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A fission track data compilation for Fennoscandia

Bart Hendriks, Paul Andriessen, Yvette Huigen, Callum Leighton, Tim Redfield, Glen Murrell, Kerry Gallagher and Søren Bom Nielsen

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A compilation of fission track data is presented here to show from where fission track data are available in Fennoscandia and to highlight potential targets for future research. Because of the relatively small number of fission track data for zircon and titanite, emphasis is put on apatite fission track data. Because of the constraints the apatite fission track database puts on vertical movements, it is a valuable tool for example for work on regional geomorphology and can be used as a baseline for onshore – offshore correlations. On the basis of sample elevation, rock type, apatite chemistry, analytical approach and data quality, a selection of apatite fission track ages and mean track lengths are presented to focus attention on first order patterns in the available datasets. The patterns of ages and mean track lengths are clearly representative of Mesozoic and Cenozoic vertical movements along the present-day Norwegian Atlantic margin, and of Paleozoic and older vertical movements further into the cratonic interior. Previously published interpretations of the available data are discussed here in brief. The current compilation will be updated when new data become available, and be available as an electronic supplement from the Geological Survey of Norway.

B.W.H. Hendriks and T. F. Redfield at Geological Survey of Norway, NO-7491 Trondheim, Norway. P.A.M. Andriessen, Y.D. Huigen and G.R. Murrell at Department of Isotope Geochemistry, Faculty of Earth and Life Sciences, Vrije Universiteit, 1081 HV Amsterdam, the Netherlands. C. Leighton at Department of Earth Science and Engineering, Imperial College London, SW7 2AZ London, United Kingdom. K. Gallagher at Géosciences, Université de Rennes 1, Rennes Cedex 35042, France. S.B. Nielsen at Århus University, Høegh-Guldbergsgade 2, DK-8000 Århus, Denmark. Corresponding author: B.W.H. Hendriks, bart.hendriks@ngu.no.

Introduction

Over 3 decades of fission track studies in Fennoscandia have resulted in a large regional database, which we summarise in this paper. During the 1970's and 1980's, fission track studies in Fennoscandia typically focussed on relatively small areas (Lehtovaara 1976; Van den Haute 1977; Koark et al. 1978; Andriessen & Bos 1986; Zeck et al. 1988; Andriessen & Verschure 1988; Andriessen 1990; Hansen et al. 1989). However, the absence of data between these isolated study areas imposed serious limitations on a regional interpretation. Beginning in the early 90's, a number of studies undertaken by doctoral students at the Vrije Universiteit Amsterdam produced regional datasets, each covering a large area (Rohrman 1995; Van der Beek 1995; Hendriks 2003; Murrell 2003; Huigen and Andriessen 2004). A similar approach was adopted by researchers from the universities of Göteborg, Sweden and Melbourne, Australia (Larson et al. 1999; Cederbom 2001; Lorencak 2003) and in ongoing work at Imperial College, London.

Sample locations from 677 fission track analyses for apatite, 40 for zircon and 24 for titanite are presented in Figure 1. Taken together, these data encompass a range of geological settings, from the passive Norwegian Atlantic margin in the west to the cratonic Archaean province in northwestern Russia and Finland in the east. Consequently, their combined distribution of fission track ages and mean track lengths can reveal, under appropriate circumstances, important geological information.

The purpose of this contribution is to depict broad trends in fission track data across the whole of Fennoscandia. Documenting offsets across individual structures, computing the amount of denudation that has occurred, or other geological problems are addressed in past and future publications by a wide variety of authors. The compilation provides a framework within which to collect and interpret new thermochronological data, enabling the thermochronological community to identify areas that deserve more attention. For example, closely-spaced transects that may help assess the influence of local topography or tectonic structures on cooling histories and hence better constrain regional exhumation.

On a first order scale, the pattern of Apatite Fission Track ages and Mean Track Lengths in Fennoscandia is clearly representative of Mesozoic and Cenozoic vertical movements along the present-day Norwegian Atlantic margin, and of Paleozoic and older vertical movements further into the cratonic interior. Because of the constraints the Fennoscandian Fission Track database puts on vertical movements, it is a valuable tool, for example, for work on regional geomorphology and can be used as a baseline for onshore - offshore correlations. With the new data from closely-spaced transects published in the last few years (e.g. Redfield et al. 2004; Redfield et al. 2005a,b), using fission track data as constraints on fault movements has also become feasible.

Because few zircon and titanite fission track data have been published, we have focussed primarily on Apatite

Table 1:

Area	Publication	Mineral / Method	Analyst	Comments
Finland	Lehtovaara (1976)	Apatite / POP	Lehtovaara	
	Larson et al. (1999)	Apatite / EDM	Stiberg	3 vertical profiles
	Lorencak (2003)	Apatite / EDM	Lorencak	Apatite (U-Th)/He, microprobe
	Murrell (2003)	Apatite / EDM	Murrell	Apatite (U-Th)/He, microprobe, Dpar, 2 vertical profiles
	Murrell & Andriessen (2004)	Apatite / EDM	Murrell	
Mid-Norway and Mid-Sweden	Rohrman (1995)	Apatite, Zircon / EDM	Rohrman, Andriessen	Siljan Gravberg1 Borehole (7.5 km)
	Larson et al. (1999)	Apatite, Zircon / EDM	Stiberg	1 vertical profile
	Cederbom et al. (2000)	Apatite / EDM	Cederbom	
	Huigen & Andriessen (2004)	Apatite / EDM	Huigen	2 vertical profiles
	Huigen (unpublished)	Apatite / EDM	Huigen	Apatite (U-Th)/He, 3 vertical profiles
Southern Sweden	Zeck et al. (1988)	Apatite, Titanite / EDM	Andriessen	
	Andriessen & Verschure (1988)	Apatite / EDM	Andriessen	
	Hansen et al. (1989)	Apatite / EDM	Haack, Dulski	
	Hansen (1995)	Apatite, Zircon / EDM	Hansen	
	Larson et al. (1999)	Apatite, Titanite, Zircon / EDM	Stiberg	3 vertical profiles
	Cederbom et al. (2000)	Apatite / EDM	Cederbom	
	Cederbom (2001)	Apatite / EDM	Cederbom	
Troms, Finnmark and Kola	Rohrman (1995)	Apatite, Zircon / EDM	Rohrman, Andriessen	Kola Super Deep Borehole (12 km)
	Green et al. (1996)	Zircon / Unknown	unknown	Kola Super Deep Borehole (12 km)
	Hendriks & Andriessen (2002)	Apatite / EDM	Hendriks	1 vertical profile
	Hendriks (2003)	Apatite / EDM	Hendriks	Apatite (U-Th)/He, microprobe, 1 vertical profile
	Murrell (2003)	Apatite / EDM	Murrell	Dpar
Northern Sweden	Koark et al. (1978)	Apatite / POP single XL	Märk	
	Hendriks & Andriessen (2002)	Apatite / EDM	Hendriks	2 vertical profiles
	Hendriks (2003)	Apatite / EDM	Hendriks	Apatite (U-Th)/He, 2 vertical profiles
Southern Norway	Van den Haute (1977)	Apatite / POP	Van den Haute	
	Andriessen & Bos (1986)	Apatite / POP, Zircon / EDM	Andriessen	
	Andriessen (1990)	Apatite / EDM	Andriessen	1 vertical profile
	Van der Beek et al. (1994)	Apatite / EDM	Rohrman, Andriessen	
	Rohrman et al. (1994)	Apatite, Titanite, Zircon / EDM	Rohrman, Andriessen	
	Rohrman (1995)	Apatite, Titanite, Zircon / EDM	Rohrman, Andriessen	3 vertical profiles
	Van der Beek (1995)	Apatite / EDM	Rohrman, Andriessen	
	Rohrman et al. (1995)	Apatite, Zircon / EDM	Rohrman, Andriessen	3 vertical profiles
	Hansen et al. (1996)	Apatite, Titanite / EDM	Hansen	
	Leighton (2007, in preparation)	Apatite, EDM	Leighton	Apatite (U-Th)/He, microprobe, vertical profiles
Møre – Trøndelag	Grønlie et al. (1994)	Apatite, Titanite, Zircon / EDM	Naeser	
	Redfield et al. (2004)	Apatite / EDM	Redfield	
	Redfield et al. (2005)	Apatite / EDM	Redfield	
Lofoten, Vesterålen, Nordland	Hendriks & Andriessen (2002)	Apatite / EDM	Hendriks	
	Hendriks (2003)	Apatite / EDM	Hendriks	Apatite (U-Th)/He, microprobe, 1 vertical profile
	Hendriks (2007, in preparation)	Apatite / EDM	Hendriks	Apatite (U-Th)/He, Dpar

