Post-Sveconorwegian exhumation and cooling history of the Evje area, southern Setesdal, Central South Norway

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Hansen, K., Pedersen, S., Fougt, H. & Stockmarr, P. 1996: Post-Sveconorwegian exhumation and cooling history of the Evje area, southern Setesdal, Central South Norway. *Nor. geol. unders. Bull. 431*, 49-58.

Fission track (FT) dating of apatite and sphene from monzonitic dyke rocks in a Middle to Late Proterozic intrusion from the Setesdal region, southern Norway, indicates cooling from intrusion temperatures to temperatures of the surroundings of approximately 250°C before 800-600 Ma. Fluid inclusion studies suggest the crustal depth to have been in the order of 4-5 km at the time. Apatite FT results indicate that during the Palaeozoic the rocks which now occur in the southern Setesdal region were subjected to heating above the closing temperature of apatite. Apatite FT-length distributions and fission track ages of nearly 300 Ma indicate that the region had been buried to a depth of more than c. 4 km before this time.

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Introduction

The Precambrian rocks of the Telemark-Agder-Rogaland area of southern Norway were formed during the Middle Proterozoic and the geological picture which appears today is a result of deformation processes during the Sveconorwegian/Grenvillian Orogeny (see, for instance, Berthelsen 1980). The effects of Caledonian deformation have not been documented within Central South Norway. The Precambrian evolution was followed by the formation of a sub-Cambrian peneplain which was covered by Lower Cambrian continental and shallow-marine sediments up to the Caledonian Front (e.g. Oftedahl 1980). The sedimentary record from both within and outside the Oslo Rift indicates that sedimentation continued into the Permian; and a sub-Permian peneplain was formed in the Oslo Rift representing a major phase of erosion of older sedimentary rocks (sandstones, limestones, shales and phyllites). Bjørlykke (1983) suggested on the basis of sedimentation features and sea-level changes that basinal subsidence occurred in the Oslo region in Cambro-Silurian time.

In the southern Setesdal area, which is considered here, pre-Sveconorwegian rocks include supracrustals and granitic to granodioritic intrusions with an assumed maximum age of 1350 Ma based on Rb/Sr whole-rock analyses (Pedersen 1980). This age has recently been reconsidered by Pedersen & Konnerup-Madsen (1994a,b) and a more realistic age of 1290 Ma has been calculated. Reliable ages greater than 1290 Ma in the Telemark-Agder-Rogaland area are rare although higher ages have been obtained on zircons and baddeleyites from Telemark (S. Dahlgren, pers. comm. 1995). The major crust-forming event apparently took place 1150-1100 Ma ago and included the accumulation of volcanic rocks, dominantly acidic but with basic components associated with plutonic rocks and interlayered immature sediments (Pedersen & Konnerup-Madsen 1994a,b).

During the last part of the Sveconorwegian Orogeny, rocks belonging to the Setesdal Igneous Province (Pedersen 1988) were emplaced into a heated crust. The Setesdal Igneous Province is divided into an older group consisting of a complex of granodioritic and dioritic rocks, and a younger group which includes a series of complicated minor and generally bimodal (granitic/monzonitic) subvolcanic rock complexes (Pedersen & Konnerup-Madsen 1994a). Minor bodies of granitic and monzonitic composition occur throughout the area suggesting that additional bimodal bodies may be present below the present-day surface. Associated with the bimodal rock bodies are the famous Iveland-Evje rare mineral bearing pegmatites (Bjørlykke 1934, Barth 1947, Fougt 1993, Stockmarr 1994.).

The present study includes a number of fission track (FT) age determinations on apatite and sphene from monzonites from one of the bimodal complexes, the Høvringsvatn Complex (Fig. 1), which belongs to the younger group of magmatic rocks within the Setesdal Igneous Province. The geology of the Høvringsvatn Complex has been studied by Pedersen (1975, 1980) who also carried out age determinations on the rocks. Rb/Sr whole-rock age studies yielded ages in the order of 900 to 950 Ma (Pedersen 1980).

The investigated area

The Høvringsvatn Complex (Fig. 1) includes rocks of granitic and monzonitic compositions. The outcrop pattern indicates that the monzonite is situated below the grani-

