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DOCTORAL THESIS

^{40}Ar - ^{39}Ar , AFT and (U-Th)/He thermochronologic implications for the low-temperature geological evolution in SE Sweden

Pia Söderlund



LUND UNIVERSITY

DEPARTMENT OF GEOLOGY

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<p>Abstract</p> <p>The Oskarshamn and Forsmark areas in the Fennoscandian Shield, SE Sweden, have been chosen as potential sites for hosting highly radioactive nuclear waste. To evaluate their respective suitability, the geological history of the bedrock in these two areas has been investigated. This study has focused on the thermal evolution, from c. 500 °C to c. 50 °C. ⁴⁰Ar-³⁹Ar geochronology on hornblende, muscovite and biotite, was applied to determine cooling from c. 500 °C to c. 300 °C, whereas apatite fission-track (AFT) and (U-Th)/He thermochronology were used to determine the thermal evolution between c. 120 °C and c. 50 °C.</p> <p>The crystalline bedrock in the Forsmark area consists of c. 1.89-1.85 Ga meta-igneous rocks that form part of the Svecofennian orogen. ⁴⁰Ar-³⁹Ar muscovite ages indicate cooling through c. 350 °C between c. 1.76 and c. 1.71 Ga. Biotite ages from surface samples suggest that the present erosion surface cooled below c. 300 °C at 1.73-1.66 Ga. The results show that the area has remained at temperatures below 300 °C since c. 1.7 Ga. The cooling of the Forsmark area reflects either slow cooling after the tectonothermal activity during the Svecofennian orogeny, or uplift in response to far-field effects of c. 1.7 Ga orogenic activity further to the west (or a combination of these processes).</p> <p>The c. 1.8 Ga rocks at Oskarshamn belong to the Transscandinavian Igneous Belt (TIB). Younger, c. 1.45 Ga granites and c. 0.95 Ga dolerite dykes are also present in the area. ⁴⁰Ar-³⁹Ar hornblende ages indicate initial rapid cooling down to c. 500 °C after the emplacement of TIB rocks. Subsequent cooling through c. 300 °C initially occurred at c. 1.6 Ga (⁴⁰Ar-³⁹Ar biotite ages). A 1.51-1.47 Ga ⁴⁰Ar-³⁹Ar biotite age group reflects either incomplete resetting by younger granitic intrusions in the area or thermal activity related to either the youngest manifestations of rapakivi intrusions or to the initiation of the Danopolonian event in the south. A 1.43-1.42 Ga biotite age group represents cooling after intrusion of the c. 1.45 Ga granites.</p> <p>The (U-Th)/He and AFT data were obtained from borehole and surface samples. Although the uncorrected (U-Th)/He and the AFT borehole ages at Oskarshamn are identical, and similar age/depth trends from the two thermochronometers are present at Forsmark, the (U-Th)/He ages are older (or AFT ages younger) than expected with respect to the closure temperatures of the two systems. The systematic age shift may be controlled by α-recoil damage of the (U-Th)/He system in U-rich apatite, possibly in combination with radiation-enhanced track annealing in the AFT system, and by invalid F_{α}-correction of the (U-Th)/He system due to a heterogeneous distribution of U in apatite.</p> <p>Thermal modelling of the AFT ages reveals similar thermal histories in the two areas. Complete track annealing indicates that the present ground surface was situated at a depth of >4 km prior to c. 200 Ma. Subsequent uplift started between Late Palaeozoic and Early Mesozoic time and waned c. 100 Ma ago. Uplift may have been related to transensional tectonics in southernmost Sweden and/or extensive volcanic activity to the south and west. After the modification in the uplift rate, continued exhumation was considerably slower.</p>		
Key words: ⁴⁰ Ar- ³⁹ Ar, (U-Th)/He, AFT, geochronology, thermochronology, cooling, uplift, Fennoscandian Shield		
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Date 2008-03-14

Till Uffe,

Herman och Vincent

The geological evolution is probably a mystery to the majority of people - to a bigger or lesser extent.

A discussion overheard by the author, on the train between Lund and Håsteholm, autumn 2007:

"Did the world exist before the Ice-age?"

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Populärvetenskaplig sammanfattning

Områdena kring Forsmark och Oskarshamn blev år 2000 utsedda till möjliga kandidatområden för slutförvar för använt kärnbränsle. År 2002 inledde SKB (Svensk Kärnbränslehantering AB) platsundersökningar i dessa områden med syfte att bland annat samla in information om berggrundens beskaffenhet och att upprätta platsbeskrivningar och modeller.

För att förstå berggrundens beskaffenhet ingår det i undersökningsarbetet att skapa sig en förståelse för den geologiska utvecklingen i de två områdena, från det att bergarterna bildades och fram till nutid. För att kunna förutspå berggrundens stabilitet under den tid som kärnbränslet anses vara farligt (ca 100000 år) är det speciellt viktigt att undersöka berggrundens geologiska historia under de senaste årmiljonerna. Den här avhandlingen behandlar i huvudsak, med hjälp av radiometrisk datering, den termala utvecklingen från det att berggrunden befann sig på ett djup där temperaturen var ca 500°C (motsvarar ca 20 km med en geotermal gradient på 25°C/km) till mer yt nära djup där temperaturen var ca 50°C (de allra översta kilometrarna).

Vid radiometrisk datering analyserar man radioaktiva isotoper som sönderfaller med känd hastighet till specifika dotterisotoper, såsom sönderfall av uran till bly eller kalium till argon. Genom att mäta koncentrationerna av moder- och dotterisotoper kan en ålder räknas ut. Åldern motsvarar den tid som åtgått sedan diffusion av dotterisotoper upphörde. Detta sker vid olika temperaturer för olika mineral och olika radiometrisk system, och temperaturen kallas dateringssystemets blockeringstemperatur. Vissa system har en hög blockeringstemperatur, t.ex. U-Pb systemet i zirkon (>900°C). Andra system har lägre blockeringstemperaturer och då pratar man ofta om avkylningsåldrar, dvs. den tid som gått sedan bergarten avkyldes under en viss temperatur. I de system som har lägst blockeringstemperatur, dvs. apatit fission-track (AFT) och (U-Th)/He i apatit, mäter man koncentrationen av spår (tracks) eller heliumpartiklar som bildas i vissa sönderfallskedjor (t. ex. uran och thorium). I detta arbete har ^{40}Ar - ^{39}Ar (en variant av ^{40}K - ^{39}Ar systemet) använts på hornblende, muskovit och biotit med respektive blockeringstemperaturer på ca 500°C, 350°C och 300°C, samt AFT och (U-Th)/He i apatitkristaller med blockeringstemperaturer på ca 110°C respektive ca 70°C.