Overview of available fission track datasets for Fennoscandia. POP, Population method for fission track dating. EDM, External Detector Method for fission track dating. Dpar, etch pit measurements. Previously unpublished data from Southern Norway (C. Leighton), Central Norway (Y.D. Huigen, B.W.H. Hendriks) and the Kola peninsula (G.R. Murrell) were made available for the purpose of this compilation.

Table 2:

Area	Publication	Vertical profile	Elevation range (m.a.s.l.)	Age range (Ma)
Finland	Larson et al. (1999)	Olkiluotto	-998 to -42	413 to 787
	Larson et al. (1999)	Kivyetti	-1011 to -55	290 to 605
	Larson et al. (1999)	Rumouvaara	-1085 to -1.5	543 to 900
	Murrell (2003)	Lavia	-829 to 88	155 to 464
	Murrell (2003)	Pori	-612 to -31	223 to 317
Mid-Norway and Mid-Sweden	Rohrman (1995)	Gravberg	-6111 to -246	13 to 397 (zircon: 560 to 620)
	Larson et al. (1999)	Gideå	-702 to -14	350 to 696 (zircon: 853 - 929)
	Huigen (unpublished)	Åreskutan	380 to 1420	171 to 225
	Huigen (unpublished)	Tjidtjakgaise	482 to 1587	206 to 283
	Huigen (unpublished)	Trofors	0 to 940	143 to 202
Southern Sweden	Larson et al. (1999)	Laxemar	-1696 to -3	206 to 340 (titanite: 711 to 820)
	Larson et al. (1999)	Fjällveden	-704 to -16	390 to 699 (zircon: 822 to 829)
	Larson et al. (1999)	Finnsjön	-665 to -15	324 to 542 (zircon: 666 to 892)
Troms, Finnmark and Kola	Rohrman (1995)	Kola Super Deep Borehole	-12207 to -1098	3 to 198 (zircon: 236 to 669)
	Green et al. (1996)	Kola Super Deep Borehole	-12052 to -7086	zircon: 271 to 537
	Hendriks (2003)	Tromsdalstinden	5 to 1238	189 to 241
Northern Sweden	Hendriks (2003)	Kiruna	-344 to 712	212 to 303
	Hendriks (2003)	Kebnekaise	575 to 2002	113 to 254
Southern Norway	Rohrman et al. (1995)	Jotunheimen	0 to 2465	106 to 175
	Rohrman et al. (1995)	Eidfjord	0 to 1620	98 to 181
	Rohrman et al. (1995)	Gausta	480 to 1845	158 to 248
	Andriessen (1990)	Hunnedalen	670 to 950	164 to 263
	Leighton (in preparation)	Aurland	0 to 1269	113 to 203
	Leighton (in preparation)	Eidfjord	0 to 1080	145 to 177
	Leighton (in preparation)	Outer Sognefjord	0 to 622	181 to 229
Lofoten, Vesterålen, Nordland	Hendriks (2003)	Higravtinden	150 to 1090	144 to 173

Overview of fission track data from vertical profiles (age vs. elevation profiles) in Fennoscandia. The age range indicated is for apatite fission track data, unless otherwise indicated.