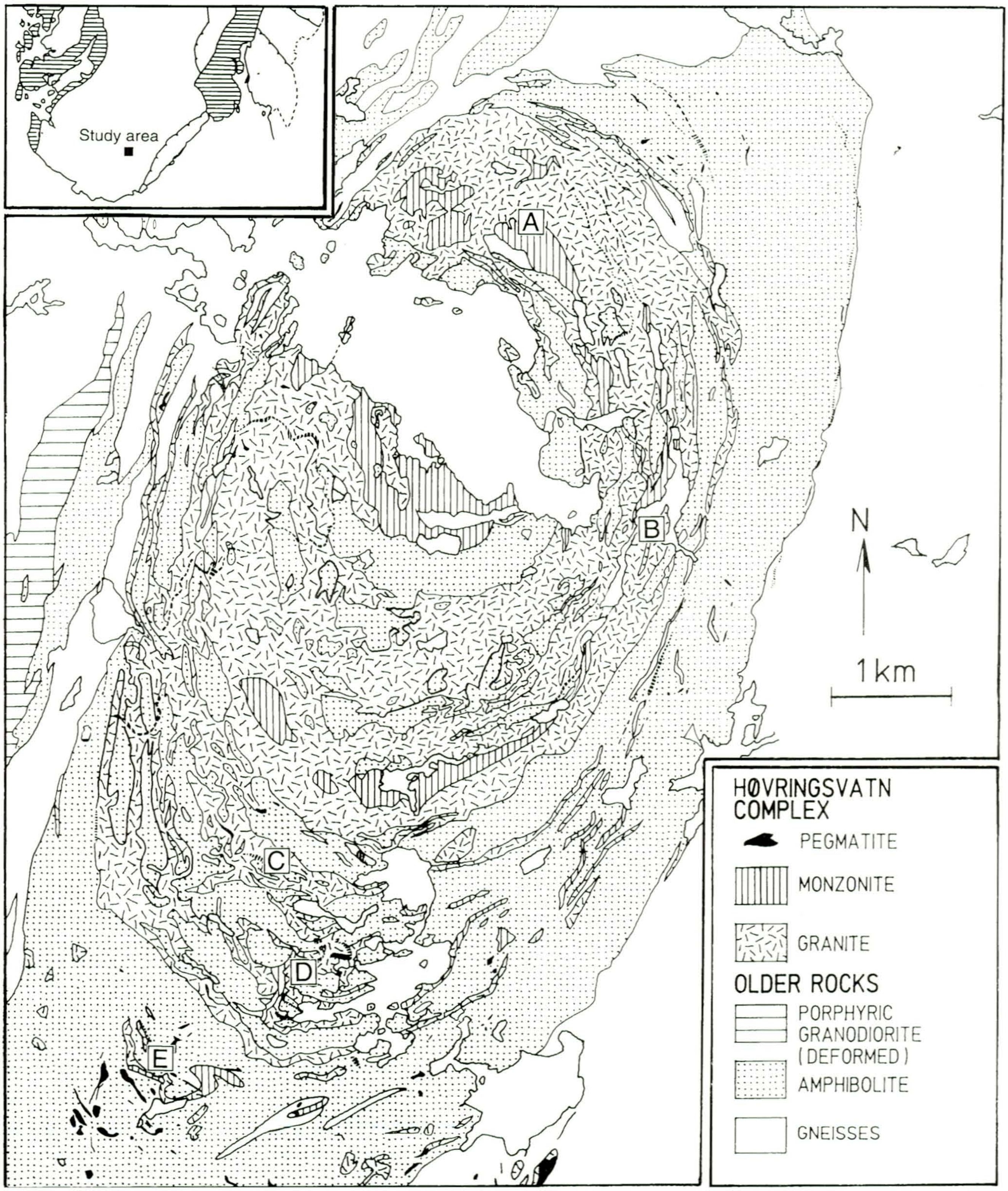

Fig. 1. Geological map of the Høvrngsvatn Complex. Sample localities are indicated (A= 1095, B=1092, C=91585, D= 91594, E=91602).

te, and that the present level of erosion is close to the roof of the intrusion. An important feature of the Høvringsvatn Complex is the development of cone sheet systems including granitic as well as monzonitic sheets. These cone sheets clearly cross-cut the main monzonite/granite body. A younger element is that of a horizontal system of monzonitic dykes which is interpreted as forming part of a bell-jar structure. Along with these two dyke systems, irregular minor bodies of monzonite or monzonite associated with granite are abundant. The youngest rocks belonging to the Høvringsvatn Complex are pegmatites. These occur in swarms especially in the southern part of the complex.

Rb/Sr whole-rock age determinations by Pedersen (1980) yielded ages of 945 ± 53 Ma (2σ) for the Høvringsvatn Complex granite and 900 ± 53 Ma (2σ) for the monzonitic cone sheet rocks, respectively. Initial Sr isotope ratios are 0.7041 ± 0.0007 for the granite and 0.7040 ± 0.0002 for the monzonitic rocks. Rb/Sr ages on minerals from two samples of the granite yielded mineral isochron ages of 921 ± 34 Ma (2σ) (whole rock - biotite: 929 ± 20 Ma (2σ)) and 853 ± 28 Ma (2σ) (whole rock - biotite: 874 ± 28 Ma (2σ)), respectively. A K/Ar age on biotite from the last sample yielded 856 ± 62 Ma (Pedersen 1973). This age is in accordance with earlier published K/Ar ages on micas from pegmatites immediately to the south. A biotite from Håverstad yielded 871 Ma (Neumann 1960) while a muscovite from Iveland gave 847 Ma (Kulp & Neumann 1961). Outside the Høvringsvatn Complex minor monzonitic and granitic bodies occur. These may belong to the complex or possibly to other, subsurface plutonic massifs.

Field relationships suggest a rather elevated temperature and a moderate pressure in the region during the intrusion of the monzonitic and granitic melts. Within the Høvringsvatn Complex irregular contacts between the intrusive rocks and their host are seen especially when the host has an acidic or intermediate composition, whereas intrusions in rocks with a basic composition exhibit more or less rectilinear contacts. Internal contacts (1) between granite and monzonite and (2) between different pulses of monzonite show very intricate structures, some of which may be primary, i.e. flow-related structures. These contact relations and the presence of abundant xenocrysts of alkali feldspars and quartz from the granite in some types of monzonite suggest that the granite was not quite consolidated when the monzonite intruded. In a single case, eutectic melting of the host - a gneiss with a granitic composition - during intrusion of a 5 m wide monzonitic dyke can be demonstrated. Pedersen (1980) suggested from studies of the granite system that this gneiss would melt eutectic at c. 600° C at a pressure below 5 kb.

