Late Mesozoic–Cenozoic exhumation history of northern Svalbard and its regional significance: Constraints from apatite fission track analysis

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Abstract

The late Mesozoic–Cenozoic was a time of profound tectonic activity in the Arctic, with incipient spreading in the Arctic Ocean, Baffin Bay–Labrador Sea and North Atlantic, as well as the northward movement of the Greenland microplate leading to collision and deformation in Greenland, Arctic Canada and Svalbard (Eurekan Orogeny). It is, however, still unclear, how northern Svalbard, situated at the northwestern edge of the Barents Sea, was affected by these processes. Furthermore, northern Svalbard has been proposed to have been a Cretaceous–Cenozoic sediment source to surrounding regions because it lacks a post-Devonian sedimentary cover. When erosion took place and how that related to the tectonic history of the Arctic, is yet unresolved. In order to reconstruct the erosion history of northern Svalbard, we constrained its thermal evolution using apatite fission track (AFT) thermochronology. Our data reveal AFT ages between 62±5 and 214±10 Ma, recording late Mesozoic–early Paleogene exhumation. Our data show that northern Svalbard was emergent and experienced erosion from the Early Jurassic and presumably through the Cenozoic, although total exhumation was restricted to ~6 km. Pronounced exhumation took place during Jurassic–Cretaceous time, probably linked to the extensional tectonics during the opening of the Amerasian Basin (Arctic Ocean). In contrast, Cenozoic ocean basin formation and the Eurekan deformation did not cause significant erosion of northern Svalbard. Nonetheless, AFT data show that Late Cretaceous–Early Paleocene fault-related exhumation affected some parts of northern Svalbard. Fault zones were reactivated due to the reorganization of Arctic landmasses during an early phase of the Eurekan deformation, which implies that this episode commenced ~20 m.y. earlier in Svalbard than previously understood.

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1. Introduction

Svalbard occupies a key position at the hinge zone between the passive margins of the Eurasian Basin and the Norwegian–Greenland Sea, forming the northwesternmost emergent area of the Barents Shelf (Fig. 1). The formation of the Amerasian Basin, Eurasian Basin and Norwegian–Greenland Sea, is associated with Late Cretaceous–Paleocene convergence between Greenland and Eurasia that led to the Eurekan Orogeny (De Paor et al., 1989).

The geology of the archipelago can be divided into three distinct areas: northern Svalbard (passive margin of the Eurasian Basin), where mainly Proterozoic basement rocks and remnant Devonian sandstones are exposed, which is dissected by major N–S trending fault zones; the West Spitsbergen Fold Belt, formed during the Eurekan deformation along the western rim of Svalbard; and the Central Tertiary Basin within southern and central Svalbard, representing the foreland basin of the West Spitsbergen Fold Belt and comprising basement units overlain by Paleozoic to Cenozoic cover strata.

Western Svalbard is more mountainous compared to southern–central Svalbard, which is shaped by high but low-relief mountain tops. Within northern Svalbard relief changes from a low-elevation platform-like morphology at the northern coastline and northeastern platforms to higher amplitudes in central and northwestern Svalbard. The highest elevations can be found in the Newtontoppen area located within southern Ny Friesland where elevations are up to 1713 m (Fig. 2). These marked differences in elevation and relief across present-day Svalbard (Fig. 2C and D) point to a complex exhumation history. Significant exhumation and erosion of the West Spitsbergen Fold Belt caused by the Eurekan deformation are dated as being Eocene–Oligocene (Blythe and Kleinspehn, 1998), resulting in the development of pronounced relief. By contrast, the low relief areas that now form northern Svalbard would imply minor erosion. Hence,
it is unknown to what extent northern Svalbard was affected by the Eurekan deformation or how this might have been influenced by the major N–S trending fault zones, which are generally believed to have experienced repeated phases of reactivation (e.g., Andresen et al., 1992; Haremo and Andresen, 1988; Haremo et al., 1993; McCann and Dallmann, 1996). Indirect evidence from adjacent sedimentary basins (e.g., the Central Tertiary Basin and the Sophia Basin; Fig. 1) suggest that northern Svalbard was a significant source of sediment during the Cretaceous and Cenozoic because unconformities indicate erosion or at least non-deposition across the northwestern Barents Shelf at that time (Dallmann, 1999; Maher, 2001; Midtkandal and Nystuen, 2009; Worsley, 2008). However, there is no direct evidence to constrain the extent, thickness and timing of erosional exhumation of post–Devonian cover rocks in northern Svalbard. The only field constraints relate to Miocene basalts that unconformably cover Devonian and basement rocks (Dallmann, 1999; Harland, 1997). Their presence means that any removal of Paleozoic–Cenozoic strata from northern Svalbard must predate 10 Ma.