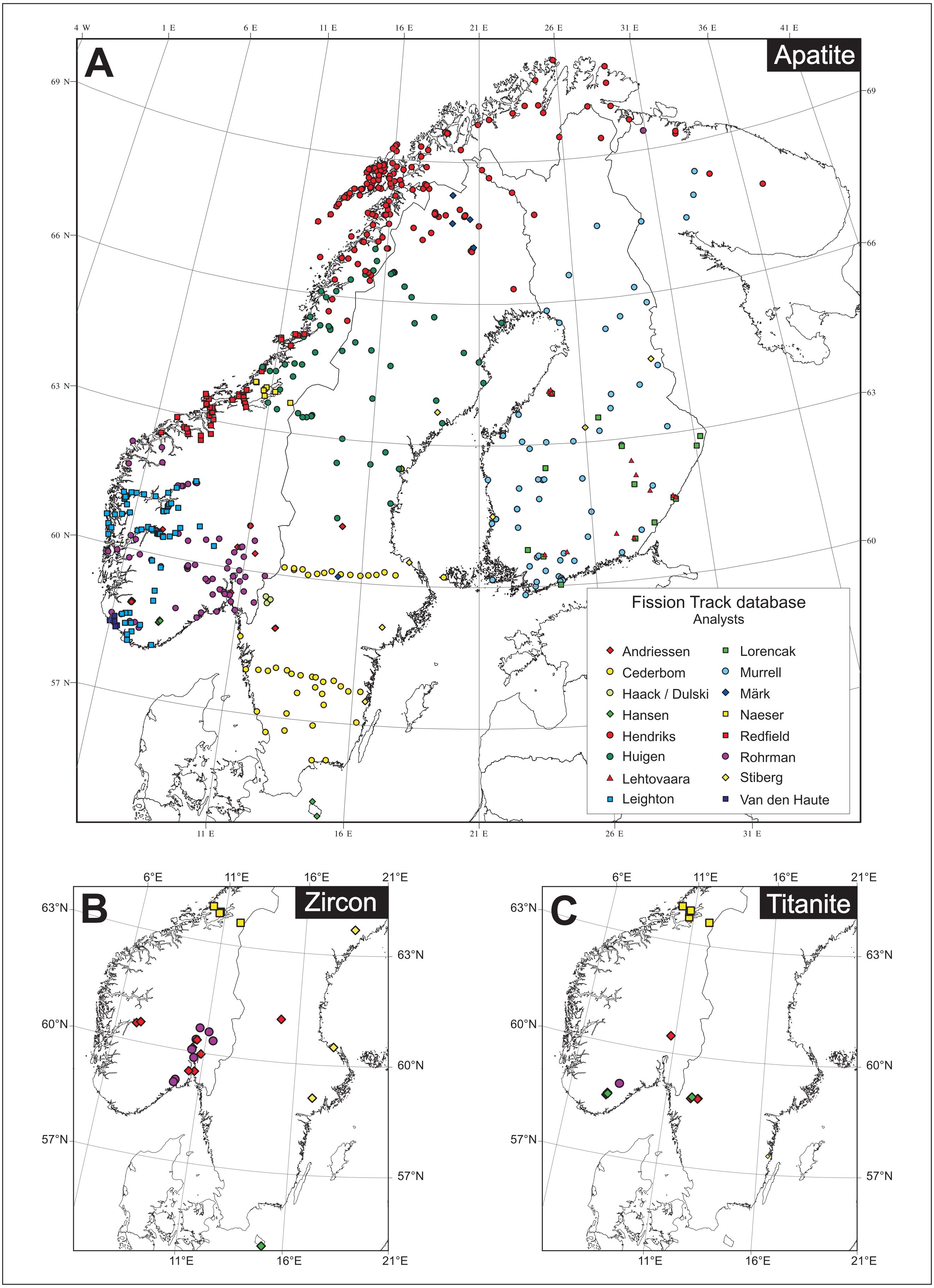

Fig. 1: Sample locations for Fennoscandian fission track data. (a) Apatite fission track. (b) Zircon fission track. Zircon fission track data are also available from the Kola Super Deep Borehole. (c) Titanite fission track. Legend in (a) applies to all three maps. Spatial reference: WGS84, Gauss-Krueger, central meridian 21°E, Latitude of Origin 63°N, false easting 1500 km.

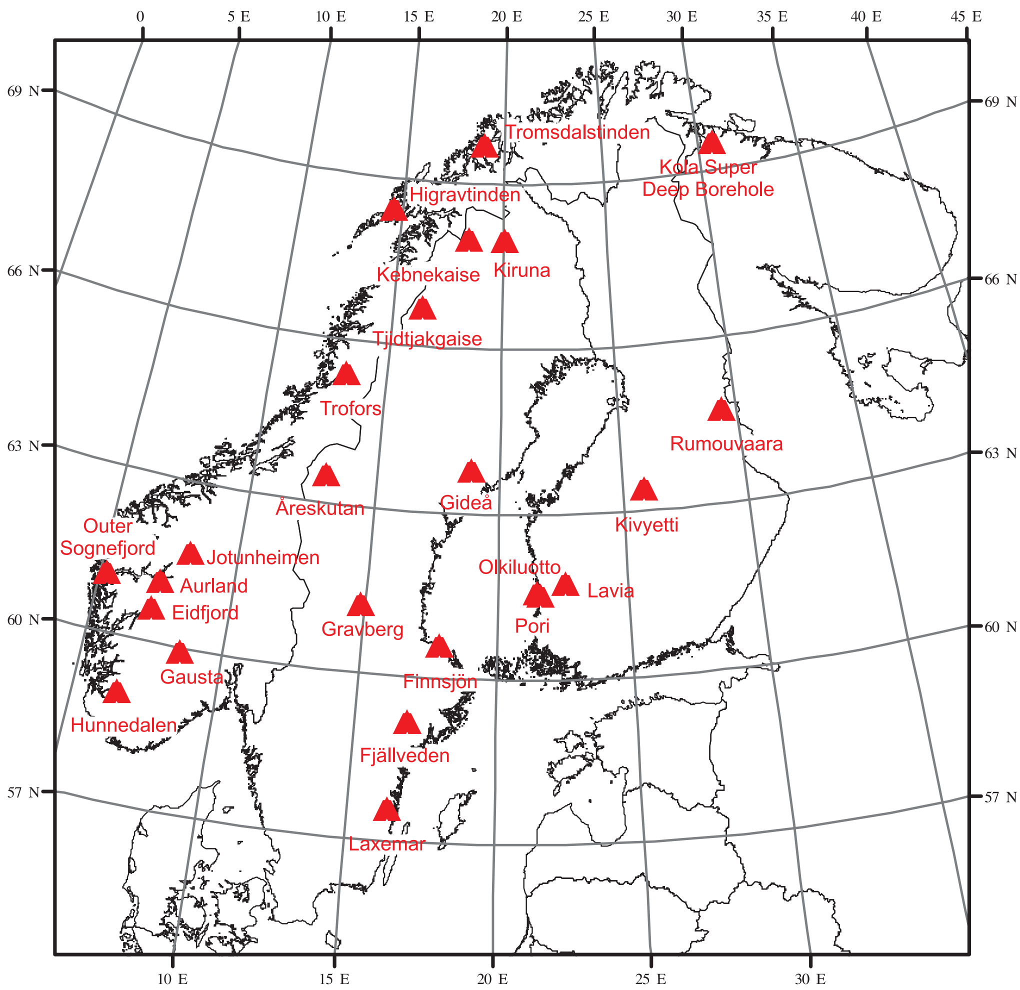

Fig. 2: Locations of vertical profiles in boreholes or from outcrops (age vs. elevation profiles) in Fennoscandia. See Table 2 for references and age and elevation ranges. Spatial reference: WGS84, Gauss-Krueger, central meridian 21°E, Latitude of Origin 63°N, false easting 1500 km.

Fission Track data. We present and discuss a selection of these data. It is beyond the scope of this publication to discuss fission track methodology. For extensive, in-depth reviews on Fission Track thermochronology and its applications see Andriessen (1995), Gallagher et al. (1998), Hendriks (2005), Tagami & O'Sullivan (2005), Donelick et al. (2005), and Tagami (2005).