Indications of the pressure conditions are also given from the intrusive pattern of the bimodal complexes. Evolution of cone sheets and horizontal dyke systems are usually limited to high or intermediate levels in the crust, and these are generally considered to be subvolcanic. The morphology of the associated chamber pegmatites indicates emplacement under conditions of horizontal stress in a brittle environment at depths of 4-6 km (Fougt 1993 and Stockmarr 1994, following the ideas of Brisbin 1986).

The above indications taken together point towards a temperature at the time of monzonite/granite emplacement in the order of 600° C and a pressure below 5 kb, probably as low as 3-4 kb. The region was subjected to ductile deformation after the formation of the monzonites, and this especially affected the monzonitic dykes and resulted in very complicated fold patterns. The granite/monzonite body as well as the host gneisses, on the other hand, were deformed to only a minor degree. Estimates of the P/T conditions from studies of fluid inclusions in the pegmatites indicate a minimum temperature at emplacement of 430° C and a pressure of 1.4 kb. The same studies indicate that the lowest temperature in the pegmatites during their formation was 280° C (Fougt 1993). This also means that the temperature in the host rock could not have been higher than 280° C at that time.

A combination of the fluid inclusion study and K/Ar and Rb/Sr age determinations indicates that the crustal conditions 850 Ma ago corresponded to a temperature of 250-280° C and a depth of around 4-5 km (equal to 1.4 kb) (Fougt 1993, Stockmarr 1994).

Fission track (FT) studies

Previous fission track (FT) studies in southwestern Scandinavia

Zeck et al. (1988) reported FT ages from the Fennoscandian Shield west of lake Vänern, southern Sweden. Sphenes yielded pre-Caledonian FT ages and apatites post-Caledonian FT ages and skewed FT length distributions. Their data suggest cooling below c. 250° C at c. 680 Ma ago and a post-Caledonian burial depth of 3-4 km. Hansen (1995) recorded similar burial depths from the island of Bornholm, which are due to a blanket of overlying sediments of c. 4 km thickness.

The evolution of the Oslo Rift has been investigated by Rohrman et al. (1993, 1994a) employing FT dating analysis. The ages obtained for the rift flanks and floor yield a thermal and uplift history related to the rift evolution compared to the surroundings. Rohrman et al. (1994b, 1995) investigated the morphotectonic evolution of southern Norway and considered the post-Palaeozoic history to be related to exhumation and basin extension followed by Neogene domal uplift and erosion. Their results showed a systematic increase in apatite FT ages inland in Norway.

Principles of the fission track method

The FT method is an age determination method which takes advantage of the time-dependent sensitivity of fission tracks to temperature. Each track keeps a record of its thermal history experienced in the temperature-sensitive interval (the annealing interval, closure or annealing temperature corresponds to 50% annealing for a simple cooling path (Naeser 1979)). In this interval, tracks can be retained but are shortened in response to temperature and time; thus, the track length distribution contains a record of maximum temperatures experienced during cooling and heating. For apatite the most sensitive interval is c. 120-60°C shifting both with composition and towards higher or lower temperatures for shorter or longer heating times, respectively (e.g. Gleadow et al. 1983, 1986, Green et al. 1989). For sphene, the closure temperature is approximately 250-200°C (Gleadow & Brooks 1979, Hurford 1986).

FT analysis of apatite is especially suited to evaluating the low-temperature history, combining evidence from FT age determinations and track-length distributions in a numerical model (e.g. Jensen et al. 1992) based on experimental work (Green et al. 1989). Knowing the track density, length distribution and uranium concentration, a thermal history can be determined. Combined with other geological information the thermal history can be interpreted in terms of tectonic development involving, for example, subsidence by burial or uplift due to exhumation which brings the rock to the surface by tectonic and/or erosional removal of the overburden. Alternatively, the thermal history could reflect changes in the thermal regime such as changing geothermal gradients.

Samples studied and analytical technique

In the present study, 5 samples of monzonitic dykes from the Høvringsvatn Complex were studied by the FT method. The samples were collected within the best mapped intrusion in the Setesdal Igneous Province in order to obtain a well defined geological control of the sampling.

The samples were crushed and separated using conventional magnetic and heavy liquid separation techniques. All samples yielded abundant apatite and sphene, while zircon occurred in much lesser amounts. The *apatites* were mounted in Araldite, polished, etched in 1N HNO_3 for c. 30 seconds at room temperature to obtain

