this earlier event is not well constrained, however, and is of lesser importance than the subsequent evolution of the crustal section.

In the first model, each sample is held at a constant temperature between 0 and 53 °C from 250 Ma to either 20 or 0.5 Ma, when each sample is then cooled at a constant rate to 0 °C at the present. In the context of a geologic history, this could represent 230–250 Myr of isothermal holding of samples in a \( \sim 1.75\)-km thick crustal block with a 30 °C/km geothermal gradient, followed by rapid incision, creating the modern topography, beginning at either 20 or 0.5 Ma (samples deeper in the valley are buried to greater depths), followed by re-exhumation of the valley at a constant rate until the present. Although these models are obviously endmembers that oversimplify the likely geologic evolution of the Kangertittivatsiaq region, they satisfy the requirements of rapid cooling of the high-elevation samples at 250 Ma, and either residence in the PRZ or reheating to PRZ-temperatures until 20 Ma for the two lower elevation samples, and they bracket the possible geologic events that could produce these conditions by either long-term isothermal holding, reheating, or some combination of the two.

The second endmember model involves isothermal holding of every sample at 0 °C from 250 to 20 Ma, followed by heating to a temperature between 23 °C to 75 °C for 0.5 Myr, and thereafter a constant cooling rate to a present-day temperature of 0 °C. This latter model essentially simulates the burial of a \( \sim 2\)-km deep valley created at 250 Ma to a depth of 0.5 km at 20 Ma (samples deeper in the valley are buried to greater depths), followed by re-exhumation of the valley at a constant rate until the present. Although these models are obviously endmembers that oversimplify the likely geologic evolution of the Kangertittivatsiaq region, they satisfy the requirements of rapid cooling of the high-elevation samples at 250 Ma, and either residence in the PRZ or reheating to PRZ-temperatures until 20 Ma for the two lower elevation samples, and they bracket the possible geologic events that could produce these conditions by either long-term isothermal holding, reheating, or some combination of the two.

Fig. 8 shows the predictions of AHe ages as a function of \(R_s\) using these endmember thermal models. For the long-term isothermal holding scenario, the model trends show only very weak size–age correlations for samples that resided at temperatures greater than about 50 °C or less than about 25 °C prior to the relatively rapid cooling event at or younger than 20 Ma. For the short-duration reheating scenario, predicted crystal-size–age correlations are very weak for samples reheated to temperatures of greater than about 70 °C or less than about 38 °C prior to the post-20-Ma cooling
event. Assuming a geothermal gradient of 30 °C/km, this means that only samples exhumed from about 1–2 km depths in the post-20-Ma exhumation event should show these correlations.

If reheating is not allowed (Fig. 8A), the two highest elevation samples were held at temperatures lower than ∼30 °C since 250 Ma, while the two lower elevation samples require ∼230–250 Myr at temperatures of ∼35–53 °C, until 20 Ma or younger. This would be consistent with relatively rapid exhumation from depths of ∼1.25 to 1.75 km after 20 Ma. If reheating sometime before 20 Ma is allowed (Fig. 8B) the two lower elevation samples cannot have been reheated to more than ∼53–70 °C. The reheating affecting the lower-elevation sample AHe ages could have been to lower temperatures for longer periods of time (as long as this heating ended after ∼20 Ma), but longer holding times flatten the predicted crystal-size–age trends to slopes lower than those observed. Extending reheating events to longer durations at lower temperatures also makes the
thermal models similar to those of the first scenario, involving prolonged residence at temperatures within the PRZ, so reheating and isothermal or nearly isothermal holding models are essentially only different in the duration of time spent in the PRZ.

The observed size–age correlation for apatites up to $R_{e}$ of about 61 $\mu$m in sample GGU438707 is similar to that predicted by models for pre-20-Ma temperatures of about 45–68 °C in both models, or a depth of about 1.5–2.3 km assuming a geotherm of 30 °C/km. The old ages of the two largest apatites in this sample, however, fall to higher ages, and we could not find a thermal history in any forward model that we examined capable of generating a size–age correlation with sufficient concave-up curvature to fall through both the smaller crystals and these data. Thus, although the smaller apatites in this sample are similar to predicted trends predicted for recent (<20 Ma) cooling of this rock from prolonged residence at ~45 °C temperatures, we cannot explain the “too-old” ages of the larger crystals.