Tidigare arbeten har visat att berggrunden i Forsmark i huvudsak bildades för 1890-1850 miljoner år sedan. Mina resultat visar att avsvälning av berggrunden, ner till ca 300°C, skedde redan för ca 1700 miljoner år sedan. I samband med avsvälningen började berggrunden svara på stress genom spröd deformation. Temperaturen har senare aldrig överstigit 300°C, förutom möjligen i sprickzoner där varma fluider kunnat passera. Huvuddelen av berggrunden i Oskarshamn bildades för ca 1800 miljoner år sedan. Inslag av yngre, ca 1450 miljoner år gamla graniter och ytterligare yngre diabasgångar finns också i området. Avsvälning ner till 500°C skedde snabbt, i direkt anslutning till magmatismen för ca 1800 miljoner år sedan. Berggrunden kyldes ner till 300°C för första gången för ca 1600 miljoner år sedan. Yngre avsvälningssåldrar kan antingen relateras till påverkan från magmatisk aktivitet i mer avlägsna områden, påverkan från tektonisk aktivitet eller till magmatismen för ca 1450 miljoner år sedan.

Den yngre termala utvecklingen, från den tid då berggrundens temperaturer sjönk från ca 120°C till ca 50°C, ser ut att vara i stort sett densamma i de två undersökningsområdena. Modellering av AFT data indikerar att dagens berggrundsytta, i båda områdena, låg på minst fyra kilometers djup för ca 200 miljoner år sedan. Mellan för ca 200 miljoner år och ca 100 miljoner år sedan utsattes berggrunden för upplyftning, eventuellt i samband med tektonisk och magmatisk aktivitet i sydligaste Sverige.

⁴⁰Ar-³⁹Ar, AFT and (U-Th)/He thermochronologic implications for the low-temperature geological evolution in SE Sweden

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Abstract

The Oskarshamn and Forsmark areas in the Fennoscandian Shield, SE Sweden, have been chosen as potential sites for hosting highly radioactive nuclear waste. To evaluate their respective suitability, the geological history of the bedrock in these two areas has been investigated. This study has focused on the thermal evolution, from c. 500 °C to c. 50 °C. ⁴⁰Ar-³⁹Ar geochronology on hornblende, muscovite and biotite, was applied to determine cooling from c. 500 °C to c. 300 °C, whereas apatite fission-track (AFT) and (U-Th)/He thermochronology were used to determine the thermal evolution between c. 120 °C and c. 50 °C.

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The 1.80 Ga rocks at Oskarshamn belong to the Transscandinavian Igneous Belt (TIB). Younger, 1.45 Ga granites and c. 0.95 Ga dolerite dykes are also present in the area. ⁴⁰Ar-³⁹Ar hornblende ages indicate initial rapid cooling down to c. 500 °C after the emplacement of TIB rocks. Subsequent cooling through c. 300 °C initially occurred at 1.6 Ga (⁴⁰Ar-³⁹Ar biotite ages). A 1.51-1.47 Ga ⁴⁰Ar-³⁹Ar biotite age group reflects either incomplete resetting by younger granitic intrusions in the area or thermal activity related to either the youngest manifestations of rapakivi intrusions or to the initiation of the Danopolonian event in the south. A 1.43-1.42 Ga biotite age group represents cooling after intrusion of the c. 1.45 Ga granites.

The (U-Th)/He and AFT data were obtained from borehole and surface samples. Although the uncorrected (U-Th)/He and the AFT borehole ages at Oskarshamn are identical, and similar age/depth trends from the two thermochronometers are present at Forsmark, the (U-Th)/He ages are older (or AFT ages younger) than expected with respect to the closure temperatures of the two systems. The systematic age shift may be controlled by α -recoil damage of the (U-Th)/He system in U-rich apatite, possibly in combination with radiation-enhanced track annealing in the AFT system, and by invalid F_T -correction of the (U-Th)/He system due to a heterogeneous distribution of U in apatite.

Thermal modelling of the AFT ages reveals similar thermal histories in the two areas. Complete track annealing indicates that the present ground surface was situated at a depth of >4 km prior to c. 200 Ma. Subsequent uplift started between Late Palaeozoic and Early Mesozoic time and waned c. 100 Ma ago. Uplift may have been related to transtensional tectonics in southernmost Sweden and/or extensive volcanic activity to the south and west. After the modification in the uplift rate, continued exhumation was considerably slower.

Keywords: ⁴⁰Ar-³⁹Ar, (U-Th)/He, AFT, geochronology, thermochronology, cooling, uplift, Fennoscandian Shield

1. Introduction

Sweden is presently a stable region of the Earth's crust, but throughout its geological history many parts have been reworked during accretional and collisional processes. The imprint of the youngest collision (about 400 million years ago) is found in the mountain range of the Swedish Scandes (Skandinaviska fjällkedjan). The youngest magmatism took place in central Scania in southern Sweden and dates back to c. 110 million years. The old and stable bedrock in central Sweden is interesting from a highly current question, namely the long term repository of highly radioactive nuclear waste.

Forsmark and Oskarshamn in southeast Sweden have been chosen to potentially host a deep repository for highly radioactive nuclear waste (SKB, 2000). Along with other information, our understanding of the geological history is a prerequisite to foresee the future stability of the crust in these areas. Earlier bedrock mapping has been performed but with little or no temporal control. The lack of Palaeozoic sedimentary rock at the two investigation sites, as in most of Sweden, precludes detailed stratigraphic reconstructions of the more recent tectonothermal history. As part of the site investigations, low-temperature geochronometers, such as ^{40}Ar - ^{39}Ar on different minerals, (U-Th)/He on apatite and apatite fission-track (AFT), were used in this PhD project to compile information on the cooling history in the areas.

The main objective of this PhD project has been to place time constraints on several important low-temperature parameters, such as the timing of the ductile-brittle transition (i.e. denote when the crystalline bedrock had cooled enough to respond to deformation by brittle fracturing rather than by ductile processes), the uplift/exhumation rate as determined from vertical sampling of cored boreholes, the cooling rate calculated by combining data sets of different geochronometers with different closure temperatures (T_c), and the timing of relatively young tectonic activity. With this information at hand, I have attempted to link radiometric age data from Forsmark and Oskarshamn with regional geological events. In addition, by using both (U-Th)/He and AFT on apatite from the same sample, I have tried to evaluate difficulties inherent to these two thermochronometers, especially when used in

old terrains.