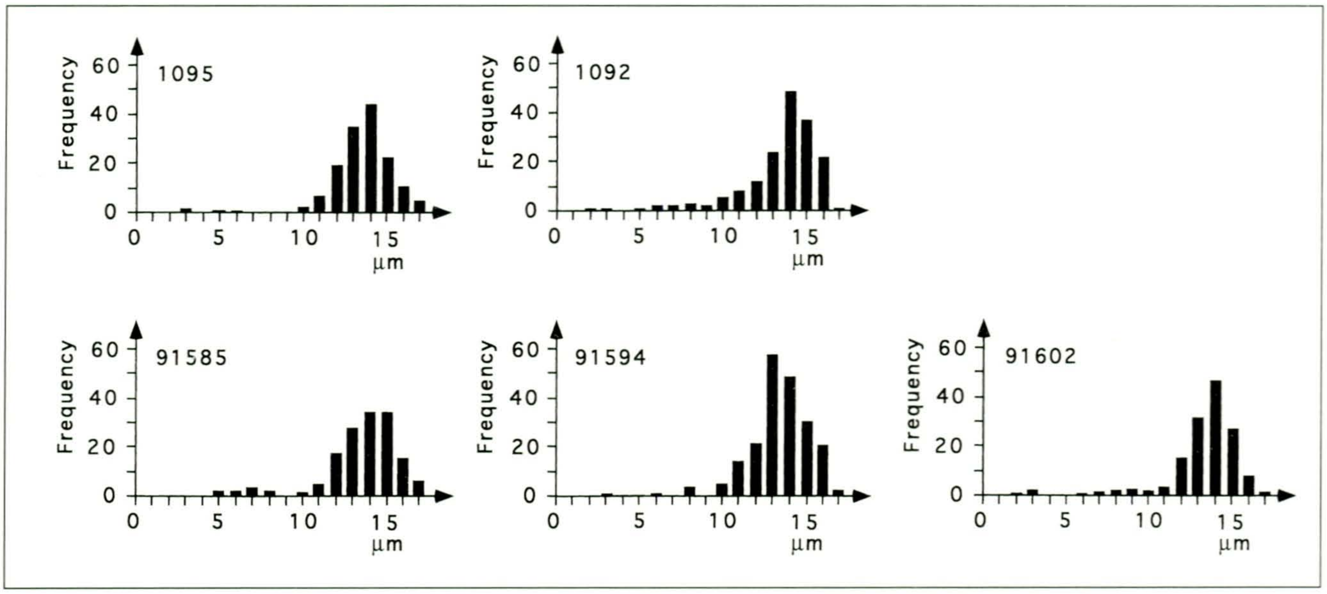

Fig 2. Measured apatite FT length distributions, Setesdal, Norway.

Table 1. Fission track ages for apatites from Setesdal, Norway.

Sample no.	FT age (Ma) ± 1σ	$\rho_s \times 10^5$ (number)	$\rho_i \times 10^5$ (number)	$\rho_d \times 10^5$ (no.) SRM612 CNI CN2	χ^2 P% grains (no.)
91602	202.94±16.52	31.06(398)	33.95(435)	13.86211(1844) 39.45161(1944) 37.59841(1853)	31% (20)
91594	223.72±14.90	17.97(766)	17.83(760)	13.74161(1827) 40.26323(1984) 37.42449(1844)	78% (20)
91585	241.13±23.53	5.127(271)	4.711(249)	13.76571(1831) 40.10091(1976) 37.45927(1846)	86% (18)
1095	281.89±27.71	5.899(290)	4.618(227)	13.81391(1837) 39.77626(1960) 37.52884(1850)	41% (20)
1092	307.07±31.78	4.596(269)	3.298(193)	13.78981(1834) 39.93858(1968) 37.49406 (1848)	>99% (19)

Rho_s, rho_i, and rho_d are track densities for spontaneous, induced and standard glass, respectively. Zeta values used are for the glass standards SRM612 324.7(3.37%), CN1 112.70 (3.61%) and CN2 121.65(3.75%). Age uncertainties are based on counting statistics and zeta value uncertainties (Galbraith 1981).