Apatites from sample GGU438713 show a distribution that is consistent with post-20-Ma cooling from temperatures of about 35–55 °C, depending on the model, corresponding to pre-20-Ma depths of about 1.2–1.8 km, although again, most of the largest crystals fall off a better apparent correlation among smaller ones, though in this case to young ages.

In summary, although these complications to the size–age correlations (as well as the inconsistencies between the AFT- and AHe-derived thermal histories, as discussed below) prevent robust interpretations, several features of the AHe data provide at least preliminary evidence for some aspects of landscape evolution in the Kangertittivatsiaq region. First, the old and size-invariant ages at high elevation suggest a period of relatively rapid cooling in the early Mesozoic. Second, the wide range of ages and size–age correlations in single samples at lower elevation samples requires residence at temperatures within the AHe PRZ, where such variations can be produced by varying fractional He retention due to diffusion domain size, through ~20 Ma or younger. Taken together, this is consistent with relatively recent and rapid exposure of the low elevation samples, no earlier, and possibly much more recently, than ~20 Ma. We therefore tentatively suggest that at least some of the deep fjords of southern East Greenland reflect glacial incision associated with a cooling climate in the latest Cenozoic. A prolonged residence time in this crustal section prior to the onset of glaciation at 7 Ma is also supported by the relatively few long tracks measured in apatites with AFT ages above 200 Ma. This interpretation can be tested by more detailed analysis of samples from this and other fjords in this region of southern East Greenland. We predict that high elevation samples will show old and crystal-size–invariant ages, and deeper samples will show younger ages that broadly correlate with crystal size, reflecting their prolonged residence in a slowly-exhuming crustal section until recent exhumation by valley incision. If exhumation has been sufficiently deep in some valley bottoms (greater than about 1.8 km), samples from these areas should also show crystal-size–invariant ages, and an age approximating the age of recent incision.

5.3. Comparisons of thermal histories from AFT and AHe data

Taken separately, the AHe and AFT data can be interpreted to constrain the qualitative thermal histories bearing on exhumation histories in the upper few kilometers of crust. These suggest broadly similar patterns of landscape evolution. Unfortunately, taken together, the model absolute temperatures in the thermal histories derived from the AFT data and the AHe data are inconsistent, assuming typically accepted thermal sensitivities of both systems. For example, for all but the highest elevation sample (GGU438711) the AFT ages predicted by standard track annealing parameters using HeFTy (Ketcham, 2005) for any thermal history required to explain the AHe data are older than 200 Ma, whereas the observed AFT ages of samples GGU438707 and GGU438713 are 134 and 143 Ma, respectively. This is not a problem for the highest elevation sample (GGU438711), because it could conceivably have resided at (or been reheated to) a temperature between the AFT and AHe closure temperatures between 836 and 250 Ma. But the three underlying samples all require temperatures less than about 70 °C since 250 Ma, which should result in AFT ages at least this old.

Conversely, although the model thermal histories required to produce the AFT ages and track length distributions (scenario b discussed in the AFT interpretation section) do indeed predict crystal-size–age correlations for some of the AHe samples, they are weaker than observed, and the predicted AHe ages are much younger than observed, due to the higher temperatures required in the AFT models. For example, using the AFT-derived thermal history for sample GGU438711 predicts AHe ages of 165–184 Ma (for $R_{e}$ of 35–70 $\mu$m) compared with observed ages of 213–242 Ma; for sample GGU438712 predicted ages are 54–110 compared with 217–250 Ma; for sample GGU438707 predicted ages are 12–19 Ma compared
with 21–102 Ma; for sample GGU438713 predicted ages are 12–18 Ma compared with 102–150 Ma. It is important to note that the problem of AHe ages significantly older than predicted by AFT-derived thermal models exists not only for the two samples with variable (and crystal-size correlative) AHe ages, but also for both high elevation samples, which have reproducible and old AHe ages.