The core aims of this study are to understand the burial and exhumation history of northern Svalbard, and more specifically to determine (i) the timing and rates of exhumation of the northern Svalbard basement provinces, (ii) the role, if any, of the major faults, (iii) the extent of any late Mesozoic–Cenozoic sedimentation, and (iv) the impact of the late Mesozoic–Cenozoic basin formation episodes around Svalbard, as well as the Eurekan deformation on the exhumation and erosion history of Svalbard. To meet these aims we conducted an apatite fission track (AFT) thermochronology study of basement rocks because this method is sensitive to exhumation-driven cooling in the upper 2–6 km of the crust (geothermal gradient 20–30 °C/km).

2. Geological setting

2.1. Geodynamic evolution of Svalbard and the northwestern Barents Shelf

The Arctic Ocean is subdivided by the Lomonosov Ridge into the late Mesozoic Amerasian and the Cenozoic Eurasian Basins (Fig. 1). Svalbard is positioned on the northwestern edge of the Barents Shelf between the passive margins of the Eurasian Basin and the Norwegian–Greenland Sea, part of the North Atlantic Ocean. During the Scandan phase (425–395 Ma) of the Caledonian Orogeny the basement terrains of Svalbard were assembled along large fault zones, which were repeatedly reactivated during later tectonic phases (e.g., Haremo and Andresen, 1988; Harland, 1997; Manby et al., 1994; Ringset and Andresen, 1988). Subsequently, the Caledonian basement was subject to erosion during the Early Devonian, as well as the Late Devonian Svalbardian deformation (Harland, 1997). Eroded material was deposited as the Old Red Sandstone of the adjacent Devonian Basin (Gjelsvik, 1991). The initial break-up of Pangea, marked by Early Jurassic spreading within the Central Atlantic Ocean (~175 Ma; e.g., Klitgord and Schouten, 1986) initiated the redistribution of the modern Arctic landmasses (e.g., Lawver et al., 2002). The tectonic evolution of the Amerasian Basin is still under debate (e.g., Lane, 1997; Vogt et al., 1982 and references therein) but it is agreed that its formation and associated magmatism dominated the tectonic evolution of the northwestern Barents Shelf region during the Cretaceous. Volcaniclastic material likely derived from magmatic sources located to the north was deposited across central and southern Svalbard during the Early Cretaceous (Helvetiafjellet Formation, e.g., Harland (1997)). Maher (2001) and Midtkandal and Nystuen (2009) also suggested that Svalbard might have been part of this source area. A regression related to the formation of the Amerasian Basin formed a subaerial Early Cretaceous unconformity preserved within the sedimentary strata of the Central Tertiary Basin of Svalbard (Maher, 2001; Midtkandal and Nystuen, 2009). Erosion or non-deposition across the northwestern Barents Shelf is indicated by a major Late Cretaceous hiatus separating the Lower Cretaceous from the overlying Paleogene strata of the Central Tertiary Basin (e.g., Harland, 1997; Maher, 2001).

Rifting commenced in the Labrador Sea southwest of Greenland during the Late Cretaceous followed by the onset of seafloor spreading in the Paleocene (Chalmers, 1991; Chalmers and Laursen, 1995; Chalmers and Pulvertaft, 2001; Roest and Srivastava, 1989). Simultaneous spreading in Baffin Bay, Labrador Sea and the North Atlantic caused a northward drift of Greenland starting ~55 Ma (Saalmann et al., 2005; Tessensohn and Piepjohn, 2000). This led to deformation...
in Northern Greenland, Svalbard and Ellesmere Island, resulting in the latest Paleocene–Eocene formation of the West Spitsbergen Fold Belt on Svalbard (starting ~56 Ma; Saalmann et al., 2005) and the Eurekan Orogen on Greenland and in the Canadian Arctic Islands (starting ~53 Ma; Tessensohn and Piepjohn, 2000). For this study we refer to the Paleogene deformation of Arctic Canada, Greenland and...
Svalbard linked to northward movement of Greenland as Eurekan deformation.