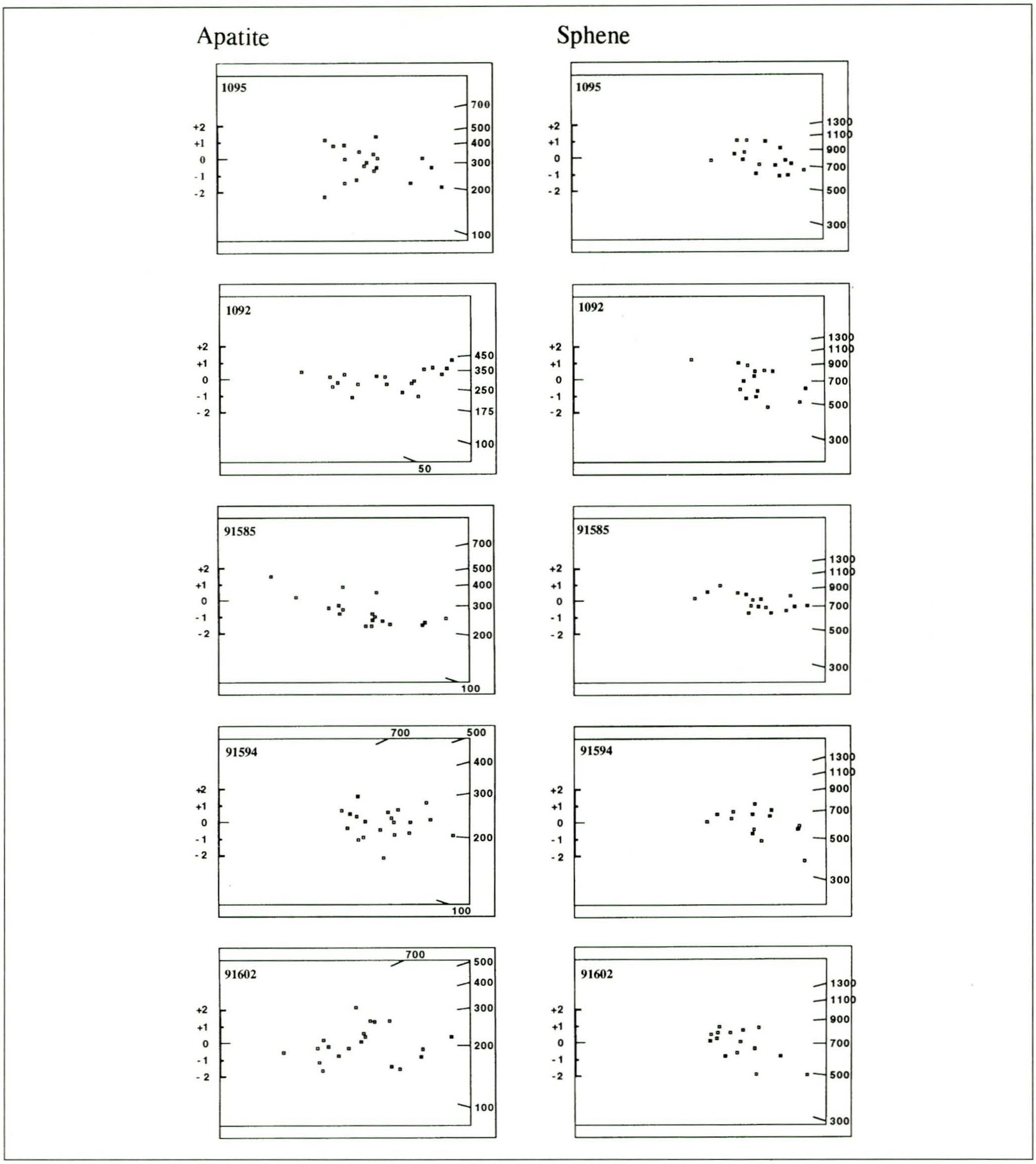

Fig. 3. Radial plots of apatite and sphene FT grain ages from samples from Setesdal, Norway.

fully etched fission tracks, wrapped in alu-foil against a low-uranium mica detector and irradiated in the DR-3 reactor at Research Center Risø, Roskilde, Denmark, with a nominal fluence (the time-integrated neutron flux) of c. 9 x 10^{15} thermal neutrons/cm^2. After irradiation the micas were etched in 40% HF for c. 38 minutes to obtain induced tracks, giving a measure of the uranium concentration in the apatite grains. Mounts and micas were mounted on an object glass and similar areas in prismatic crystal faces of apatites and mica mirror images were counted (dry) under a Zeiss Universal Microscope at a nominal enlargement of c. x1600 in transmitted light. The calibration was carried out following the suggestions of Hurford & Green (1983), using apatite from the Fish Canyon tuff

Table 2. Apatite length distributions form Setesdal, Norway.

Sample no.	mean length (μm)	uncertainty (μm) 1 σ	no. of tracks measured
91602	13.19±0.19	2.38	151
91594	13.41±0.13	1.88	205
91585	13.51+0.18	2.23	149
1095	13.45±0.17	2.07	149
1092	13.42±0.19	2.45	171

(Naeser et al. 1981) and the Mt. Dromedary banatite (Miller et al. 1990) as age standards. Fluence was monitored using the glass standards NBS612, CN1 and CN2, the last two obtained from Corning Glass Works, USA.

Zircon and *sphene* were mounted in Teflon, etched in a eutectic melt of KOH-NaOH at c. 230°C and a mixture of HF, HNO_3, HCl and H_2O, respectively, wrapped in mica, irradiated and counted at c. x1600 (oil) enlargement in transmitted light. Again, only prismatic faces were counted. The calibration procedure was as for the apatites, but using Fish Canyon zircon (Naeser et al. 1981) and Mt. Dromedary sphene (Miller et al. 1990) for a common calibration of zircon and sphene. The Setesdal zircons were not well suited for FT determination, crumbling during the etching of most grains, whereas the sphenes yielded well etched mounts. In this paper only apatite and sphene will be considered.

Track-length measurements for apatite were carried out measuring only the totally included horizontal tracks parallel to prismatic faces, using a Kurta digital tablet at high resolution connected to a computer. The precision of the measurements is believed to be better than 0.2 μm.

Results

Apatite fission track ages vary between c. 200 and 300 Ma (Table 1) and length measurements (Table 2) show mean track lengths of c. 13.5 μm and skewed length distributions (Fig. 2) dominated by a single-stage exhumation pattern (Gleadow et al. 1986). The FT ages and length distributions suggest that this pattern is of post-Caledonian age and that cooling below temperatures of 60-70°C (e.g. Gleadow et al. 1986) probably occurred rather late. Differences in the cooling paths are suggested by the pattern of the apatite ages.

Radial plots (Galbraith 1990) depict uncertainty versus age for single grain ages (Fig. 3). The uncertainty bar on the left hand side in each diagram applies to all points in the diagram. Age uncertainties can be obtained by drawing a line through the centre of the uncertainty bar on the y-axis and the 1σ or 2σ ends of the bar transferred to the point to the age scale. Precision increases towards the right side of the diagram. From the diagrams for apatites it can be seen that the statistical uncertainty may be the only parameter responsible for the variation in age in each sample, although compositional differences may cause additional variation.

Sphene fission track ages (Table 3) vary between 590 and 790 Ma. These post-Sveconorwegian - pre-Caledonian ages represent points on the pre-Caledonian cooling paths which preceded general uplift and peneplanation of southwestern Scandinavia (e.g. Oftedahl 1980). Radial plots (Fig. 3) show that single-grain age variations may be due to statistical variation solely for sphenes.

Model calculations

The modelled thermal history (Fig. 4) is based on apatite FT length distribution and FT age (Jensen et al. 1992). The program uses the experimental results and the annealing model of Green et al. (1989). The age of the oldest track, which is also the shortest, in each sample is calculated in an inverse calculation procedure which also gives ages and temperatures of individual histogram columns. This inverse calculated thermal history is then adjusted to the measured histogram in a forward calculation avoiding

Table 3. Fission track ages for sphenes from Setesdal, Norway.