In the following sections, I will briefly present the geological setting of the Forsmark and the Oskarshamn areas, provide an introduction to the analytical techniques, summarize the papers included in this thesis and, finally, present a short synthesis of the results.

2. Geological setting

Sweden is part of the Fennoscandian Shield, which has a long and protracted history. The oldest rocks occur in the north and are of Archaean age. Throughout the Proterozoic, younger terrains were subsequently accreted to the Archaean nucleus through a number of orogenic events associated with juvenile magmatism and accretational tectonics (e.g. Gaál and Gorbatshev, 1987; Nironen, 1997). In Sweden, the bedrock of the Fennoscandian Shield is dominated by the strongly eroded Palaeoproterozoic Svecofennian orogen to the east and the Meso- to Neoproterozoic Sveconorwegian orogen to the southwest. The NS trending Palaeo- to Mesoproterozoic Transscandinavian Igneous Belt contains both unmetamorphosed rocks and rocks that were reworked during either the Svecofennian orogeny to the east and the Sveconorwegian orogeny to the west (Fig. 1)

Forsmark and Oskarshamn are situated on the shoreline of the Baltic Sea in central and south-central Sweden, respectively (Fig. 1). The bedrock in the Forsmark area consists of two igneous rock suites dated to 1.89-1.87 Ga and 1.86-1.85 Ga (Hermansson et al., 2007; 2008). Rocks of the older suite underwent penetrative ductile deformation under amphibolite-facies metamorphic conditions prior to intrusion of rocks of the younger suite. Possibly at 1.85 Ga and certainly by 1.83 Ga, parts of the area had started to cool beneath c. 500 °C (Hermansson et al., in review). During the time interval 1.85 to 1.80 Ga, discrete ductile deformation was localised to NW to WNW trending deformation belts, and temperatures remained above c. 500 °C in these belts. Tectonothermal activity at 1.81 to 1.80 Ga caused exhumation to higher crustal levels and all the rocks in the Forsmark area finally cooled below 500 °C (Hermansson et al., in review).

In the Oskarshamn area, the bedrock is dominated by c. 1.80 Ga intrusive rocks, which

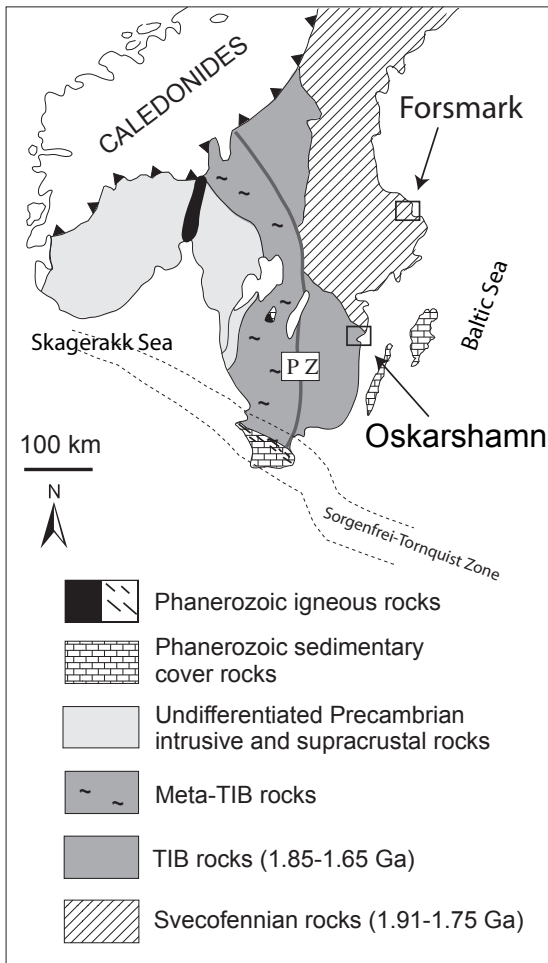


Figure 1. Major tectonic units in the Fennoscandian Shield. The locations of Forsmark and Oskarshamn are indicated. PZ=Protogine Zone, TIB=Transscandinavian Igneous Belt

belong to the 1.85-1.65 Ga Transscandinavian Igneous Belt (see Högdahl et al., 2004 and references therein). The bedrock in this area features only a weak deformational and metamorphic overprint. A second magmatic event at c. 1.45 Ga (Åberg et al., 1983; 1984; Åhäll, 2001) involved emplacement of granitic plutons. These granites are coarse-grained, homogeneous and well-preserved.

Between 1.1 and 0.9 Ga, the Sveconorwegian orogeny caused deformation and metamorphism in western Fennoscandia. Zircon fission-track ages, which have been suggested to reflect the existence of a several kilometres thick foreland basin, have been obtained in both Oskarshamn and Forsmark (Larson et al., 1999). Additionally, the far-field effects of

Sveconorwegian activity have been recorded by either neocrystallization of fracture filling minerals or the thermal disturbance of isotope systems in such minerals (Sandström et al., 2006; Drake et al., 2007).

In southern Sweden, the Fennoscandian Shield is characterized by a sub-Cambrian peneplain, which developed during the later part of the Proterozoic (e.g. Lidmar-Bergström, 1996). After formation of the sub-Cambrian peneplain, the bedrock was locally disturbed by brittle faulting (Bergman et al., 1999). In both Forsmark and Oskarshamn, fluid activity and neocrystallization of fracture minerals also occurred after the establishment of the sub-Cambrian peneplain (Sandström et al., 2006; Drake et al., 2007). Cambrian to Silurian sediments covered the peneplain during the Early Palaeozoic (Lidmar-Bergström, 1995). During the Late Ordovician, Baltica and Avalonia collided (Cocks and Torsvik, 2005), and this was followed by a collision between Baltica-Avalonia and Laurentia in the Silurian, which continued into the Early Devonian (Gee, 1975). The collision between Baltica-Avalonia and Laurentia gave rise to the formation of the Caledonian orogen in western Sweden with eastward transport of thrust sheets. A thick and wide sedimentary foreland basin sequence developed over southeast Scandinavia, in front of the mountain range (e.g. Samuelsson and Middleton, 1998; Larson et al., 1999; Huigen and Andriessen, 2004). Sedimentary loading, in connection with the development of this foreland basin, and subsequent uplift, denudation and exhumation has influenced the Fennoscandian crust some 500 km away from the mountain range (Tullborg et al., 1995; Cederbom, 2001). Following the Caledonian orogenic collapse, pressure release in the foreland caused uplift of the basin and enhanced erosion (Milnes, 1998; Plink-Björklund and Björklund, 1999). In southernmost Sweden, most of the sediments in the basin were stripped off and redeposited elsewhere during the Late Palaeozoic. None of the sediment originally deposited in the foreland basin remain in Sweden today. However, Late Palaeozoic fossils are identified in Mesozoic sediments in southernmost Sweden indicating an event of sediment reworking (Guy-Ohlson and Norling, 1988). During the Late Carboniferous to Early Permian, transtensional tectonics, possibly induced by the distant Variscan