Subsidence of the associated foreland Central Tertiary Basin provided accommodation space for deposits from northern and western Svalbard, reaching a km-scale thickness as indicated by the presence of hard coals within Paleocene and Eocene strata (Harland, 1997). Coevally, seafloor spreading of the Eurasian Basin commenced around 55 Ma (Kristoffersen, 1990; Vogt et al., 1979) and separated the Lomonosov Ridge from the northern Barents Shelf, thus placing Svalbard again in a passive margin setting (Brozena et al., 2003). The Sophia Basin between northern Svalbard and the Yermak Plateau is thought to have formed during the Cretaceous as a failed rift during the early phase of Eurasian Basin opening. The Sophia Basin comprises ~9 km of Cretaceous to Pleistocene sedimentary rocks (Geissler and Jokat, 2004). The northward drift of Greenland ceased while spreading within the Eurasian Basin continued, which finally led to the opening of the Fram Strait separating Svalbard from Greenland by Oligocene time (Engen et al., 2008; Tessensohn and Piejohann, 2000) (Fig. 1).

2.2. Regional geology of northern Svalbard

Northern Svalbard is bordered by the Central Tertiary Basin to the south, the West Spitsbergen Fold Belt toward the southwest, and the shelf areas of the Norwegian–Greenland Sea, the Eurasian Basin, and the Barents Sea toward the west, north and east, respectively. Major N–S trending fault zones (e.g., the Billefjorden and Lomfjorden Fault Zones, Fig. 2), some of them dating back to the Caledonian assembly of Svalbard, subdivide the region into distinct terrains: Albert I Land and Haakon VII Land on northwestern Spitsbergen; Andrée Land on central Spitsbergen, comprising mainly of outcrops of the Devonian Basin; Ny Friesland and Olav V Land on northeastern Spitsbergen; Nordaustlandet lies furthest east. Exposed bedrock in these terrains comprises Proterozoic basement units and Devonian Basin sandstones, plus some Carboniferous to Upper Triassic sedimentary rocks within southwestern Nordaustlandet, southeastern Ny Friesland and Olav V Land. The basement units also contain post-tectonic Caledonian granites, such as the Hornemanntoppen Granite (zircon Pb evaporation method, 424±56 Ma (Balasov et al., 1996)) and the Newtontoppen Granite (K–Ar biotite ~400 Ma (Gayer et al., 1966)) (Fig. 2). Within parts of Andrée Land, and locally also in Ny Friesland, the Proterozoic basement and Devonian strata are unconformably overlain by Miocene basaltic (Seidjfellet Formation, Dallmann, 1999; Harland, 1997). The basalt of Ny Friesland, first described by Tebenkov and Sirotkin (1990), was dated by the K–Ar method that yielded an age of 8.7 Ma (Prestvik and Ohta, pers. comm. cited in Dallmann, 1999), whereas basaltic capping mountain tops within Andrée Land yielded ages between 10.4±1.1 and 11.5±1.2 Ma (K–Ar dating; Prestvik, 1978). This indicates that at least parts of northern Svalbard were exposed to the surface during the Late Miocene.

3. Method and sampling strategy

AFT thermochronology is based on the spontaneous decay of $^{238}$U, which creates lattice defects within the crystal, accumulating over time. These fission tracks are semi-stable features that anneal due to diffusion when exposed to elevated temperatures over time. For the more common fluorine-rich apatites total annealing takes place when temperatures exceed 100–120 °C for durations $>10^7$ yrs, whereas only limited annealing ($<10\%$) occurs when temperatures are kept below 60 °C (Gleadow and Duddy, 1981; Spiegel et al., 2007). Tracks partially anneal during the passage through the temperature range of 60 to 120 °C (Partial Annealing Zone (PAZ)). The extent of annealing experienced by a sample can be assessed from the length of the fission tracks, which in most cases relates to cooling from crustal depths in the range between 2 and 6 km (geothermal gradient 20–30 °C/km). The timing and rate of cooling (thermal history) can be recovered from the AFT data (AFT age, track length distribution and apatite grain compositions) using forward and inverse modeling procedures that incorporate algorithms that describe the track annealing process in apatite for a given composition (e.g., Ketcham et al., 2007). The cooling history can then be converted into exhumation rates by using measured or assumed geothermal gradients.