Apatite Fission Track (AFT) ages are a function of the thermal history of the host rock. It is important to state formally that a fission track age generally does not indicate the timing of cooling through a specific temperature boundary, but instead represents an integrated record of the thermal history of a sample. Fission track ages therefore usually do not correspond directly to discrete geological events. Only in the case of very rapid cooling (e.g volcanic extrusion), may fission track ages correspond to a specific geological event. For more slowly cooled samples, apatite fission tracks will undergo annealing (i.e. shortening) whilst residing at depths corresponding to temperatures between ~60°C to 120°C, in what is known as the 'Partial Annealing Zone' (PAZ). Nevertheless, even at room temperature fission tracks are slowly annealed (Vrolijk et al. 1992). Thus, annealing and shortening of tracks in the PAZ will result in a unique distribution of track lengths. Track length distributions are routinely measured, and these track length data are critical to reconstruct a thermal history.

Data sources

An overview of fission track datasets from different areas within Fennoscandia is presented in Table 1. To our knowledge, this overview is complete at the time of manuscript submission. Out of the total of 677 AFT data included in this database, 190 are previously unpublished, including 63 samples from southern Norway that will be fully presented and interpreted elsewhere (Leighton et al. in prep). In general, datasets that overlap geographically are compatible with each other. A number of Age vs. Elevation profiles ('vertical profiles') have also been published (Figure 2, Table 2). The database will be updated with results from ongoing and future fission track projects, and will be made available through the website of the Geological Survey of Norway.

Methodological constraints

The various AFT datasets that together constitute the Fennoscandian AFT database are based on different analytical approaches and data quality varies between, as well as within them. Also, the Fennoscandian AFT database includes samples from a large range of elevations and apatite chemistry is variable. Before any conclusions can be drawn about patterns of ages and mean track lengths, the database therefore needs to be filtered according to the criteria below.

Elevation

When sampling strategies are designed it is common to sample over a range of elevations. Because of the generally systematic increase in temperature with depth in the crust, sampling over a range of elevations can provide valuable information for example on the thermal gradient. Each sample in a vertical profile will experience a slightly different temperature path. Samples towards the base of a vertical profile will have a greater initial paleodepth, will have cooled from partial annealing temperatures more recently, and will therefore have a younger AFT age.

In order to best compare like with like, we have selected data from between 0.0 and 0.5 km above sea level. This balances the inclusion of as much data as possible against the introduction of complexity in the map. Existing vertical profiles (e.g. Rohrman et al., 1995; Hendriks & Andriessen 2002) in the most elevated parts of the Southern and Northern Scandes yield AFT ages within the specified 0.5 km elevation range that generally overlap within 2σ uncertainties. Away from these highland regions, the available data are mostly below 0.3 km above sea level. As such, other than in the central parts of the Southern and Northern Scandes, our elevation filter excludes very few data.

Apatite chemistry

While temperature is the primary control on annealing, the annealing kinetics (and consequently the temperature sensitivity) of the fission-track system is dependant upon apatite composition. Chlorine exerts a strong compositional control on track-retention in apatite (e.g. Green et al. 1986). Studies have indicated that there are a range of other elemental substitutions, such as Mn, Sr, OH, Fe, and the rare earth elements, that may also significantly influence track-retention in apatite (e.g. Barbarand et al. 2003, Carlson et al. 1999). Composition is typically determined by electron microprobe analysis or etch-pit measurements, which are widely considered a proxy for annealing kinetics and composition (Donelick et al. 1999). To partially mitigate the effect of chemical variability, yet maximize the total available data we have chosen not to include data from samples whose resistance to annealing is higher than that of the Durango and Fish Canyon apatite standards. Durango and Fish Canyon apatites are the most commonly used (inter-)calibration standards for AFT dating, and have etch pits sizes (Dpar) of 1.83 and 2.43 μm (Donelick et al. 1999) and chlorine concentrations of 0.39 and 0.83 oxide wt.% respectively (Barbarand et al. 2003). At present, a more refined selection of apatite chemistries is hindered by the lack of measured constraints in most of the available data.

Due to the large intra-grain variation in apatite chemistry for sedimentary samples, and also because of the potential of inheritance of fission tracks from the eroded source rock, we excluded all 26 sedimentary sample AFT data from this compilation.

Analytical approach and data quality

To maintain internal consistency we have excluded data obtained by the Population method (POP). The Population method was effectively replaced by the External Detector Method (EDM) in the 1980's, which allows the assessment of intra-sample grain age variation (Gleadow 1981). For all regions from which POP ages have been reported (Southern Norway - Van den Haute 1977; Andriessen & Bos 1986; Andriessen 1990; Sweden - Koark et al. 1978; Zeck et al. 1988; Hansen et al. 1989; Finland - Lehtovaara 1976) extensive EDM datasets have been later presented. Nevertheless, we note that POP data are generally in good agreement with regional EDM data. All included EDM data met a minimum criterion of 5 grains with $P(\chi)^2 > 5\%$. For the mean track length data, we used all of the above selection criteria, plus a minimum requirement of 50 measured track lengths.

Discussion

The filtered database of Fennoscandian Apatite Fission Track data is presented in Figure 3 (AFT ages) and Figure 4 (Mean Track Lengths). Contouring was done in a WGS 1984 Stereographic projection (Central Meridian 21°E, Latitude of Origin 63°N) with ArcGIS 9.1 using the Inverse Distance Weighted option and a variable search radius. For the Møre-Trøndelag Fault Complex and Lofoten - Vesterålen regions, faults and lineaments documented on the 1:2M Geological Map of the Fennoscandian Shield (Koistinen et al. 2001) were entered as barrier polylines. The contouring function considers barrier polylines as breaklines that limit the search for input sample points to those that are on the same side of the barrier as the current processing cell. The employment of barrier polylines causes the contour pattern to mimic the structural grain.