orogeny in central Europe, caused a complex system of rifts and grabens to develop in the Skagerrak Sea (Erlström and Sivhed, 2001; Thybo, 2001). This probably also triggered the formation of the highly magmatic Oslo Rift in southeast Norway (Fig. 1) (Neumann et al., 1992). In addition, dolerite sills in southwest Sweden and dolerite dykes along the Sorgenfrei-Tornquist Zone in southernmost Sweden (Fig. 1) are associated with the Permian igneous activity (Klingspor, 1976; Tappe, 2004). Three pulses of basalt volcanism in Scania, at 191-180 Ma, 145 Ma and 110 Ma, have been associated with the contemporaneous tectonic activity in the North Sea region (Bergelin et al., submitted).

Preserved Cretaceous sediments in southernmost Sweden evidence that significant deposition occurred in this region at this period of time. Some indirect low-temperature thermochronological indications of Late Mesozoic sedimentation have been obtained by AFT borehole data at Oskarshamn (Larson et al., 1999) and from surface samples from western and southeastern Sweden (Cederbom 2002). During Cretaceous, inversional tectonics formed a system of horsts and grabens in Scania. Re-exhumation occurred during Neogene in southern Sweden, which caused the formation of the South Swedish Dome (e.g. Lidmar-Bergström and Näslund, 2002).

3. Analytical methods – an introduction

When placing time constraints on geological events, there are two main approaches: 1) Relative dating, which means that different events are placed in a relative chronological order, and can be constrained in the field by studying, for example, cross-cutting relationships between different rock units and/or deformational fabrics. 2) Absolute dating, which means that an age is determined for a specific event or process. The use of radioactive isotopes for absolute dating is often referred to as “radiometric dating”.

The known rate of decay (called half-life) of any radiogenic parent isotope to a stable daughter isotope is the basis of radiometric dating. The parent isotope was incorporated into a mineral when the mineral was formed. At high temperatures, the daughter isotopes will be mobile and able to diffuse through and possibly leave the mineral but, below a certain temperature (closure temperature, T_c), the daughter isotope will become immobile and thus

remain in the mineral. At this event, or temperature, the radiometric clock starts. Million of years later, we can measure the amount of both parent and daughter isotopes in the mineral – in short the ratio between parent and daughter isotopes will be a function of time. By knowing the decay constant for the specific radioactive isotope, we can calculate the exact age, which will reflect the amount of time elapsed since the mobility of the daughter isotope ceased or became negligible. Different minerals and different isotopic systems have different closure temperatures and the respective clocks will therefore start at different times. In this thesis, ^{40}Ar - ^{39}Ar geochronology has been used on hornblende, muscovite and biotite, with closure temperatures of c. 500 °C, 350 °C and 300 °C, respectively (McDougal and Harrison, 1999). These temperatures usually reflect cooling after a thermal event, such as the heating of rocks from nearby magmatic activity or metamorphism. (U-Th)/He thermochronology on apatite, with a closure temperature of c. 70 °C (Farley, 2002), has been used on surface and borehole samples from both Forsmark and Oskarshamn. The low T_c makes the (U-Th)/He method useful to constrain the latest tectonothermal evolution such as burial beneath sediments or late exhumation, driven either by tectonic activity or simply by erosion.

Apatite fission-track (AFT) thermochronology is also based on the radioactive decay of isotopes. However, there are considerable differences relative to other radiometric techniques. Rather than measuring a parent/daughter ratio, AFT thermochronology is based on the spontaneous fission decay of ^{238}U and involves analysing the tracks, or ‘fingerprints’, of such a process. In short, ^{238}U decays by spontaneous fission, which results in two highly and equally charged fragments. These fragments repel from each other due to the equal charge. On their way through a mineral, the fragments will cause damage in the atomic lattice (fission-tracks). Tracks will be continuously produced and always of a certain length in a specific medium (c. 16.5-15.9 μm in apatite). The tracks will anneal (=heal) instantaneously at high temperatures, whereas the annealing process is progressively slower between c. 120 °C and 60 °C (Gleadow and Duddy, 1981). Below 60 °C, annealing is negligible. The observed relationship between distribution of track lengths and geological time scale forms the

basis for the AFT technique.

In this project, AFT analyses were performed on samples from two boreholes at Forsmark and Oskarshamn, and compared with the results from (U-Th)/He apatite ages. By using the two techniques with similar T_c on the same sample, the accuracy of the two techniques can be tested.

4. Including papers

Paper I

Biotite and muscovite ⁴⁰Ar-³⁹Ar geochronological constraints on the post-Svecofennian tectonothermal evolution, Forsmark site, central Sweden. P. Söderlund, T. Hermansson, L. Page, M. Stephens. *Accepted for publication in International Journal of Earth Sciences.*

Background: Although several studies have addressed the tectonic evolution of the Svecofennian orogen, little is known about the cooling history following this major orogenic event. At Forsmark, the cooling history through 500 °C has been investigated by ⁴⁰Ar-³⁹Ar geochronology on hornblende (Hermansson et al., in review). In this paper, cooling through 350 °C and 300 °C at Forsmark was studied by ⁴⁰Ar-³⁹Ar dating of muscovite and biotite, respectively, at different levels in borehole samples and in several surface samples in different structural blocks.