Sample no.	FT age (Ma) ± 1σ	ρ_s x 10^5 (number)	ρ_i x 10^5 (number)	ρ_d x 10^5 (no.) SRM612 CNI CN2	χ^2 P% grains (no.)
91602	675.23±52.70(48.25)	270.5(1150)	55.52(236)	8.77591(1784) 26.36207(1949) 25.16981(1861)	61% (15)
91594	590.16±45.64(42.05)	187.5(1021)	44.80(244)	8.89250(1810) 26.45426(1956) 25.42633(1880)	76% (15)
91585	730.48±61.98(57.95)	139.0(997)	26.35(189)	8.79777(1789) 26.37936(1951) 25.21791(1866)	>99% (16)
1095	786.88±67.37(63.08)	146.2(1039)	25.75(183)	8.86700(1803) 26.43409(1954) 25.37021(1876)	92% (16)
1092	686.88±61.37(57.78)	146.7(838)	29.76(170)	8.83421(1796) 26.40817(1952) 25.29807(1871)	70% (16)

As Table 1 but the zeta values used are for SRM612 329(1.74%), Cn1 111 (2.03%) and CN2 118 (1.99%). Figures in parantheses in column 2 represent counting statistic uncertainty for individual grains and their mica images alone.

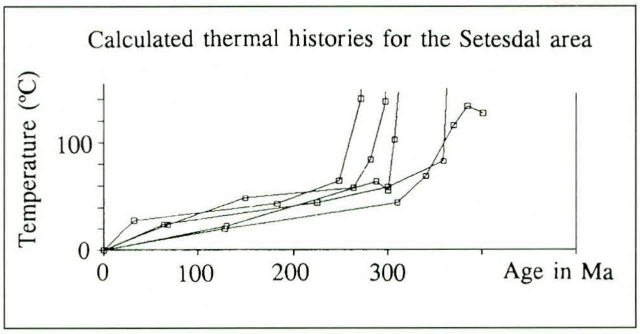

Fig. 4. Calculated thermal histories of samples from Setesdal, Norway.

scatter assumed to relate to uncertainties in the measurements. The obtained thermal history is believed to represent a possible post-Caledonian geological thermal history for the area, best in the low-temperature part due to the higher number of measured tracks in that part of the histogram. Calculated histograms are shown in Fig. 5 and are seen to have similar shapes to the measured histograms.

Disregarding the rather uncertain evidence from the oldest tracks, the modelling suggests that there has been a long period of constant cooling since 250 - 300 Ma BP. This cooling was presumably related to uplift and erosion following a period of higher temperatures, indicating a burial before 250-300 Ma of 3 - 6 km (geothermal gradient 20 - 40°C/km and maximum temperatures for accumulating fission tracks in apatite of 120°C, e.g. Gleadow et al. 1986). The rate of cooling was perhaps slightly enhanced during the last 50 - 100 Ma, but the data are inconclusive. The sphene FT ages were not reset after peneplanation. This suggests that post-peneplanation temperatures can be roughly estimated at less than 250°C (closure temperatures of sphene c. 250-200°C, Gleadow & Brooks 1979, Hurford 1986).

Discussion

The sphene FT ages reported in this study indicate that the sphene ages are associated with the general cooling pattern after the Sveconorwegian Orogeny. The post-Sveconorwegian uplift and thermal history of the area may then have been as follows:

At around 900 - 950 Ma ago the temperature and pressure of the region, based on field evidence and investigation of the granite system, are estimated to have been in the order of 600°C and 3-4 kb, respectively. At the time of pegmatite formation at c. 850 Ma it can be demonstrated from studies of fluid inclusions that the temperature in the host rocks was approximately 280°C and that the pressure was in the order of 1.4 kb.

The fission track ages of the sphenes indicate that the temperature of the investigated crustal level cooled below c. 250 -200°C (closure temperature, e.g. Gleadow & Brooks 1979, Hurford 1986) by at least 700 Ma BP. The K/Ar and Rb/Sr systems of the micas gave similar or higher ages than sphene FT ages at similar locations and thus probably cooled slightly earlier through their blocking temperatures of approximately 300°C (Purdy et al. 1976, Wagner et al. 1977). The fast cooling (age) and the fluid inclusion data may reflect a rapid exhumation of the area. Between 700 and 600 Ma BP southwestern Scandinavia was probably affected by a general uplift and peneplanation (as pointed out e.g. by Oftedahl 1980).

Pooled or bulk FT apatite (except 91602 and 1092) or sphene ages are similar within the 2 σ uncertainty. Linear regressions of distance versus sphene and apatite ages,