The western margin of Fennoscandia is cut by numerous faults (Gabrielsen et al. 2002 and references therein) and abrupt age juxtapositions at the western margin have been shown to correlate with faults and deeply incised topographic lineaments (Redfield et al. 2004; Redfield et al. 2005a,b). Many are of Caledonian age, although many have undergone subsequent reactivation. A pioneering fission track study by Grønlie et al. (1994) investigated the Møre-Trøndelag Fault Complex (MTFC) with an eye towards resolving its Phanerozoic offset history. More recent AFT studies at the Geological Survey of Norway documented Mesozoic and potentially Cenozoic net vertical offset along

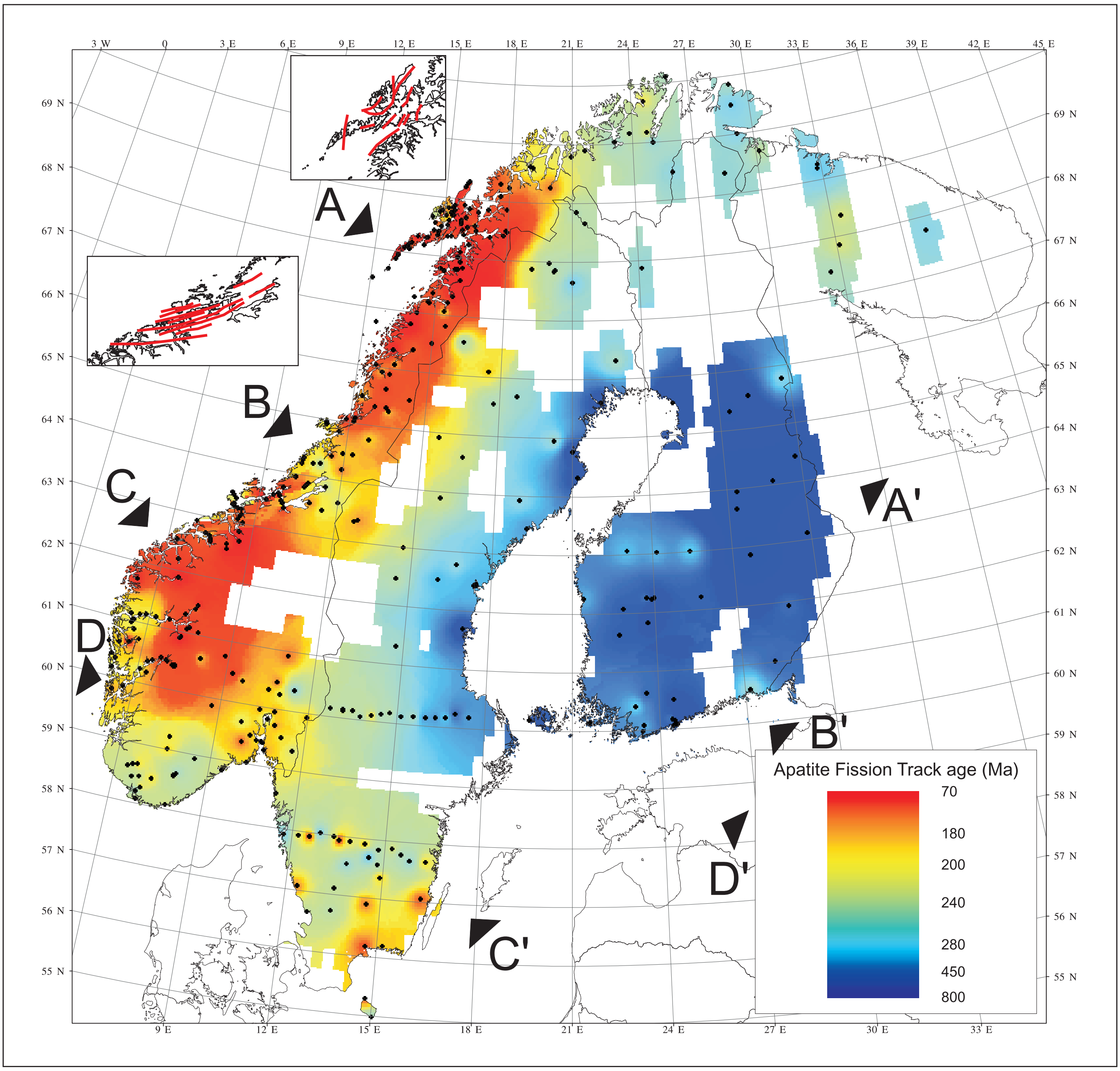

Fig. 3: Pattern of Apatite Fission Track ages in Fennoscandia. Out of a total of 677 available ages, 375 are selected based on elevation, apatite chemistry and analytical approach and data quality (see text for explanation). Areas where no published data exist or where data are excluded as a result of the filtering criteria are blanked. Insets: barrier polylines used as breaklines for contouring. Transects refer to Figure 5. Spatial reference: WGS84, Gauss-Krueger, central meridian 21°E, Latitude of Origin 63°N, false easting 1500 km.

major fault structures on the Norwegian Atlantic margin (Redfield et al. 2004; Redfield et al. 2005a,b). Furthermore, work in central southern Norway indicates that crustal scale structures have had a significant influence on topographic development and denudation (Leighton 2007).

Inspection of the maps (Figures 3 and 4) and the transects (oriented perpendicular to the Norwegian Atlantic margin, Figure 5) reveals how the AFT ages and Mean Track Lengths vary with distance to the margin and with topographic elevation. In order to avoid a forced representation of abrupt changes in AFT age or Mean Track Lengths, the transects in Figure 5 are located away from the barrier polylines that were used in contouring the data. At a coarse level, the map of AFT ages (Figure 3) reflects the topographic distribution, with relatively young AFT ages found in both the Northern and Southern Scandes. The range of AFT ages found in the Northern and Southern Scandes is fairly similar (Figure 3). The Mean Track Lengths for both regions are clearly different however (Figure 4). In the Southern Scandes, the Mean Track Lengths in the most elevated parts of the range are typically ~ 1 μm shorter than in the most elevated part of the Northern Scandes range. Considering the range of Mean Track Lengths of 10.2 – 14.6 μm for the entire Fennoscandian database, the 1 μm difference is clearly significant. Based on a correlation with the Cenozoic stratigraphy offshore southern Norway, Rohrman (1995)