Summary: Five cored boreholes and several surface samples (Fig. 2) were chosen for ⁴⁰Ar-³⁹Ar dating on biotite. In addition, two muscovite samples from one borehole were dated. The ⁴⁰Ar-³⁹Ar biotite ages indicate that the present erosion surface at Forsmark, central Sweden, cooled below 300 °C at 1.73-1.66 Ga. The results indicate that the changeover from ductile to brittle deformation occurred as early as between 1.8 Ga and 1.7 Ga. The variation in surface ages is suggested to reflect relative vertical displacement of crustal blocks separated by WNW to NW trending brittle deformation zones, after the establishment of the sub-Cambrian peneplain. Minor variation of ages within a single crustal block may be due to disturbance along ENE to NNE trending fracture zones. A model for the cooling history from 500 °C to 300 °C was calculated from ⁴⁰Ar-³⁹Ar hornblende, muscovite and biotite ages in the time interval from 1.80 Ga to 1.66 Ga, and an uplift rate of c. 22 m/m.y. was calculated from borehole biotite

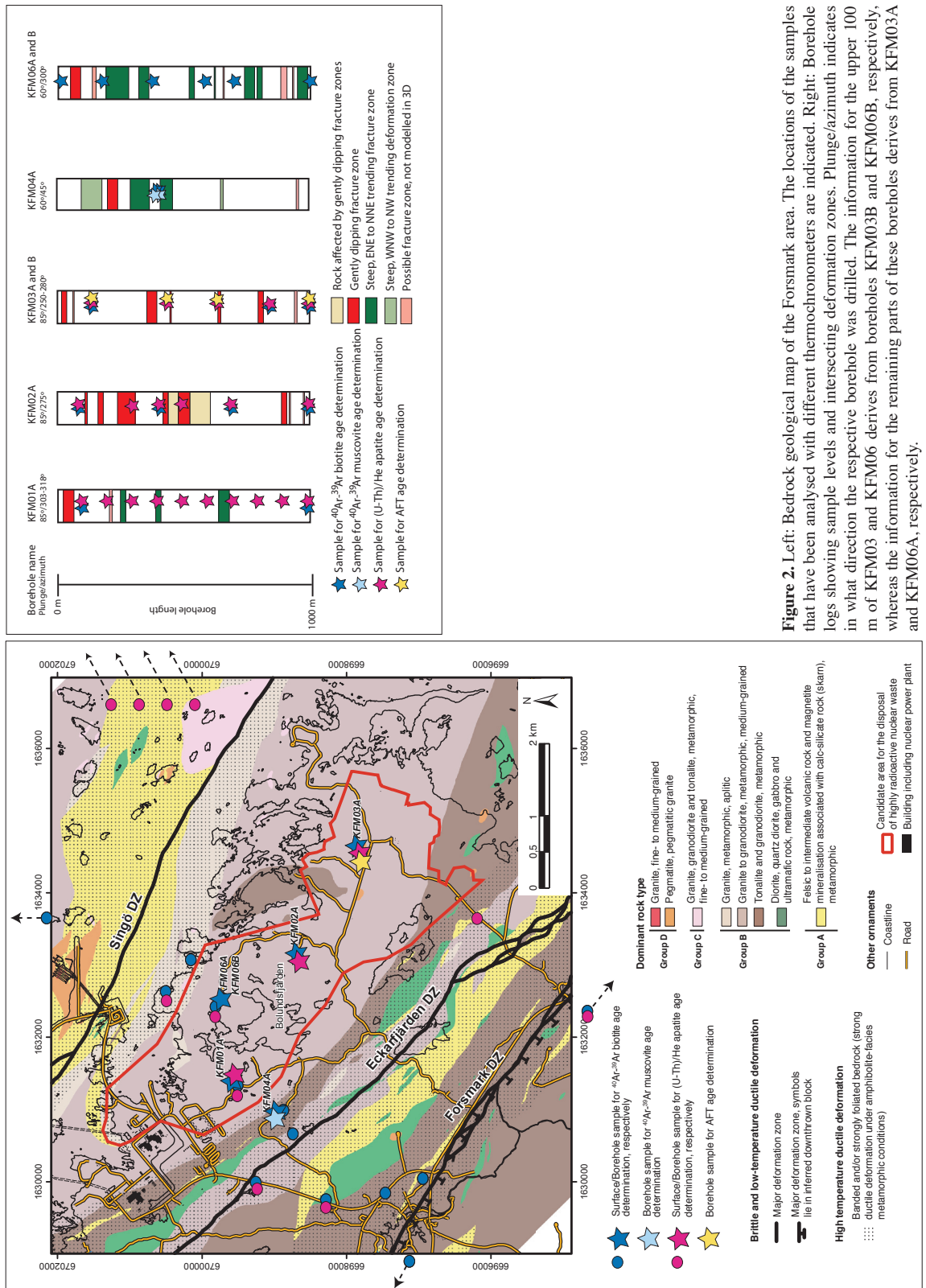
data for the time interval between 1.69 and 1.64 Ga. The combined cooling and uplift data reflect either simple cooling after the Svecofennian orogeny or, alternatively, crustal movement in response to the far-field effects of 1.7 Ga orogenic activity further to the west.

Paper II

⁴⁰Ar-³⁹Ar biotite and hornblende geochronology from the Oskarshamn area, SE Sweden: Discerning multiple Proterozoic tectonothermal events. P. Söderlund, L. Page, U. Söderlund. *In press, Geological Magazine.*

Background: The bedrock in the Oskarshamn area consists of c. 1.80 Ga TIB intrusions and subordinate c. 1.45 Ga granites. The cooling history after these separate events has previously been unknown. In this study, we investigate cooling through c. 500 °C and c. 300 °C by the use of ⁴⁰Ar-³⁹Ar hornblende and biotite geochronology, respectively, on borehole- and surface samples.

Summary: Three surface samples were dated with ⁴⁰Ar-³⁹Ar biotite geochronology (Fig. 3). Furthermore, various levels in three cored boreholes were dated by ⁴⁰Ar-³⁹Ar hornblende and biotite geochronology (Fig. 3). The ⁴⁰Ar-³⁹Ar hornblende and biotite data revealed three age groups: ≥ 1.62 Ga, 1.51-1.47 Ga and 1.43-1.42 Ga. In the first group, two hornblende analyses yielded ages of 1.80 Ga and 1.77 Ga, which were interpreted to date initial fast cooling of TIB rocks. Two biotite ages of 1.62 Ga were proposed to relate to regional cooling below 300 °C after intrusion of the youngest 1.67 Ga TIB rocks, which outcrop some 130 km west of the Oskarshamn area. The 1.51-1.47 Ga ages were enigmatic to interpret and three possible geological scenarios were discussed: 1) Partial resetting related to the thermal affects of the c. 1.45 Ga granite plutons. 2) Cooling following emplacement of distant rapakivi magmas that intruded episodically between c. 1.65 and c. 1.45 Ga. 3) Thermal activity related to the initiation of the Danopolonian event. None of the scenarios can be dismissed until further studies have been carried out. The 1.43-1.42 Ga biotite age group represents cooling ages following a thermal disturbance related to the intrusion of the c. 1.45 Ga granites in the studied area. Later events



have probably thermally affected the bedrock in the area as indicated by a poorly defined biotite age of 928 ± 6 Ma in borehole KSH03A. This is further indicated by ⁴⁰Ar-³⁹Ar dates at 989 ± 2 Ma and 401 ± 1 Ma of adularia in fracture zones in KSH03A (Drake et al., 2007).

