

Fission-track and K-Ar dating of tectonic activity in a transect across the Møre-Trøndelag Fault Zone, central Norway

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Fission-track dating of apatite, zircon and sphene, and K-Ar dating of K-feldspars in samples taken from a transect across the Møre-Trøndelag Fault Zone in Trøndelag confirm the long-lived nature claimed for this complex fault zone. Apatite, zircon and sphene, which have blocking temperatures of $125^{\circ} \pm 25^{\circ}\text{C}$, $200^{\circ} \pm 50^{\circ}\text{C}$ and $250^{\circ} \pm 50^{\circ}\text{C}$, respectively, together indicate a complex history of post-Caledonian tectonism. Uplift and cooling are indicated in Early Palaeozoic (Late Ordovician–Early Carboniferous) and Triassic–Jurassic times, with erosion of at least 3 km of Early and possibly Late Palaeozoic supracrustal cover since the Late Palaeozoic. Late Jurassic activity is indicated along the Verran Fault.

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Introduction

The Møre-Trøndelag Fault Zone (MTFZ) is commonly regarded as an important Caledonian and Mesozoic fault zone (Gabrielsen & Ramberg 1979; Aanstad et al. 1981). Its deformational history has been related to the structural evolution of offshore areas adjacent to central Norway (Gabrielsen et al. 1984; Doré & Gage 1987; Brekke & Riis 1987).

To furnish temporal constraints on episodes of faulting in the MTFZ, a programme of palaeomagnetic and isotopic dating was undertaken. The programme comprises fission-track dating of apatite, zircon and sphene from fault rocks and other less deformed rocks, as well as potassium-argon (K-Ar) dating of K-feldspars from thorium-mineralized hydrothermal veins. Samples have been taken in a transect across the MTFZ from Åfjord, northwest of the Hitra-Snåsa Fault to Verdalen, southeast of the Trondheimsfjord (Fig. 1). Samples were collected between 0 and 100 m above sea level, except sample AG-2, which was collected at 460 m above sea level.

The purpose of the present paper is to present and interpret the results of this geochronological investigation. Results from palaeomagnetic dating of fault rocks have been published earlier by Grønlie & Torsvik (1989).

Geological setting

In Inner Trondheimsfjord the MTFZ comprises a complex fault zone with a width of approximately 50 km (Fig. 1). In the northwest, the bedrock involved in the

faulting includes a basal Precambrian crystalline complex of heterogeneous gneisses. This is tectonostratigraphically overlain by amphibolite facies psammites, schists and amphibolites. Higher up, low-grade metasediments and greenstones occur (Wolff 1976). The cover rock sequences represent fragmented slices of the Lower to Upper Allochthons of the Caledonide orogen (Gee et al. 1985). The Precambrian gneisses, forming part of the Western Gneiss Region, are themselves strongly Caledonized (Tucker & Krogh 1988). South of the Verran Fault, the bedrock consists mostly of Caledonian Nappe rocks, mainly of the Gula and Støren Nappes and the underlying Precambrian basement rocks (Bryhni & Sturt 1985).

An important element of MTFZ geology is that of the late-orogenic Old Red Sandstone sediments on Ørlandet, Hitra and Smøla. These sandstones and conglomerates are of Late Silurian to Middle Devonian age (Steel et al. 1985).

In Beitstadfjord, pebbles of coal and boulders of sideritic ironstone of Middle Jurassic age have been found on the western and northern shores (Horn 1931; Oftedahl 1972, 1975) showing that important fault movements postdated the deposition of these Mesozoic sediments. This evidence has been further supported by results of a shallow seismic profiling survey (Bøe & Bjerkli 1989).

K-Ar dating of K-feldspars

Methods

Mineral separates of the potassium feldspar fractions of four of the thorium-rich carbonate vein samples (Table