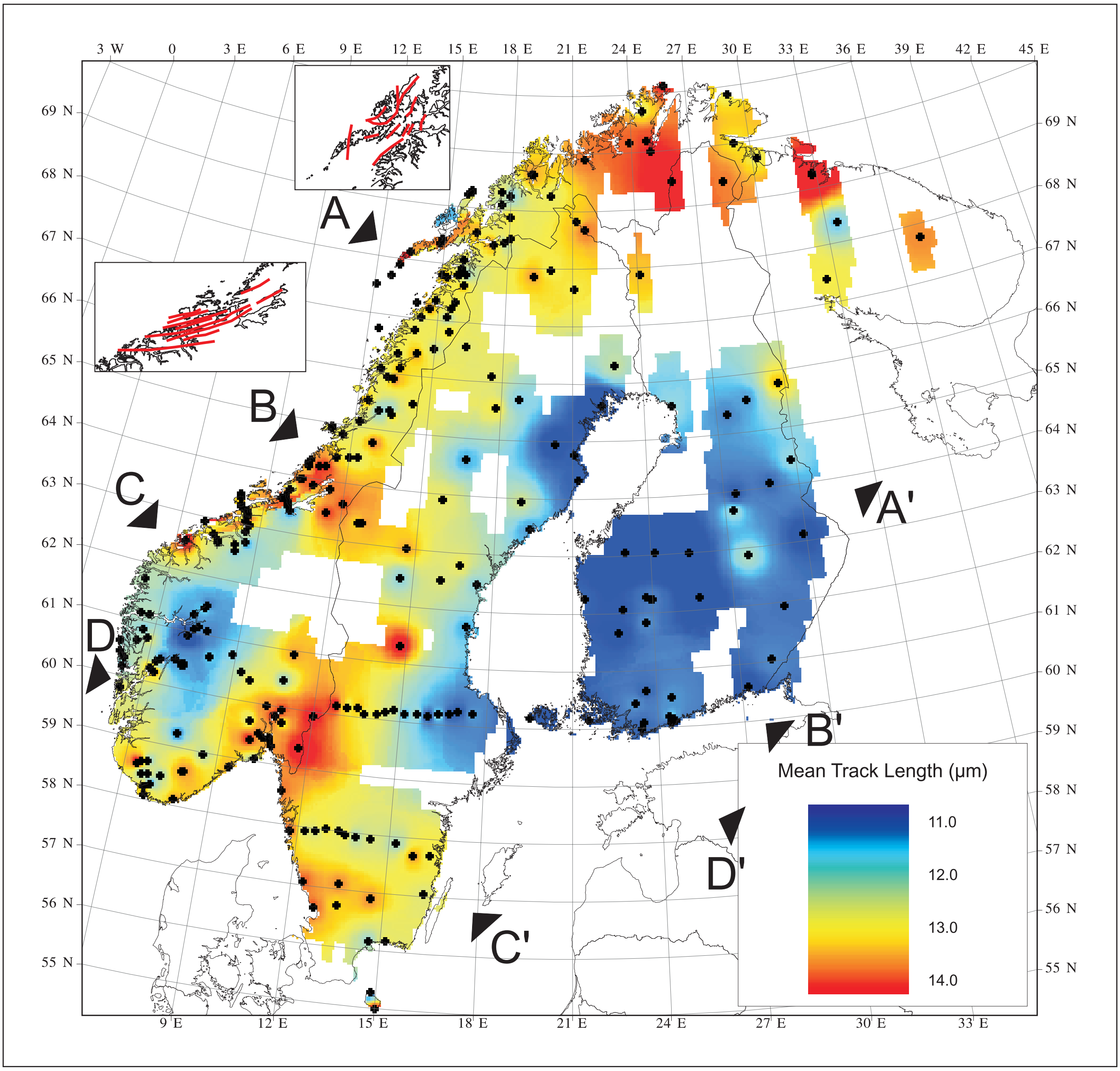

Fig. 4: Pattern of Mean Track Lengths in Fennoscandia. Out of a total of 677 available samples, 285 are selected based on elevation, apatite chemistry and analytical approach and data quality (see text for explanation). Areas where no published data exist or where data are excluded as a result of the filtering criteria are blanked. Insets: barrier polylines used as breaklines for contouring. Transects refer to Figure 5. Spatial reference: WGS84, Gauss-Krueger, central meridian 21°E, Latitude of Origin 63°N, false easting 1500 km.

interpreted the relatively short Mean Track Lengths in his dataset from the Southern Scandes as evidence for a late stage cooling event. Further away from the margin, contours are roughly coast-parallel, their age increasing as the topographic elevation decreases (Figure 5). AFT ages greater than ~300 Ma show a high degree of local variability in northernmost Norway, eastern Sweden and Finland, reflecting variations in annealing behaviour magnified over very long time scales (Hendriks & Redfield 2005).

An effective graphical method for first order interpretation of regional datasets is a plot of fission track age vs. mean track length. Such diagrams are commonly referred to as boomerang plots due to their characteristic concave-up shape (Green 1986). The distinctive pattern arises when samples from a region that has undergone broadly coeval cooling have a range of initial paleodepths (i.e. samples are taken from different elevations and/or areas that have undergone different total amounts of erosion). In a boomerang plot old ages with long MTLs correspond to samples that have been residing near the surface (and therefore at sub-PAZ temperatures) for an extended period.

Figure 6 shows the boomerang plot for the filtered Fennoscandian data. The older ages with long MTLs are dominantly the Finnish samples from the cratonic inte-