Sampling for this study was carried out during field expeditions in 2007 (expedition CASE10 operated by the German Federal Institute for Geosciences and Natural Resources) and in the 1990’s (Swedartic expeditions, Sweden, and Polar Marine Geological Research Expedition, Russia). Samples were taken along transects across northern Svalbard and the major N–S trending fault zones. This allows us to infer the eventual throw accommodated by these faults and the timing of active faulting. Sampling vertical profiles in order to constrain exhumation rates was difficult because of the flat morphology within most parts of northern Svalbard and local conditions, such as ice cover. The best samples for such an approach were those collected from the Newtontoppen area covering an altitude difference of around 750 m (844 to 1596 m) and a horizontal distance of ~11.5 km. The remaining samples were taken at elevations of 0 to 250 m (Nordaustlandet), 91 to 537 m (Ny Friesland), and 342 to 493 m (Albert I Land).

4. Results of apatite fission track analysis

Twenty-eight samples from northern Svalbard (Albert I Land, Ny Friesland and Nordaustlandet) were analyzed and the results are shown in Table 1 (see also Appendix A). AFT central ages display an overall spectrum from 62±5 to 214±10 Ma, with the oldest AFT ages found on eastern Nordaustlandet (114±17 to 214±10 Ma); while the youngest age (62±5 Ma) was measured in the westernmost parts of the Newtontoppen area (southern Ny Friesland). Similar young ages, around 75 to 82 Ma, were also derived from southwestern and northern Ny Friesland, as well as from the Hornemanntoppen Granite (Albert I Land). $\chi^2$ test values $>5\%$ indicate a single age population for most samples. Only three samples failed the $\chi^2$ test, but these do not show significant overdispersion and therefore can be effectively regarded as single age populations. AFT age spectra from the different sampled provinces are wide and largely overlap each other. Ages from Albert I Land range from 78±6 to 108±5 Ma, ages from Ny Friesland from 75±9 to 175±30 Ma, and from Nordaustlandet from 114±17 to 214±10 Ma. The AFT ages show no clear correlation with sample elevations. Within Albert I Land, ages show a smaller age range in comparison to Ny Friesland and Nordaustlandet and imply a slight age trend toward younger ages in the northwest of Svalbard. Samples with elevations between 0 and 537 m show a more or less continuous pattern across the major fault zones (Fig. 3). An exception, however, is the Newtontoppen area, which lies on the highest elevations of the sampled provinces between 844 and 1596 m and comprises the youngest ages of 62±5 to 84±5 Ma. As a result, the Newtontoppen Granite exhumed later through the PAZ than other parts of northern Svalbard. Differential vertical motion offsetting the Newtontoppen Granite against the surrounding areas was likely fault controlled, given the nearby locations of the Veteranen Line and Lomfjorden Fault Zone (see Fig. 2). Further, samples from western and northern Ny Friesland show AFT ages decreasing toward the Billefjorden Fault Zone and Veteranen Line. We interpret this as an effect of motion along these fault zones.

Sampling was difficult at Newtontoppen so that it was not possible to collect more than three samples. AFT ages (62±5 to 84±5 Ma) show a negative correlation with sample altitude (Fig. 4). Such an unusual trend can have a variety of causes. Differences in grain composition, which can be ruled out for the Newtontoppen, cause variations in the annealing behavior, and thus in the central ages of the samples. Further, relief changes during exhumation may result in a negative age-elevation relationship (Braun, 2002). This explanation
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<td>Granite</td>
<td>50</td>
<td>10</td>
<td>1.2</td>
<td>6679</td>
<td>5.3</td>
<td>14.1</td>
<td>494</td>
<td>1327</td>
<td>17.85</td>
<td>47.37</td>
<td>0.25</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1**

Results of AFT analyses: ¹ages calculated using dosimeter glass IRMM540, analyst N.D. (IRMM = 304 ± 10, irradiated at FRMII); ²ages calculated using dosimeter glass CNS, analyst A.C. (CNS = 339 ± 5, irradiated at Risø) calibrated by zeta calibration approach ([Hurford, 1990]) and external detector method ([Gleadow, 1981]). Central age is a modal age, weighted for different accuracies of individual crystals ([Galbraith and Laslett, 1993]). N — number of crystals, ρ — track density, ρd — dosimeter track density, Nd — number of tracks counted on dosimeter, ρd N (μm) — spontaneous (induced) track densities, χ2 — probability for obtaining χ2 value for v degrees of freedom, where v = no. of crystals – 1, N(L) — number of tracks measured, MTL — mean track length, calculated from c-axis unprojected track lengths, SD — standard deviation.
also appears unlikely, because evidence for Late Cretaceous–Early Paleocene relief changes has not been observed in any part of northern Svalbard. Consequently, we favor faulting along the larger fault zones, coeval with exhumation, as the most likely cause for internal dissection of the Newtontoppen area. This is in good accordance with field observations of strike-slip faulting between the Veteranen Line and Lomfjorden Fault Zone (Piepjohn, 2010, pers. comm.).