To summarize, thermal histories required to explain the AFT data consistently predict AHe ages that are significantly younger than observed, and thermal histories required to explain the AHe data consistently predict AFT ages that significantly older than observed. Put simply, there is a mismatch between the thermal models from the two methods. There is no obvious evidence for analytical effects that could lead to “too-old” AHe ages such as microscopic inclusions or preferential proximity of apatites near high U–Th phases in these rocks (although careful petrographic analyses to confirm this have not been done). Samarium contents were not routinely measured on apatites in the Yale lab during the period in which these samples were analyzed, and this could conceivably lead to overestimates of the AHe ages. However, it is unlikely that accounting for $^{147}\text{Sm}$-produced $^4\text{He}$ would increase these AHe ages more than a few percent at most, because experience from subsequent analyses of a large number of apatites from many different locations, as well as other work (e.g., Carter, 2003), shows that in the vast majority of cases Sm only contributes more than 1–2% of He when U concentrations are significantly lower than they are in nearly all of these samples.

Another possible origin of at least some of the discrepancy lies in the combined effects of alpha-ejection and He diffusion on apatites that have resided for long periods of time in the AHe PRZ. In such cases, substantially decreased rates of diffusive He loss can arise from modification of the He concentration profile by alpha-ejection near the crystal margin, causing application of a standard alpha-ejection correction to effectively overcorrect He ages (Farley, 2000; Meesters and Dunai, 2002b; Lorencak et al., 2004; Ketcham, 2005; Dunai, 2005). Using numerical simulations, Farley (2000) showed that at least for certain thermal histories this phenomenon has the effect of increasing the AHe closure temperature by only $∼2$ °C, which would be negligible for many thermal histories. However, Meesters and Dunai (2002b) and Dunai (2005) have noted that for thermal histories involving prolonged residence in the He PRZ, the effect of alpha-ejection on He diffusion can lead to ages that are as much as 10–20% older than ages without alpha-ejection, and forward modeling using Ketcham’s (2005) HeFTy code, which accounts for the effect in a mathematically different but equivalent way, confirms this. In practice it is not straightforward to account for the apparent over-correction in applied alpha-ejection corrections that could potentially arise for grains with certain thermal histories, without independent constraints on the thermal history itself. In theory, thermal histories could be constrained, a priori, from AFT models or geologic constraints (e.g., Lorencak et al., 2004), but this assumes that the latter are well calibrated and accurate. Perhaps more importantly for the present problem, even decreasing the AHe ages of all the samples in this study by a relatively extreme $∼20\%$, still results in AHe ages that are considerably older than predicted by AFT-derived thermal models, so this phenomenon alone cannot account for the discrepant AHe and AFT data. We also note that even if the AHe ages of the lower elevation samples in this study are significantly affected by the interaction of alpha-ejection and He diffusion and do require downward age estimates, this supports one of the main interpretations of the study—that the lower elevation samples resided in the He PRZ (depths of $∼1$–2 km) until recently (since 20 Ma or later).

Several recent empirical studies have also found evidence suggesting that in slowly-cooled rocks with old cooling ages such as some cratons, AHe ages are sometimes older than AFT ages (inconsistent with expectations based on their relative diffusion and annealing kinetics) or thermal histories from AHe data predict older AFT ages than observed (Hendriks, 2003; Lorencak, 2003; Belton et al., 2004; Crowhurst et al., 2004; Hendriks and Redfield, 2005; Söderlund et al., 2005). At this point it is unknown whether the AFT ages are “too-young” or the AHe ages are “too-old”, or both. Further, it is not clear whether this discrepancy only develops in samples with long-term low-temperature thermal histories, or if the discrepancy is always present but only becomes apparent and clearly resolvable in these cases.