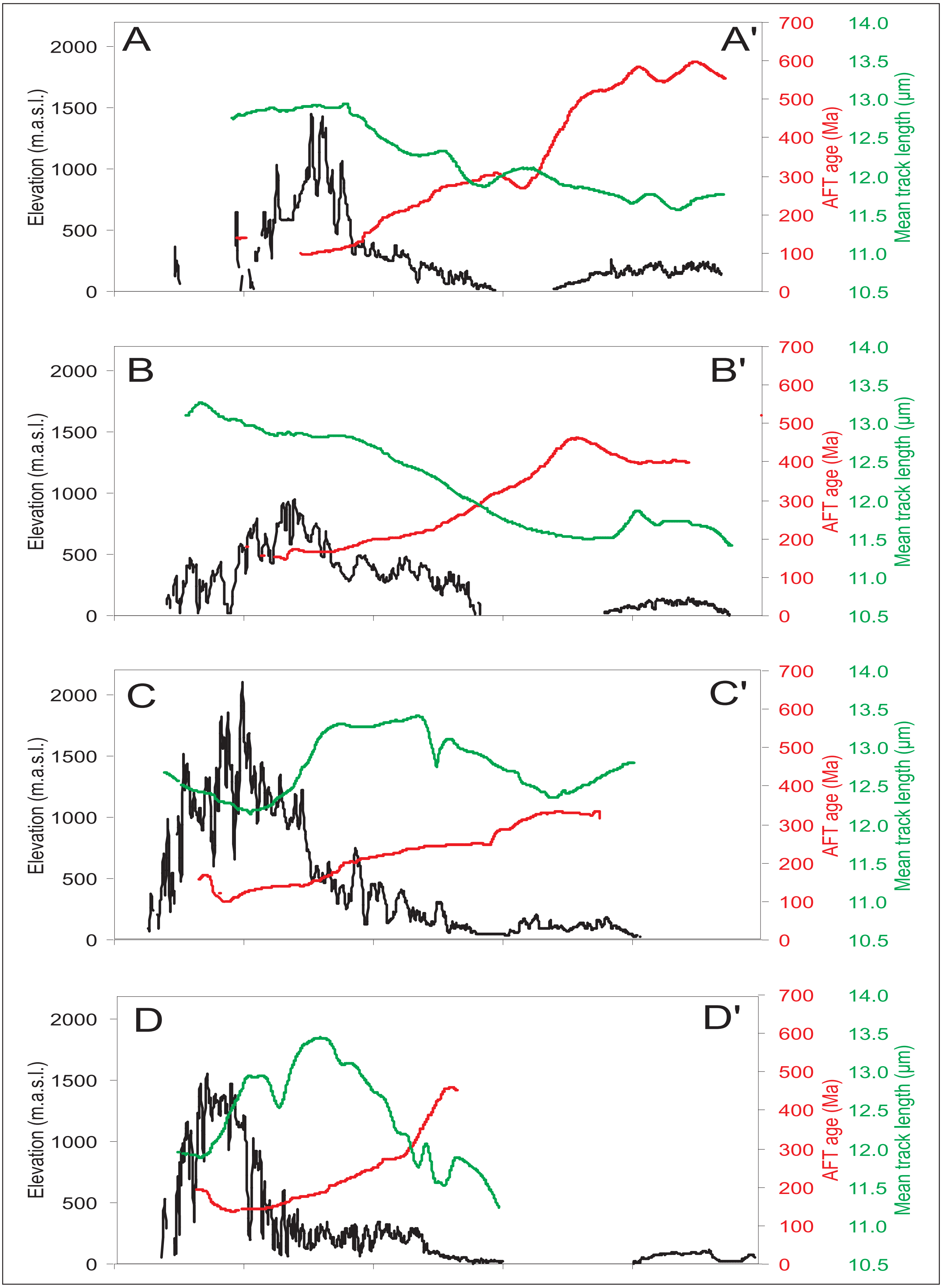

Fig. 5: Transects through the contoured AFT age map (red, see Figure 3) and the contoured map of Mean Track Lengths (green, see Figure 4). Topography along the transects in black.

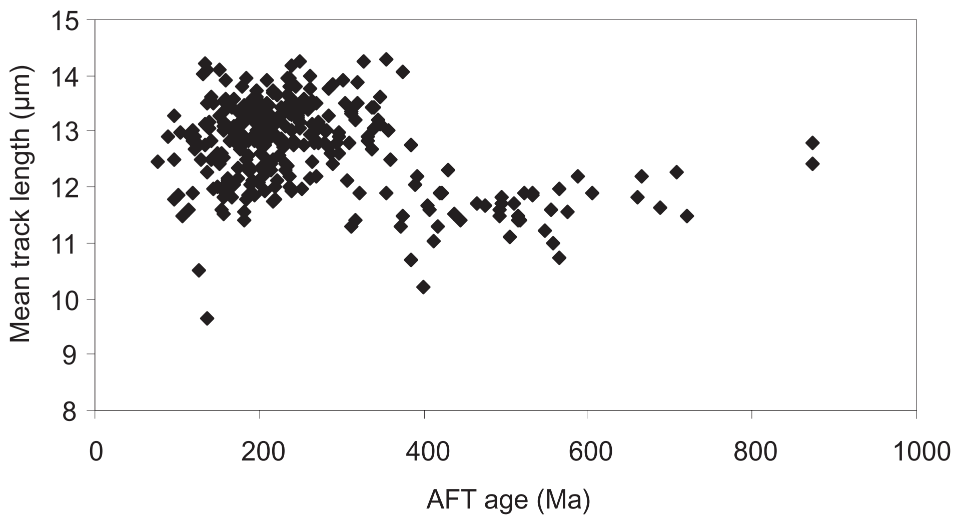

Fig. 6: Relationship between Apatite Fission Track age and Mean Track Length for the suites from Figure 3 and 4 ('boomerang plot').

rior. Intermediate ages have the lowest MTLs; these are samples that have spent most time at PAZ temperatures prior to cooling to surface temperatures. The youngest ages with long MTLs are samples with the highest initial paleotemperatures. In this case such samples hail generally from areas of southern Norway with the highest topography and along the north Atlantic passive margin.

If a dataset does not show this distinctive boomerang pattern it may perhaps be inferred that the denudation history is more complex than simple regional cooling. The large degree of scatter in the Fennoscandian data may be due to local deviations from the regional erosion trend. Causes might be structural and/or lithological heterogeneity, or chemical variation, not surprising given the range of geological settings sampled. If the boomerang trend is observed the timing of the most recent major cooling event that can be resolved by the data may be estimated to be coincident with the youngest fission-track ages, provided that the MTLs are in the range of 14 - 15 µm. In Figure 6, this corresponds to a large number of samples with ages of 100-250 Ma. Secondary boomerang trends could in principle exist within this group of ages, but the degree of variation is too large for a more detailed, meaningful interpretation.

Below we briefly discuss the Fennoscandian data in a regional context.

Southern Scandes

An early study of zircon, apatite fission-track, and other ages from southern Norway suggested that 13 km of crust has been removed since 390 Ma (Andriessen & Bos 1986). This study was carried out before track lengths were routinely measured during fission-track analysis. The large scale Mesozoic and Cenozoic morphotectonic development of southern Norway was first addressed using AFT by Rohrman et al. (1995). Rohrman et al. (1995) found that sea level samples on the south and west coast of Norway yielded relatively old ages (180-200 Ma), whereas inland samples tended to be younger (100 - 150 Ma). They concluded that a domal style of post-rift uplift in southern Norway was responsible for both the age distribution and the present-day topography. Two discrete cooling events were identified using thermal history modelling. Rohrman et al. (1995) suggested a Jurassic cooling event was responsible for the exhumation of a paleo-PAZ, based on a break in slope in age-elevation profiles at 160 Ma and coincident with a major phase of North Sea rifting and progradation of deltas from the Norwegian mainland. They inferred a second cooling event from the upward warping of AFT isochrons, assumed to be horizontal when formed. Apparent warping of isochrons as young as 100 Ma suggests this event must be post-Cretaceous. Rohrman et al. (1995) conjectured that this warping took place in the Neogene based on correlation with the offshore stratigraphy and thermal modelling.

New data by Leighton (2007) are compatible with the results of Rohrman et al. (1995). However, whilst earlier studies have often assumed that central areas have behaved as a coherent block since the Permian, the new data offer a different perspective. Leighton's dataset crucially contains many more samples around major structures and new vertical profiles. Rather than warped isotherms, lateral age variations may result from 1) changes in landscape morphology from coastal to inland areas and 2) fault activity. Both mechanisms can produce differential erosion and hence lead to the observed age distribution. In particular, the higher sampling density of the new data allowed Leighton to resolve km-scale movements of faults in the Sognefjord area, following an approach earlier adopted by Redfield et al. (2004) and Redfield et al. (2005a,b) in the Møre-Trøndelag region.