Track length measurements from twenty-five of the samples gave mean track lengths (MTL) between 10.4 and 14.4 μm (without c-axis projection) with a simple unimodal distribution in most cases (see Appendix B). Some distributions are skewed toward shorter track lengths (e.g., SV14, SV06, CX48, and CX14), which indicate that these samples resided longer within the higher temperature region of the PAZ. We used both Dpar values and chlorine contents of apatites as kinetic indicators. Electron microprobe analyses yield mean values between 0.0025 and 0.106 wt.% chlorine indicating near fluorine-apatite end member for the samples. Mean Dpar values range between 1.3 and 1.8 μm, all with relatively low SD values (<0.2 μm). Kinetic indicators thus indicate homogeneous annealing characteristics for all samples (see also Appendix A).

Fig. 5 shows MTL plotted against AFT ages (Green, 1986). Samples with long MTL delineating periods of enhanced cooling cluster within two age groups: an older age group with Mid Jurassic to Early Cretaceous ages obtained from samples from Nordaustlandet and Ny Friesland. In contrast, samples from Albert I Land and Newtontoppen, as well as from western and northern Ny Friesland, yielded AFT ages belonging to a younger, Late Cretaceous to Paleocene age group. Furthermore, samples from Albert I Land show a negative correlation between decreasing MTL (13.5 to 11.5 μm) and increasing AFT ages (~80 to ~110 Ma). We interpret this trend to be the result of faulting, presumably after 70 Ma, offsetting samples with different thermal histories against one another.

Fig. 3. The upper part of the figure shows the AFT ages of the samples according to their position from west to east and the position of the major fault zones (dashed lines). Black symbols indicate samples close to the northern coast of north Svalbard; gray symbols are samples from southwestern Ny Friesland and the Newtontoppen area. The lower part of the figure shows the topography along the northern coast of northern Svalbard (black line; along cross-sections A – A’ and B – B’ – B” in Fig. 2) and southwestern Ny Friesland and the Newtontoppen area (schematic; gray line) to show the differences in elevation between the samples. Note the high elevations but young AFT ages of the samples from the Newtontoppen. BF — Breibogen Fault Zone, BFZ — Billefjorden Fault Zone, LFZ — Lomfjorden Fault Zone, RF — Raudfjorden Fault Zone, VL — Veteranen Line.

Fig. 4. Samples from the Newtontoppen area show a negative trend of AFT ages with increasing elevation. The most likely of several explanations appears to be an internal dissection of the area (schematic sketch above). Samples might be offset along east-dipping normal faults linked to strike-slip faulting between the Veteranen Line and Lomfjorden Fault Zone. See text for further explanation.
heating to temperatures and information on the earlier history was lost by pre-late Mesozoic during the Devonian with subsequent reburial as indicated by the AFT system had been reset. The occurrence of clasts from the Caledonian Orogeny, which is the last time when we can be confident that the AFT system had been reset. The start of the thermal history for all samples considered was set to high temperatures during the Caledonian Orogeny, which is the last time when we can be confident that the AFT system had been reset. The occurrence of clasts from the basement of Albert I Land within the Devonian Basin sandstones indicates that the basement must have been exhumed to surface levels during the Devonian, although the absolute magnitude of exhumation is not clear. To further explore this process, two different cooling histories were modeled: (i) simple cooling from high temperatures (>120 °C); (ii) exhumation to near surface temperatures (<60 °C) during the Devonian with subsequent reburial as indicated by the late Paleozoic to early Mesozoic sedimentary rocks preserved in central and southeastern Svalbard. However, the pre-Mesozoic to early Cenozoic thermal history is poorly constrained from the AFT data and information on the earlier history was lost by pre-late Mesozoic heating to temperatures ≥120 °C. Consequently thermal histories are dominated by the most recent cooling during the late Mesozoic–early Cenozoic. The occurrence of Miocene basaltic and volcanic rocks unconformably overlayers parts of the Devonian Basin and Caledonian basement units within Ny Friesland indicates that the basement of southwestern Svalbard had again reached surface levels by ~10 Ma. This information was also used as a constraint for thermal history modeling. Finally all models end with the rocks at 0 to 5 °C at 0 Ma. Because kilometer-thick Paleogene strata within the Central Tertiary Basin of Svalbard indicate substantial deposition, at least in that part of Svalbard, thermal history models were also tested for Cenozoic reburial in northern Svalbard. AFT data are in agreement with Cenozoic reheating (re-burial) to ~60 °C, but this is not required within the uncertainties of the model.