Paper III

Extending the time range of apatite (U-Th)/He thermochronometry in slowly cooled terranes: Palaeozoic to Cenozoic exhumation history of southeast Sweden. P. Söderlund, J. Juez-Larré, L.M. Page, T.J. Dunai, 2005. *Earth and Planetary Science Letters* 239, 266-275.

Background: Since Phanerozoic sediments are absent in most of Sweden, other means than stratigraphic investigations are needed to constrain the Phanerozoic history. Prior to this study, only sparse (U-Th)/He work had been carried out on Precambrian rocks. Samples from different levels of a cored borehole in the Oskarshamn area (Fig. 3) had previously been dated with the AFT technique (Larson et al, 1999), which gave an excellent opportunity to compare (U-Th)/He ages with the existing AFT ages. If the (U-Th)/He technique proved to be successful, the young tectonic activity in the area could be constrained in detail.

Summary: Samples from two cored boreholes, 1000 m and 1700 m deep, respectively, and rocks from an inclined tunnel, from surface to 500 m depth, were analysed (Fig. 3). The F_T -corrected (U-Th)/He ages decrease with increasing depth from c. 270 Ma to c. 120 Ma. In the longer borehole, a change in slope in the age/depth relationship at the c. 1400 m level indicates a change in exhumation rate. From the data trend above the inflection point, a period of exhumation (c. 17 m/m.y.), suggested to be linked to the isostatic uplift of the Caledonian foreland basin, was revealed. The cessation of exhumation was estimated to have occurred at approximately 100 Ma. In comparison with samples from the same borehole, previously analysed with AFT thermochronology, the (U-Th)/He ages were consistently younger, as expected. However, the age difference was too small bearing in mind the accepted closure temperatures of the two systems. It was suggested that the AFT ages were too young due to radiation-enhanced annealing.

Paper IV

Assessment of discrepant (U-Th)/He and apatite fission-track ages in slowly cooled Precambrian terrains: a case study from SE Sweden. P. Söderlund, J. Juez-Larré, L.M. Page, F.M. Stuart, P.A.M. Andriessen. *Manuscript*

Background: This study initially aimed to constrain the regional low-temperature geological evolution of the Forsmark area, using (U-Th)/He analyses. Due to complications arising from the reliability of (U-Th)/He and/or AFT analyses (Paper III) performed on old, Precambrian rocks, additional (U-Th)/He analyses were carried out on Oskarshamn samples. Furthermore, AFT analyses were performed on two of the (U-Th)/He dated borehole samples at both sites. With the combined results from the two thermochronometers, the revised aims were: 1) To investigate possible problems pertinent to the application of the thermochronometers in ancient geological settings. 2) To obtain age constraints for the time when the temperature went from c. 120 °C to c. 40 °C, for the two areas.

Summary: Samples from four 1000 m deep borehole- and 15 surface samples at Oskarshamn and Forsmark, SE Sweden (Fig. 2 and 3) were dated with the (U-Th)/He method. Two boreholes, one previously dated with (U-Th)/He (Paper III) at Oskarshamn and one dated with (U-Th)/He at Forsmark were additionally analysed with the AFT method.

At Oskarshamn, the uncorrected (U-Th)/He ages and the AFT ages are identical, whereas at Forsmark, the AFT ages are younger than both the uncorrected and the corrected (U-Th)/He ages. Depth versus age trends in both data sets, at both sites, are comparable. We suggested that the systematic shift is controlled by α -recoil damage ((U-Th)/He system), possibly together with radiation-enhanced annealing (AFT system) in U-rich apatite, and incorrect F_T -correction due to heterogeneous distribution of U in apatites with a slow cooling history. Intra-sample (U-Th)/He age variations can be explained by variation in crystal morphology and by zonation of U and/or Th and the following effects on the F_T -correction. The effect of these factors becomes increasingly profound the longer the samples reside in the helium partial retention zone.