There are suggestions that AFT annealing at low-temperatures over long time periods is greater than commonly assumed in some models (e.g., Vrolijk et al., 1992). However, the fanning curvilinear model of Ketcham et al. (1999) that was used in the HeFTY (Ketcham, 2005) modeling described above, predicts low-temperature annealing consistent with the results of Vrolijk et al. (1992), and its use for inversion in general does not lead to spurious late cooling episodes sometimes obtained when other annealing models are employed. Because the HeFTy modeling shows similar
discrepancies between the AFT- and AHe-derived thermal histories for these samples, simply using an annealing model that satisfies Vrolijk et al.’s (1992) results does not solve the problem. More significant long-term, low-temperature annealing effects have been proposed by Hendriks and Redfield (2005), who suggested that AFT annealing may be enhanced as the result of radiation-induced lattice restoration, which would be apparent in samples with older cooling ages.

On the other side of the issue, however, Crowley et al. (2002) suggested that older-than-expected AHe ages from the cratonic Wyoming Province may be due to increased He retentivity in apatites with long-term low-temperature histories. A He diffusion experiment from some of these same apatites showed higher He retentivity than Durango, consistent with this (Reiners and Farley, 2001). Farley (2000) also proposed that some features of step-heating He diffusion experiments in apatite could be explained by a correlation between defects arising from radiation damage and He retentivity, so that fission-track abundance in apatite may scale with He retentivity and thus closure temperature.

At this point we do not have a preferred interpretation for the origin of the discrepancy between thermal histories required by the AFT and AHe data from southern East Greenland, and we note that reasonable explanations for miscalibration of both AFT annealing and He retentivity have been proposed for samples held at low-temperatures for long periods of time. The discrepancy posed by these results may contribute to the ongoing debate about how to reconcile the thermal sensitivities of these two systems. We also note that regardless of this discrepancy, however, several important qualitative features of the thermal histories are the same, including a period of rapid cooling in the late Cenozoic consistent with recent incision to create the modern topography.

6. Conclusions

Apatite fission-track and (U–Th)/He ages from the coastal region of southern East Greenland (62°N–67°N) range from 60 Ma (20 Ma if Tugtilik is included) to 840 Ma, and 21 to 250 Ma, respectively, and generally increase with elevation and distance from the coast. Taken together, the data are consistent with a relatively simple thermal history involving slow cooling through the Paleozoic (although multiple heating and cooling cycles from burial and exhumation cannot be ruled out), followed by increased cooling rates inferred to represent regional exhumation, which may have created a widespread low-relief landscape, between about 250 and 200 Ma. Abundant ∼200-Ma AFT ages, remnants of relatively subdued relief, and similar model temperatures in the Skjoldungen area may reflect little topographic change in this region since this time until Neogene exhumation. Both fission track length distributions and age–elevation relationships and crystal-size–age correlations in low-elevation samples for the AHe system are also consistent with either slow cooling or reburial and exhumation from ∼250–200 Ma through most of the Cenozoic, followed by an episode of more recent rapid cooling occurring sometime after ∼20 Ma. The outer coast in the Skjoldungen region may have been covered by some hundred meters of pre-breakup deposits. Relationships between AHe age, elevation, and crystal sizes in the Kangertittivatsiaq region suggest that samples currently exposed at low elevations cooled from temperatures of about 35–55 °C, depending on the model, some time more recently than ∼20 Ma. For typical geothermal gradients, this implies exhumation from pre-20-Ma depths of about 1.2–1.8 km. This may reflect localized incision of the topography, possibly associated with glacial erosion, starting at 7 Ma.

Taken together, although the general qualitative features of the exhumation histories derived from the AFT and AHe data are consistent, the specific thermal histories derived from each are not, assuming conventionally accepted thermal sensitivities of both systems. AFT-derived histories predict AHe ages younger than observed, and AHe-derived thermal histories predict AFT ages older than observed. This discrepancy persists even when the potential effects of interaction between alpha-ejection and He diffusion are considered, indicating an underlying problem with thermal-sensitivity calibration for one or both systems. Similar observations have been made in other cases with old cooling ages and slow-cooling histories, and may be due to the effects of increased He retentivity or increased track annealing (or both) in such cases.

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