Northern Scandes

Data by Hendriks & Andriessen (2002), Hendriks (2003), Huigen & Andriessen (2004) and unpublished data by

Huigen (Mid-Norway) as well as Hendriks (Nordland and Troms) define the pattern of AFT ages in the northern part of Fennoscandia. Here the data define an elongated oval region of Mesozoic AFT ages, the youngest being c. 90 Ma. From the continental interior towards the Atlantic margin, a westward younging of the timing of cooling from the PAZ was observed by Hendriks and Andriessen (2002). Hendriks (2003) stated that the overall pattern of ages, like the topography, was clearly asymmetric in an east-west transect through the Northern Scandes. Such a pattern is typical for a rift shoulder that has undergone scarp retreat. In the Lofoten and Vesterålen archipelago, kilometer scale vertical offset in the Mesozoic and Cenozoic along several faults is indicated by AFT ages that are statistically different at the 2σ level on both sides of known lineaments (Hendriks 2003). East of the Northern Scandes range and into the Kola peninsula, the AFT data do not display a clear pattern. Rather, the region is characterized by large variability in the AFT ages, with no geological evidence for structural juxtaposition.

Finland

Finland has the oldest AFT ages that have been documented anywhere on Earth. However, the large age variation that is observed throughout Finland, with ages sometimes varying by hundreds of millions of years over distances of just a few kilometers, has - in the absence of any obvious chemical influence on annealing - historically complicated interpretations (e.g. Murrell 2003).

In many parts of Finland, remnants of the so-called sub-Cambrian peneplain (Högbom 1910, Lidmar-Bergström & Näslund 2002) are considered to be preserved in the present day land surface. Nevertheless, many AFT ages from near the sub-Cambrian peneplain are much younger than Cambrian time. Lorencak (2003), Murrell & Andriessen (2004) and Murrell (2003) suggested several kilometers of burial over much of Finland are required in order to explain this observation. Murrell (2003) however noted a conflict between the results of the inverse modelling and other geological data from Finland which he considered cast doubt on the possibility of deep sedimentary burial. Upon discovering a distinct inverse correlation between AFT ages and uranium concentrations in samples from central Finland, Hendriks & Redfield (2005) suggested an alternative explanation. Samples low in uranium (such as those typical for the Archaean crystalline basement in eastern Finland) are systematically associated with older AFT ages, and longer Mean Track Lengths, whilst samples higher in uranium are systematically associated with younger AFT ages and shorter Mean Track Lengths. Hendriks and Redfield (2005) suggested the Finnish data are a natural example of Radiation Enhanced Annealing (where natural decay of alpha emitting actinides can lead to annealing of fission tracks without raising temperatures), thus challenging the validity of modelling AFT data in cratonic and potentially other settings. Recent data by Donelick et al. (2006) show that the inverse correlation between AFT age and concentration of alpha emitter actinides is observed also for single grain data from individual hand samples from Finland and Canada, indicating beyond doubt that temperature variation alone (i.e. burial and re-exposure) cannot be responsible for the observed variation in single grain ages. However, although Radiation Enhanced Annealing is a process well known in the physics community (see Ewing & Wang 2002 and references therein) the interpretation of Hendriks & Redfield (2005) has been hotly debated within the AFT community (e.g. Green & Duddy 2006) and remains controversial.

Sweden

Cederbom et al. (2000) and Cederbom (2001) presented two transects with closely spaced samples across southern Sweden. Huigen and Andriessen (2004) presented AFT data from central Sweden, where Larson et al. (1999) had previously dated samples from boreholes. For southernmost Sweden, Cederbom (2001) hypothesized that, following Carboniferous - Middle Triassic cooling and denudation, the area underwent exhumation in the Jurassic. Larson et al. (1999) and Cederbom et al. (2000) interpreted data from eastern Sweden in terms of deep burial beneath a Caledonian foreland basin. Although the preservation of the sub-Cambrian peneplain here indicates that some burial clearly must have occurred, Hendriks & Redfield (2005) challenged these interpretations, re-interpreting the data in terms of Radiation Enhanced Annealing. Igniting a lively debate, Larson et al. (2006) presented an additional interpretation that they believed constituted solid evidence for a Caledonian foreland basin. However, Hendriks & Redfield (2006) demonstrated that the supporting data (vitrinite reflectance, conodont alteration index, stratigraphy, etc.) presented by Larson et al. (2006) were equivocal: alternative explanations, many preferred by the original authors, could be advanced for each observation. Hendriks & Redfield (2006) concluded that several kilometres of Caledonian foreland basin deposition are not required. Exactly to what extent the annealing process is influenced by factors other than the thermal control clearly needs to be more closely investigated; the Swedish and Finnish datasets constitute an obvious starting point.

Concluding remarks

The large scale, first order patterns of AFT data presented in this compilation lay a firm foundation for future, more detailed studies. Given that during the Mesozoic the Fennoscandian Atlantic margin has undergone multiple phases of rifting on the Møre and Vøring Norwegian margins (see Brekke 2000 for an overview), and that all of the youngest AFT ages are located on the present day North Atlantic passive margin, a reasonable first-order interpretation is that the dominant control on Fennoscandian cooling, particularly near the margin, has been multi-stage rifting in the North Atlantic. Although the overall regional-scale pattern of ages and mean track lengths presented here is unlikely to change much with additional data, we anticipate more local age variation. In areas such as Møre-Trøndelag and Lofoten–Vesterålen (and probably also in parts of Troms and southern Norway), vertical offsets in the range of hundreds of meters or more are detectable as large AFT age differences across deeply incised lineaments. Future AFT studies targeting the Fennoscandian margin should be designed to document fully both the boundaries and interrelationships of individual, potentially juxtaposed, structural domains. Focussed common-elevation transects perpendicular and parallel to the structural grain, concordant with the collection of structural data, will likely prove productive. Also, recent developments in modelling strategies allow new insights to be gained from modelling of multiple samples grouped in 3D to infer displacements across structures in a statistically robust manner (Gallagher et al. 2005, Stephenson et al. 2006).

Vast tracts of Fennoscandia remain under-explored even at the first order scale, and constitute obvious targets for valuable future work. AFT data from vertical profiles, surface samples, and boreholes provide records of the paleogeothermal gradient. In theory, these records can be recovered, given an appropriate annealing model that incorporates all known sources of variation in annealing behaviour. Future developments in the methodological and technical aspects of apatite fission track dating (e.g. incorporation of non-thermal annealing effects like Radiation Enhanced Annealing; introduction (Hasebe et al. 2004) of Laser Ablation ICP-MS based AFT dating, etc.) are expected to greatly improve today's models, allowing us to clarify more accurately the denudation history of Fennoscandia, in much more detail.

Other low temperature thermochronological techniques such as Apatite (U-Th)/He dating (e.g. Farley 2002) will complement the AFT dataset and impose further constraints on the late Mesozoic - Cenozoic cooling histories. Because this map will be electronically updated throughout the foreseeable future, thermochronologists are invited to archive finalized low temperature thermochronology data at the Geological Survey of Norway.

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