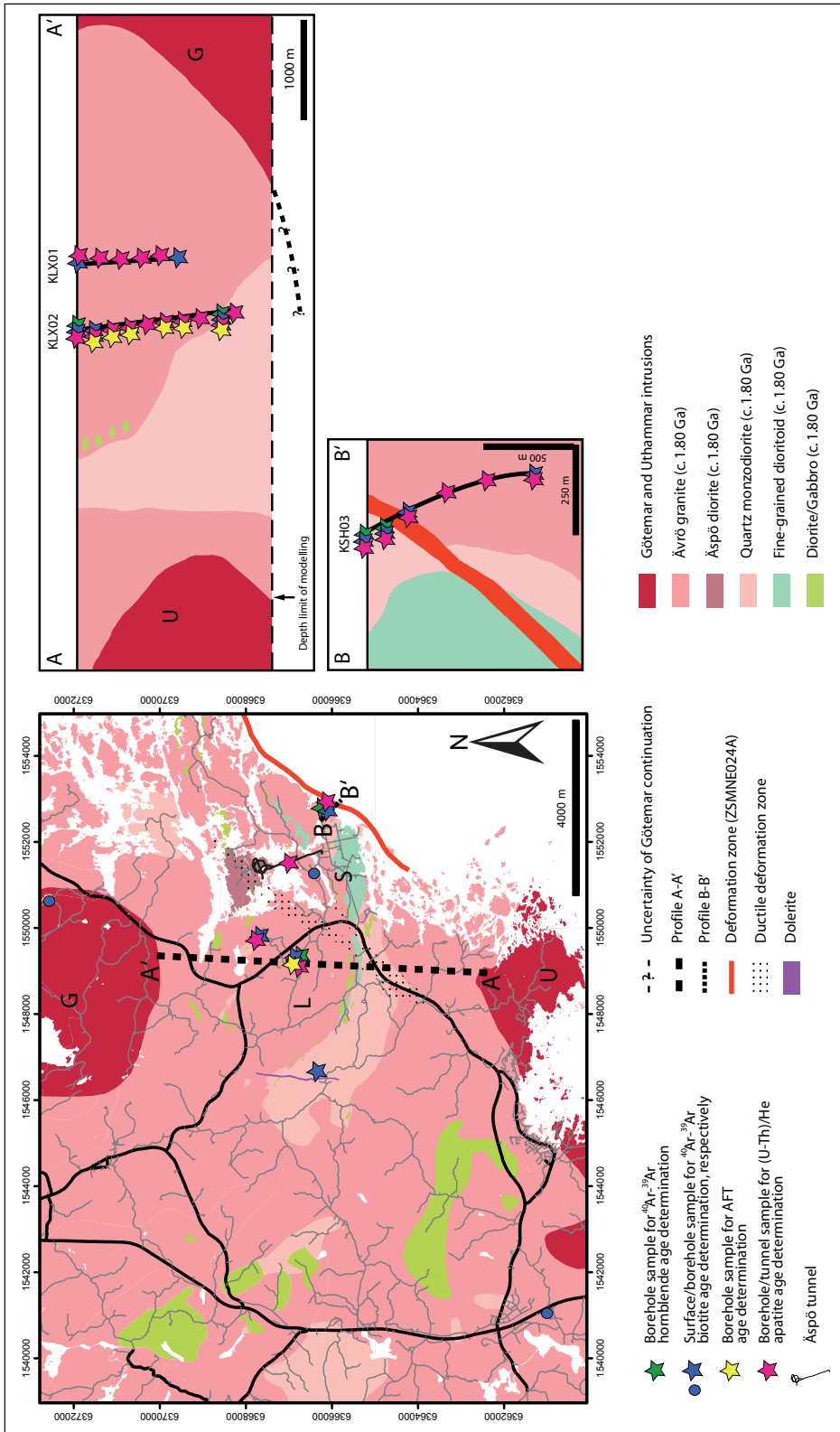


Figure 3. Left: Bedrock geological map of the Oskarshamn area. Profiles A-A' and B-B' are enlarged on figures to the right. G=Götemar granite, L=Laxemar investigation area, S=Simpevarp investigation area, U=Uthammar granite. Upper right: Profile A-A' of the bedrock at depth around boreholes KLX01 and KLX02. Lower right: Profile B-B' of the bedrock at depth around borehole KSH03. The bedrock map to the left is made after Permission M2001/5268, 2007-05-14, 09:43, from GSD-Fastighetskartan@Lantmateriet, Gävle 2001.

Thermal modelling of the AFT ages revealed identical thermal histories of the two areas. Complete track annealing indicates that the present surface was buried to a depth of >4 km after the sub-Cambrian peneplanation. Subsequent uplift started between Late Palaeozoic and Early Mesozoic time and waned c. 100 Ma ago. Uplift and denudation may have been related to transtensional tectonics in southernmost Sweden and/or extensive volcanic activity to the south and west. After the tectonically controlled uplift, continued exhumation was considerably slower. The thermal model allows for a c. 1 km sedimentary cover and/or a few hundred metres of new sediments younger than c. 100 Ma.

5. Discussion

5.1. Geological cooling histories of the Forsmark and Oskarshamn areas – a synthesis

The timing of early cooling subsequent to orogenic and magmatic activity in the Forsmark and Oskarshamn areas differ. At Forsmark, cooling from high temperatures to c. 300 °C reflects the later phase of the Palaeoproterozoic Svecofennian orogeny (Paper I). At Oskarshamn, the older hornblende and biotite ages (Paper II) reflect the initial cooling evolution, down to c. 300 °C, after the magmatic activity of the 1.85-1.65 Ga Transscandinavian Igneous Belt.

After the Svecofennian orogeny, the rocks at the present erosion surface in the Forsmark area cooled below 300 °C at 1.73-1.66 Ga, as indicated by ⁴⁰Ar-³⁹Ar biotite ages (Paper I). Some time between 1.8 and 1.7 Ga, the bedrock in this area could respond to stress by brittle deformation (Paper I). The cooling and exhumation (exhumation rate of c. 22 m/m.y. between 1.69 and 1.64 Ga) relate either to cooling after the Svecofennian orogeny, or to vertical movement in response to far-field effects of 1.7 Ga orogenic activity further to the west, or a combination of the two (Paper I). Since there are no time constraints on the period from late Palaeoproterozoic (i.e. from 1.66 Ga) to Early Palaeozoic, it is difficult to discern the thermal evolution of the Forsmark area during this time period. However, the absence of ⁴⁰Ar-³⁹Ar biotite ages younger than 1.66 Ga demonstrate that the area stayed at temperatures below 300 °C since that time, although later events locally had an influence, as indicated by younger ⁴⁰Ar-³⁹Ar adularia ages in fracture zones (Sandström et al., 2006).

Our ⁴⁰Ar-³⁹Ar hornblende data in Paper II, indicate that the Oskarshamn area cooled rapidly (within a few million years) down to 500 °C after the emplacement of 1.80 Ga TIB intrusions. Continuing cooling of the rocks may have been slowed down or temporarily interrupted by younger TIB intrusions until the area cooled below 300 °C at 1.6 Ga, reflected by two biotite ⁴⁰Ar-³⁹Ar ages from one sample. Younger biotite ⁴⁰Ar-³⁹Ar ages (1.51-1.47 Ga) may represent incomplete resetting during thermal heating from the c. 1.45 Ga Götömar and Uthammar intrusions. However, the narrow time span of this age group, together with the presence of similar ⁴⁰Ar-³⁹Ar hornblende ages in the nearby Loftahammar-Linköping Deformation Zone indicate that the bedrock may have been affected by thermal activity either related to the youngest manifestations of rapakivi intrusions or to the initiation of the Danopolonian event in the south (Paper II). The intrusion of the c. 1.45 Ga Götömar and Uthammar granites caused heating and resetting of the ⁴⁰Ar-³⁹Ar hornblende and biotite system in the adjacent bedrock, which subsequently cooled below c. 500 °C at c. 1.44 Ga and below c. 300 °C at 1.43-1.42 Ga (Paper II). A younger magmatic pulse, evident by a dolerite dyke, occurred at c. 900 Ma. The ⁴⁰Ar-³⁹Ar biotite ages of this dyke are younger than the 978-946 Ma Blekinge-Dalarna-Dolerites but they may all be reflecting the period of crustal extension at the waning stage of the Sveconorwegian orogeny.