Mean cooling rates for the time samples exhumed through the PAZ vary between 0.4 and 6 °C/m.y. amongst the different provinces. The onset and timing of cooling through the PAZ differ (Fig. 6) with the Newtontoppen area passing last through the PAZ in Late Cretaceous–Early Eocene time.

6. Implications for northern Svalbard

6.1. Late Mesozoic–Cenozoic erosion history of northern Svalbard

Because of the absence of post-Devonian cover strata, northern Svalbard may have been a significant source of sediment for the surrounding Cretaceous to Paleogene depocenters, such as the Central Tertiary Basin or the Sofia Basin. The results of this study provide the first direct evidence to support this interpretation. We find that all samples experienced substantial cooling throughout the late Mesozoic. The total depth of exhumation experienced by samples and the timing of the onset of cooling cannot be obtained from the AFT thermal history models, because exhumation initiated from temperatures higher than the PAZ, i.e. beyond the resolution of the method. But it is clear that circa 60 °C of cooling (from ~120 °C to 60 °C), equivalent to 2–3 km at a geothermal gradient of 20–30 °C/km, took place between the Early Jurassic and Late Cretaceous (later cooling for the Newtontoppen area is the only exception). A similar magnitude of cooling must have taken place since the Cretaceous, although it is possible that this may have been interrupted by deposition of Cenozoic sedimentary rocks. The latter could not have been thicker than ~2–3 km or reburial would have caused re-heating and produced much younger fission track ages and shorter mean track lengths than observed. Overall the data show that total exhumation since ~180–80 Ma is in the 4–6 km range. However, the nature of the eroded section is not clear. It may have comprised mostly basement rocks, or upper Paleozoic and Mesozoic cover strata. Preserved Upper Carboniferous to Upper Triassic–Upper Jurassic strata of southeastern and central Svalbard have thicknesses of ~3.0 to ~3.5 km (calculated from sediment thicknesses by Dallmann, 1999 and Harland, 1997), well within the estimated range of the eroded section.

The AFT data are unable to detect Cenozoic reheating by reburial because the rocks had cooled to <60 °C by this time and subsequently never exceeded this threshold (i.e., above the PAZ). As a result the thickness of any Cenozoic sedimentation on northern Svalbard must be less than ~2–3 km. Furthermore, the time span of any Cenozoic deposition is minimized to a few tens of millions of years. For example, northeastern Svalbard is assumed to have acted as a source for the Paleocene sediments of the Central Tertiary Basin until 55 Ma and that deposition ceased in Mid Oligocene in the basin (Harland, 1997). Miocene plateau basalts unconformably overlying the strata of the Devonian Basin and basement units of Ny Friesland further constrain the removal of any cover strata and/or basement to being older than ~10 Ma.