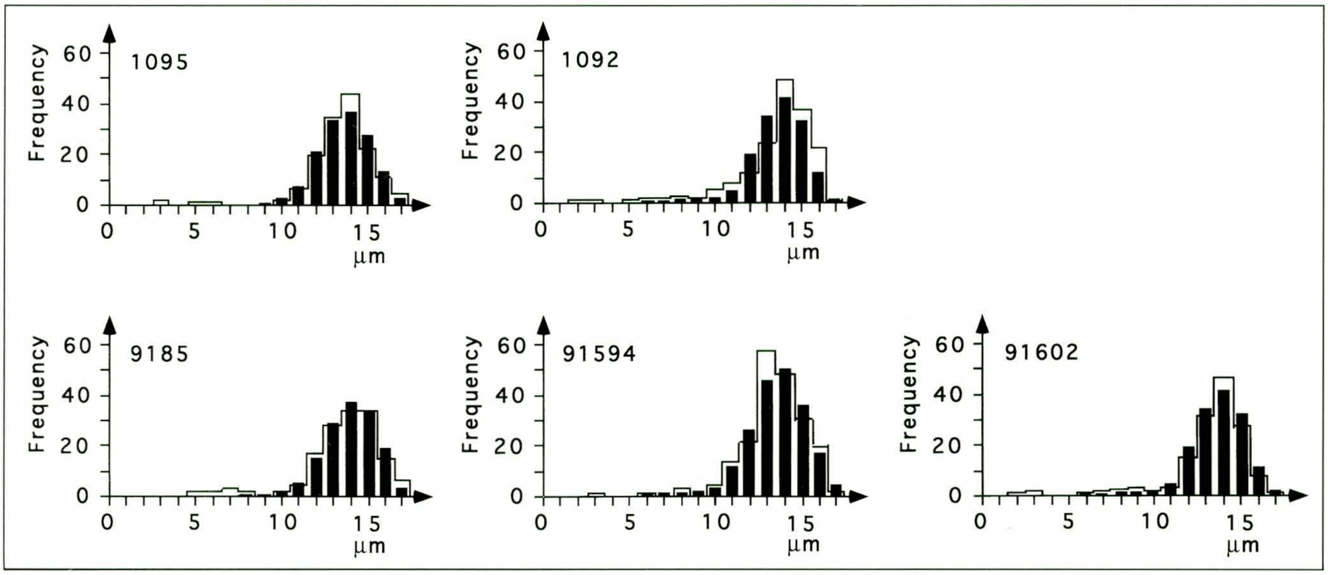

Fig. 5. Calculated length distributions, based on thermal histories. For comparison, the measured FT histograms are shown as thin lines.

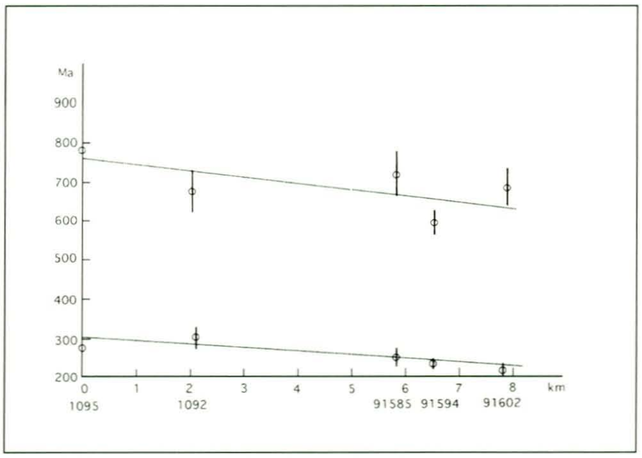

Fig. 6. Measured distance versus age diagram. Also shown are linear regression lines for sphene and apatite, respectively. The regression lines are not altitude corrected, but such a correction only changes their positions slightly.

respectively, yield a regression line of y = -14.3x + 746 (Ma) for sphene and y = -11.3x + 297 (Ma) for apatite (correlation coefficients 0.7 and 0.9, respectively), for FT ages corrected to a similar elevation (440 m) (Fig. 6). The regression lines may reflect changing mean exhumation rates (m/Ma) along the line for apatite as follows: 1/[age/elevation above the closure ("100°C") isotherm = age/(1000x(100/ geothermal gradient) + surface elevation (m))] giving 12.7 m/Ma (site 1095) and 18.0 m/Ma (site 91602) at a distance of 7.75 km between the end points. This suggests a probable post-Caledonian tilting of the area of c. 5.3 m/Ma or c. 1600 m in 300 Ma between the ends of the profile (11.6°). The age variation may thus suggest a post-peneplain tilting and a pre-peneplain thermal stratification in the area, as altitude dependence may have occurred before the peneplanation.

The apatite FT data of Rohrman et al. (1995) for the Hunnedalen profile, southern Norway, are interpreted as indicating that the rocks cooled slowly through the annealing interval in Jurassic times. Their ages are slightly younger than those found for our samples, which show a similar age/elevation dependence and mean track length. The apatite ages of the Setesdal profile fit well into the general apatite age pattern given in Rohrman et al. (1995). The suggested differential exhumation of c. 1600 m obtained from linear regression, however, differs significantly from the regional exhumation pattern suggested by Rohrman et al. (1995) and may relate to local evolution and uncertainty in age determination. The cooling ages for sphene and the modelled cooling paths for apatites suggest that temperatures in the period between 600-800 Ma and 325-275 Ma ago did not exceed c. 200-250°C in the study area and since then have not exceeded c. 120°C. If the present surface is close to or below the sub-Cambrian peneplain (e.g. Oftedahl 1980) but above the sub-Cambrian 120°C isotherm, the area was later buried to depths with temperatures in excess of c. 120°C, this overburden again having been removed.

The presence of Lower Palaeozoic phyllites in the Hardangervidda area (Hardangervidda Group, Oftedahl 1980) suggests that there were slightly elevated temperatures during the post-peneplanation stage. The sedimentation pattern in front of the Caledonian nappes may suggest that the sub-Permian surface is likely to be close to the earlier (sub-Cambrian) peneplain (Bjørlykke 1983) and probably part of the so-called Paleic surface (Gjessing 1967). The much lower FT ages within the Oslo Rift are attributed to deposition and erosion of the lava pile (Rohrman et al. 1994a). The FT and geological evidence taken together provide no conclusive evidence of the depth to which the rocks of the Setesdal area were buried before the formation of the sub-Permian peneplain. However, the Setesdal rocks were at more than 120°C, corresponding to a depth of >4 km (geothermal gradient of 30°C/km), before c. 300 Ma BP and to c. 3 km at c. 300 Ma BP.