The similar results of AFT modelling from both Oskarshamn and Forsmark (Paper IV) indicate that both areas underwent practically the same cooling evolution, at least during the later part of the Palaeozoic until Early Cretaceous. Prior to the results published in Paper III and Paper IV, AFT studies suggested that the Oskarshamn area was covered by c. 3 km thick Palaeozoic sedimentary rocks (e.g. Larson et al., 1999; Cederbom, 2001). The cover in Forsmark was assumed to be somewhat thinner due to only partially reset AFT ages (Larson et al., 1999; Cederbom et al., 2000). In paper IV, we suggest that both areas were covered by >4 km of overburden prior to exhumation, as indicated by totally reset AFT ages. Uplift is recorded for the period between c. 200 and c. 100 Ma when the temperature was low enough for fission-tracks to start to accumulate. However, it is possible that uplift started earlier but that temperatures were still high

enough to continuously heal the tracks. The period of uplift can possibly be linked to Late Palaeozoic and Mesozoic transtensional tectonics along the Sorgenfrei-Tornquist Zone in southernmost Sweden (Erlström and Sivhed, 2001) and/or to doming effects from contemporaneous extensive volcanism in areas west and south of the studied areas (e.g. Klingspor, 1976; Bylund and Halvorsen, 1993; Torsvik et al., 2008; Bergelin et al., submitted). Both (U-Th)/He and AFT data indicate that uplift finally waned at c. 100 Ma, which coincides with the latest volcanism in southernmost Sweden (c. 110 Ma, Bergelin et al., submitted). Contrary to earlier indications of Mesozoic reheating (Larson et al., 1999), the new data solely allow for a c. 1 km thick remnant cover and/or a few hundred metres of new sediments deposited after c. 100 Ma. Although the tectonically induced uplift waned, exhumation due to denudation has probably occurred until present time.

5.2. Reflections on the AFT and (U-Th)/He systematics

The too small difference between the (U-Th)/He ages in Paper III and earlier AFT ages (Larson et al., 1999) was suggested to relate to enhanced track-annealing of the fission-tracks, which lowered the AFT ages. In Paper IV, it was shown that the new AFT ages and the uncorrected (U-Th)/He ages from the same borehole at Oskarshamn yielded identical ages and similar thermal evolution models. As of now, there is no explanation why the two AFT data sets differ (i.e. the data set obtained by Larson et al., 1999 and the one presented in Paper IV).

Along with the AFT and (U-Th)/He analyses presented in Papers III and IV, we looked at zoning patterns of U in apatite, grain size and morphology of different samples and estimated U concentration. The results showed that the zoning pattern was extremely complex for Forsmark apatites, that the grain size was generally smaller than in Oskarshamn and that apatite grains in general were more euhedral in Oskarshamn samples than in Forsmark samples. These observations, together with the older (U-Th)/He ages and larger intra-sample variability, lead us to be careful in interpreting the (U-Th)/He ages and give more credibility to the AFT ages, why these were used for the geological interpretation.

The results in Paper III and Paper IV show some of the difficulties to interpret (U-Th)/He and

AFT analyses of apatite from old terrains. Careful selection of individual apatite grains with similar 3D grain morphology and absence of inclusions are fundamental criteria. Clearly, control of zonation patterns, preferably of both U and Th, and possibly also of He, is needed to correctly apply an individually adjusted F_T -correction. Future studies that aim to investigate the diffusion mechanisms of He through zoned apatite grains are viable in order to accurately calculate the F_T -correction factor. Our results indicate that this factor is unique for each individual grain.

In Paper IV, the overlap in AFT and (U-Th)/He ages for the Oskarshamn samples, and similarity of thermal evolution models, indicate that the T_C of the (U-Th)/He system may be underestimated and vice-versa for the T_C of the AFT system. More studies are needed to understand the mechanisms of enhanced He-retention in radiation-damaged crystal lattice and radiation-enhanced track-annealing of these thermochronometers. Single AFT or (U-Th)/He data sets should be interpreted with extreme caution and humbleness.

6. Conclusions

- * The bedrock in the Forsmark area started to respond to stress in a brittle way some time between 1.8 and 1.7 Ga. The present surface cooled below c. 300 °C between 1.73 and 1.66 Ga (^{40}Ar - ^{39}Ar biotite ages) and the area hasn't been heated above 300 °C since, except for local influence in fracture zones. The cooling below 300 °C relates either to cooling after the Svecofennian orogeny, or to vertical movement in response to far-field effects of 1.7 Ga orogenic activity further to the west, or to a combination of these two processes.
- * The 1.80 Ga batholith at the Oskarshamn area, belonging to the Transscandinavian Igneous Belt, cooled rapidly (within 25 m.y.) down to c. 500 °C (^{40}Ar - ^{39}Ar hornblende ages) after crystallisation. Subsequent cooling may have been slowed down or temporarily interrupted by younger TIB intrusions until the area cooled below c. 300 °C at 1.6 Ga (^{40}Ar - ^{39}Ar biotite ages). A 1.51-1.47 Ga ^{40}Ar - ^{39}Ar biotite age group reflects either incomplete resetting by younger granitic intrusions in the area or thermal activity related to either the youngest

rapakivi intrusions or to the initiation of the Danopolonian event in the south. The c. 1.44 Ga ⁴⁰Ar-³⁹Ar hornblende age and 1.43-1.42 Ga ⁴⁰Ar-³⁹Ar biotite ages represent cooling after local heating by c. 1.45 Ga granitic intrusions in the area.

- * Similar apatite fission-track age results and thermal models of the Forsmark and Oskarshamn areas show that both sites were heated above c. 120 °C prior to 200 Ma and that the present surface, at that time, was at c. 4 km depth. Uplift is recorded for the period between c. 200 and c. 100 Ma, which may reflect Late Palaeozoic and Mesozoic transtensional tectonics along the Sorgenfrei-Tornquist Zone in southernmost Sweden and/or to doming effects from contemporaneous extensive volcanism in areas west and south of the studied areas. After c. 100 Ma only minor amounts of sediment can have accumulated in the two areas.
- * Heterogeneous distribution of U in apatite, together with large intra-sample age variations indicates that the F_T-correction factor is not uniform but unique for individual grains. Therefore, future studies aimed to understand the diffusion mechanism of He through apatite are necessary.
- * The discrepant (U-Th)/He and AFT ages with similar age/depth relationship, show that the mechanisms controlling enhanced He-retention in radiation-damaged crystal lattice and radiation-enhanced track-annealing are not fully understood.

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Appendix

Other contributions not included in the thesis:

Reviewed articles:

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- Page, L., Söderlund, P., Wahlgren, C.-H., 2007. $^{40}\text{Ar}/^{39}\text{Ar}$ and (U-Th)/He Geochronology of samples from the cored boreholes KSH03A, KSH03B, KLX01, KLX02 and the access tunnel to the Äspö Hard Rock Laboratory. Oskarshamn site investigation. Swedish Nuclear Fuel and Waste Management Company, Stockholm, SKB P-07-160.
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