6.2. Impact of the Eurekan deformation and passive margin tectonics on the exhumation of northern Svalbard

The late Mesozoic to earliest Paleocene AFT ages of this study are in marked contrast to the Eocene–Oligocene ages of the West Spitsbergen Fold Belt (Blythe and Kleinspehn, 1998). Because AFT data from northern Svalbard do not display the thermal signature of the Eurekan deformation, we conclude that this region was generally unaffected by the Eurekan deformation, in the form of significant exhumation and erosion. Jurassic–Cretaceous exhumation of Albert I Land, Ny Friesland and Nordaustlandet coincides with the Mesozoic opening of the Amerasian Basin. Thus, although northern Svalbard was located far from the shelf break during the late Mesozoic because the Lomonosov Ridge was still attached to the Barents Shelf, rift flank uplift on the margin of the Amerasian Basin most likely has caused the late Mesozoic exhumation (Fig. 7).
Fig. 6. A–F Results of inverse thermal history modeling together with track length distributions. Time (Ma) is plotted against temperature (°C) for each sample. Panel G illustrates the differential timing of cooling of the single provinces based on the acceptable paths derived from thermal history modeling of all modeled samples. AL — Albert I Land, NA — Norraustlandet, NF — Ny Friesland, NT — Newtontoppen.
On the Alaskan side of the basin, where the tectonic evolution is much more complex compared to Svalbard (including, e.g., subduction), exhumation of northern Alaska and rift shoulder uplift along the Barrow Arch rift margin (~135 and ~100 Ma) were also attributed to the formation of the Amerasian Basin (Cole et al., 1997; O'Sullivan et al., 1997) (Fig. 1). Furthermore, the basin margins along the Canadian Arctic Islands developed during the late Mesozoic (Sweeney, 1985), although these, together with northern Greenland, were later overprinted by the Eurekan deformation. A comparison between Alaska and northern Svalbard reveals that exhumation related to margin uplift commenced slightly earlier along the Svalbard margin (onset of Nordaustlandet exhumation ~160 Ma; Fig. 6) than along the Alaskan margin of the Amerasian Basin (~135 Ma).

Because exhumation within the Barents Shelf started earlier toward the northeast (Green and Duddy, 2010) our data are consistent with other data in predating exhumation from the area of Bjørnøya (Fig. 1) where exhumation was dated between 90 and 60 Ma (Ritter et al., 1996). The summary thermal history models show that the earliest cooling took place in the Nordaustlandet region, followed by Ny Friesland and Albert I Land (Fig. 6G). This pattern of exhumation does not follow a simple trend across the island and must therefore reflect strong, local fault control on block exhumation. The deepest exhumation, and by implication most active faulted block, is that of the Newtontoppen area. The youngest AFT ages are found in this area, which is consistent with rapid cooling between 80 and 60 Ma (Fig. 5). Fault activities along the Billefjorden and southern Lomfjorden Fault Zones are assumed to be related to reactivation of the faults during Paleogene thrusting in western Svalbard (Harland, 1997), however the exhumation and dissection of the Newtontoppen in latest Cretaceous to Paleocene times imply an earlier reactivation of at least the Veteranen Line and Lomfjorden Fault Zone. Fault activities within northern Svalbard thus predate seafloor spreading in the Norwegian–Greenland Sea and the Eurasian Basin at 55 Ma, when the Lomonosov Ridge was separated from the Barents Shelf. As a result, faulting was likely related to the latest Cretaceous–earliest Paleocene reorganization of Arctic landmasses, probably associated with early plate movements driven by processes such as rifting in the Labrador Sea. Although the exhumation precedes the main phase of the Eurekan deformation this earlier fault-related exhumation in northern Svalbard may relate to an early stage of the Eurekan deformation. This in turn may indicate that the Eurekan deformation on Svalbard commenced at ~80 Ma, i.e. ~20 m.y. earlier than previously assumed. Furthermore, small-scale later...
reactivation of faults driven by transtension or extension during the separation of Svalbard from Greenland after ~34 Ma cannot be ruled out as a trigger for motion.

AFT analysis on the passive margins around the Atlantic and southern Australia (Gallagher and Brown, 1999; Gallagher et al., 1994; Kohn et al., 1999; O'Sullivan et al., 1995; Raab et al., 2005) showed that AFT ages significantly post-date the related rift event. Japsen et al. (2006; 2010) related episodic post-rift uplift as a delayed response to rifting. Differential extension of the mantle lithosphere and crust at extending plate boundaries could lead to imbalance of crustal forces resulting in uplift and exhumation as a regional response (Green and Duddy, 2010) with significant temporal and spatial separation between rifting and uplift. Green and Duddy (2010) and Japsen et al. (2006; 2010) outline phases of more or less simultaneous exhumation on the margins around the northern North Atlantic and Arctic Ocean during the Cenozoic and Japsen et al. (2006) further showed that relief development within west Greenland occurred much later than the final rifting event. In contrast, our new AFT data from northern Svalbard do not suggest that exhumation was a delayed response to rifting. The AFT data coincide well with the formation of the Amerasian Basin and predate the latest Cenozoic rifting events during formation of the Norwegian–Greenland Sea and Eurasian Basin. This pattern might be related to the fact that the formation of the Eurasian Basin and Norwegian–Greenland Sea did not cause much exhumation in northern Svalbard, which was instead linked to the ultraslow spreading within the Eurasian Basin. Although the Cenozoic exhumation history of northern Svalbard needs to be further constrained, AFT data from this study allow a better understanding of why exhumation may be delayed long after rifting.