Modelling results for apatite FT length distributions (Figs. 4 and 5) indicate a rapid exhumation (and cooling) up to approximately 275 Ma BP. After this time the cooling (exhumation) rate declined. Such a cooling path may relate to the removal of overlying supracrustals (volcanic and sedimentary rocks) and/or nappes, the break occurring at the time of formation of the sub-Permian peneplain. Continued cooling corresponds to a further erosion of up to two km of overlying material. The data cannot resolve the history in detail, but further evidence from seismic profiles and maturity measurements south of the Norwegian coast suggest that sedimentary rocks may have covered the coastal parts of southern Norway (Jensen & Schmidt 1992, Riis & Jensen 1992) in Mesozoic times. The sediments may infer changes in uplift/cooling rates in southern Norway. Furthermore, Neogene uplift is inferred by the tilting of these sedimentary rocks and by accumulation of a thick succession of Tertiary sediments in the Central Trough.

Rohrman et al. (1995) documented cooling into the apatite annealing interval in Jurassic times from the FT data of coast-near samples, southwestern Norway, a slow cooling through the Jurassic and Cretaceous, and finally further FT data indicated fast cooling to surface temperatures since Tertiary times. Such a cooling path is compatible with the general cooling scheme of the Setesdal samples, for which, however, cooling into the apatite annealing interval occurred already c. 300-250 Ma ago and perhaps at a higher crustal level. Also, the modelled cooling paths for the Setesdal apatites are very similar to the cooling paths found for the Bamble sector south of the Oslo Rift (Rohrman et al. 1994a). The apatite FT data from the Oslo Rift yield similar (on the rift flanks) or younger (on the rift floor) ages for the apatites but with more variable mean track lengths (Rohrman et al.1993, 1994a), suggesting that the thermal history outside the rift is continuous with that of the Setesdal province.

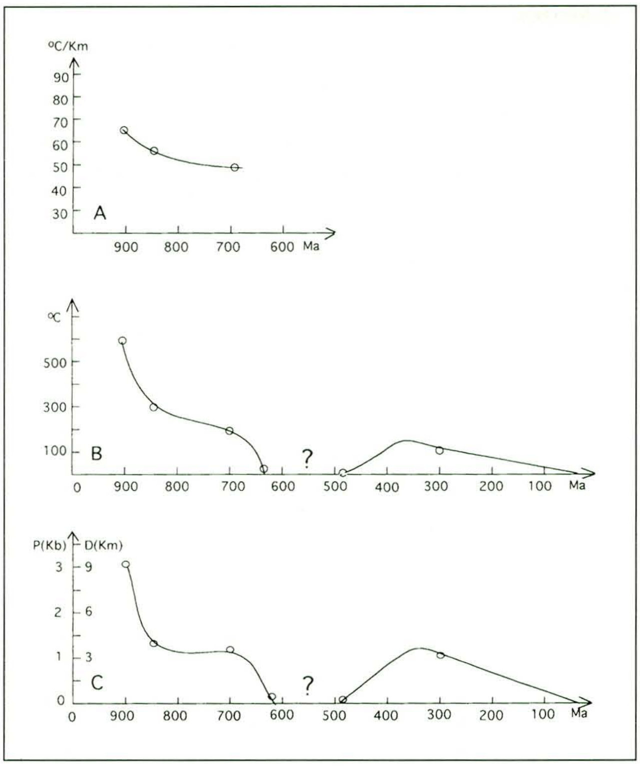

Fig. 7 (A). Late Precambrian geothermal gradient evolution in the southern Setesdal area. (B) Suggested Precambrian to recent thermal history. (C) Suggested pressure history. Points represent points of the known thermal/pressure history.

Conclusions

FT analyses performed on apatite and sphene from monzonitic dykes in the Høvringsvatn Complex in southern Setesdal, Norway, show that cooling from intrusion temperatures reached the temperatures of the surroundings of c. 250 °C before c. 800 - 600 Ma BP. Fluid inclusion studies suggest an intrusion depth of 4 - 5 km and thus the geothermal gradient was c. 50°C/km. The cooling paths are shown in Fig. 7.

The apatite results indicate that since the time of the sub-Cambrian peneplanation, the southern Setesdal region has been subjected to temperatures above the closure interval of apatite (e.g. Gleadow et al 1983). Apatite ages of nearly 300 Ma indicate that the rocks of the region were at least at 4 km depth in Late Devonian - Early Permian times, assuming a geothermal gradient of 30°C/km.

The early history revealed by sphenes reflects a cooling and exhumation probably close to the present surface in Precambrian times, while the late thermal and exhumation history revealed by the apatites was part of the general evolution of southern Norway after the formation of the sub-Cambrian peneplain, including the removal of c. 4 km of overburden.

Modelling of apatite FT length distributions reflect the formation of a sub-Permian peneplain and a reduced exhumation rate through the Late Palaeozoic and the Mesozoic. A possible increased Neogene exhumation is not revealed from the data. The similarity of the apatite and sphene FT data for southwestern Sweden and southern Norway may point to a common post-Caledonian evolution for Fennoscandia.

Acknowledgements

This study was carried out using glass standards supplied by Dr. Schreuers, Corning Glassworks and age standards supplied by Drs. C.W. Naeser, U.S. Geological Survey, and A.J.W Gleadow, La Trobe University, Melbourne, Australia. Dr. C.K. Brooks and Dr. J. Konnerup-Madsen (both from the University of Copenhagen) corrected and discussed the manuscript. One of the referees in particular is thanked for valuable suggestions for improving the manuscript. Dr. D. Roberts kindly improved the English.

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Manuscript received August 1995; revised manuscript accepted April 1996.