7. Conclusions

In this study we tried to resolve the erosion history of northern Svalbard and relate it to the tectonic evolution of the Arctic realm. Our data and modeling show that samples from northern Svalbard yield AFT ages between $62 \pm 5$ and $214 \pm 10$ Ma. AFT ages and track length distributions indicate single-stage cooling through the upper 2–6 km of the crust (geothermal gradient of 20–30 °C/km) between the Jurassic and early Paleogene. The amount of the removed section is consistent with the amount of Paleozoic–Mesozoic strata preserved within central and southeastern Svalbard, indicating that most of the section removed was composed of sedimentary rocks not basement. The onset and rate of cooling vary between the single provinces, with exhumation prograding from the northeast. Our data provide the first direct evidence that northern Svalbard functioned as a sediment source to the surrounding basins, such as the Sofia Basin and Central Tertiary Basin, at least during the latest Mesozoic to earliest Paleogene. However, some later reburial and reheating up to ~60 °C cannot be precluded.

The late Mesozoic exhumation of northern Svalbard coincides with the opening of the Cretaceous Amerasian Basin. We therefore interpret this exhumation as a direct consequence of rift shoulder uplift along the margin of the Amerasian Basin. Exhumation along the Amerasian Basin seems to have been diachronous based on the fact that exhumation of northern Svalbard started earlier than in northern Alaska.

Our data do not record significant erosion related to the opening of the Norwegian–Greenland Sea and the Eurasian Basin, or to the Eurekan deformation on Svalbard. We therefore conclude that, in contrast to western Svalbard, the Eurekan deformation did not cause significant exhumation in northern Svalbard, and that exhumation driven by margin tectonics associated with the formation of the Eurasian Basin was minor.

However, an early phase of Eurekan deformation seems to have caused reactivation of major fault zones, leading to fault-related exhumation in some parts of northern Svalbard (e.g. Newtontoppen) during the Late Cretaceous–Early Paleocene, and the dissection of the Newtontoppen area. We therefore suggest that Eurekan deformation commenced ~20 m.y. earlier on Svalbard than previously assumed.

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Appendix A

The samples for this study were processed in cooperation between the laboratories of the University of Bremen and Birkbeck College London. Procedures vary partially according to laboratory routines. In both laboratories samples were prepared using standard separation, grinding and polishing techniques. All samples were prepared for the external detector method. AFT mounts were etched with 5 M HNO₃ at room temperature for 20 s and were irradiated in the thermal facilities of FRMII at Garching, Germany, and Risø Reactor at Roskilde, Denmark, together with dosimeter glasses IRMM540 and CN5, respectively. Mica plates of the CX coded samples were etched with 48% HF at room temperature for 16 min, and SV samples for 25 min. Fission tracks were counted and track lengths and Dpar measured using a Zeiss Axioplan with total magnifications of 1250×. Calibration followed the International Union of Geological Sciences recommended zeta calibration approach (Hurford, 1990). Samples with low uranium content were additionally irradiated with 152-Cf-derived fission fragments at the facilities of Melbourne University, Australia, to enhance the track density for confined length measurements. All samples were irradiated with a distance of 10 mm to the calibration source for 2.5 h. For the determination of chlorine contents of theapatite grains electron microprobe analysis was applied at Birkbeck College, London, using a JEOL 8100 Superprobe with 15 kV and a defocused beam with a diameter of 10 µm and a counting time of 20 s. Fluorine diffusion during the exposure of the beam was minimized by using a low beam current (12 nA) and a short counting time (Stormer et al., 1993). Durango apatites were used as an internal standard (0.39 wt.% chlorine (Barbarand et al., 2003)).

Appendix B

Track length distributions with lengths (µm) plotted against frequency for samples with more than forty confined track lengths measured. Distributions are all unimodal, in some cases skewed toward shorter track lengths indicating that samples resided longer within the higher temperature range of the PAZ.
measured. Kinetic parameters were used to calculate the initial track length of the analyzed apatites.

References


Late Mesozoic–Cenozoic exhumation history of northern Svalbard and its regional significance: Constraints from apatite fission track analysis, Tectonophysics (2011), doi: 10.1016/j.tecto.2011.10.007