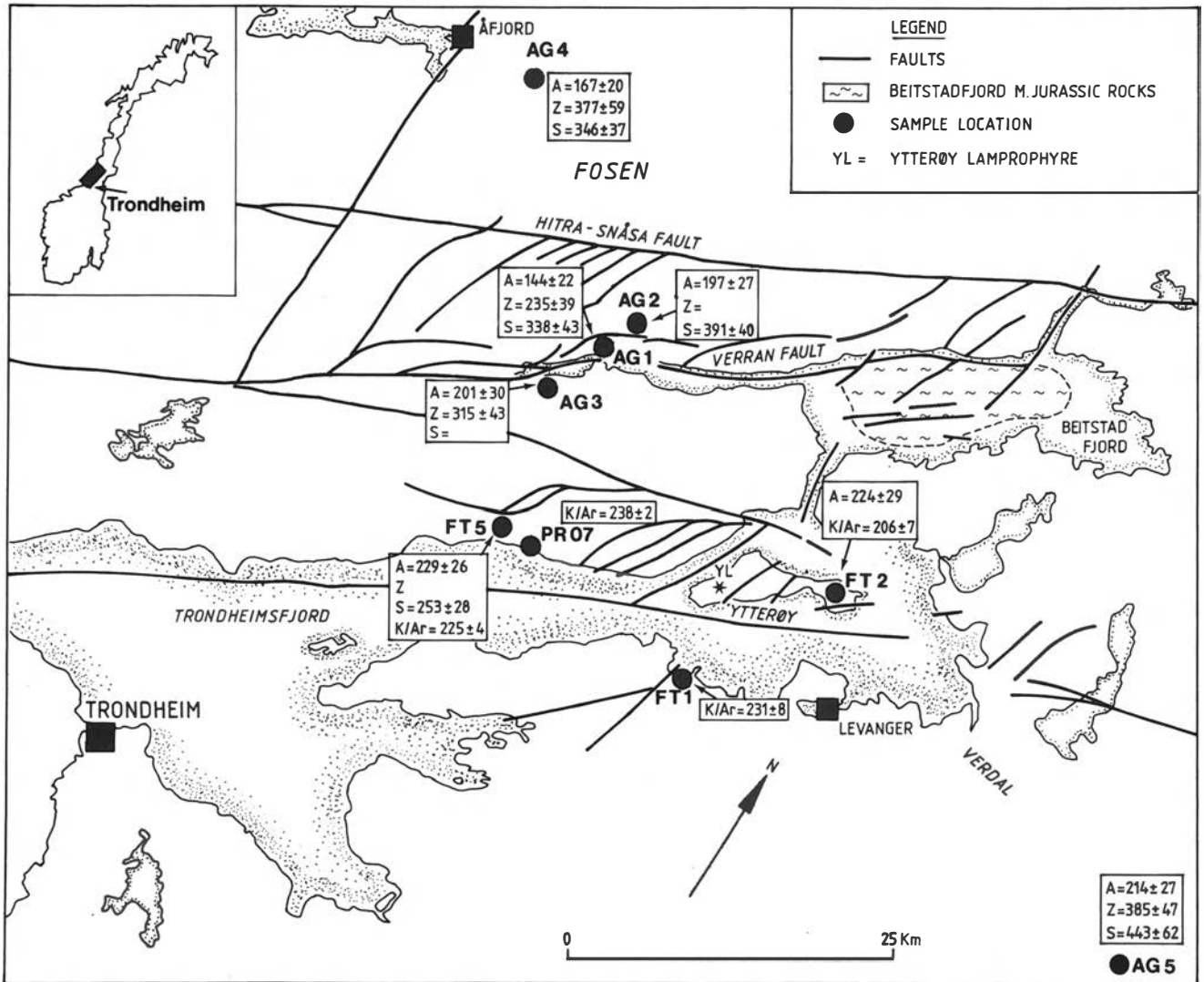


Fig. 1. Fault pattern of the Møre-Trøndelag Fault Zone in the Fosen-Trondheimsfjord region. Fission-track and K/Ar sample locations, with results, are shown (see also Tables 1 & 2). Beitstadfjord fault pattern is simplified from Bøe & Bjerkli (1989). A, Z, S = apatite, zircon & sphene fission-track ages (in Ma), K/Ar = potassium/argon age (in Ma).

Table 1. Potassium-argon analytical data.

Sample number	Mineral	K ₂ O (wt.%)	Radiogenic ⁴⁰ Ar	Atmospheric contamination (%)	Age (Ma ± 1σ)
FT-2	Microcline	16.71 ± 0.55	(1.179 ± 0.008) × 10 ⁻¹	3.8	206 ± 7
PR-07	Microcline	15.14 ± 0.05	(1.245 ± 0.008) × 10 ⁻¹	4.4	238 ± 2
FT-1	Adularia	15.13 ± 0.18	(1.204 ± 0.008) × 10 ⁻¹	4.1	231 ± 8
FT-5	Adularia	16.32 ± 0.30	(1.263 ± 0.009) × 10 ⁻¹	7.7	225 ± 4

$$\lambda_e = 0.581 \times 10^{-10} \text{a}^{-1}; \lambda_\beta = 4.962 \times 10^{-10} \text{a}^{-1}; {}^{40}\text{K}/\text{K} = 1.167 \times 10^{-4} \text{ atom/atom.}$$

1) were obtained by conventional mineral separation techniques. The resulting separates were of >99% purity.

X-ray diffraction analyses, using a Phillips PW1450 diffractometer at 35 kV with a copper target and 1/8° per min. scan rate, showed samples FT-2 and PR-07 to be microcline. Detailed interpretation of the diffraction data for samples FT-1 and FT-5 indicates that they are both adularia. The powder pattern for FT-1 shows no evidence of splitting of the (130) and (131) peaks, whereas

FT-5 shows splitting of both. FT-1 may, therefore, be regarded as a monoclinic adularia while the FT-5 structure incorporates an unquantified proportion of triclinic material. The consequences of structural state variations in adularias for potassium-argon age interpretations have been discussed by Halliday & Mitchell (1976).

Conventional potassium-argon ages were determined for the four feldspar separates. Potassium was determined in triplicate by flame photometry using a Corning

EEL 450 instrument with a Li internal standard. Argon was extracted from 300 mg aliquots of the powders by fusing them in an RF furnace followed by gas purification using Ti sponge and Al-Zr alloy getters. The measurement of argon was performed in duplicate on a VG1200C mass spectrometer by isotope dilution using a ^{38}Ar spike. Interlaboratory calibrations using standard minerals suggest an accuracy of these procedures of better than 2%. Data from these analyses are presented in Table 1.

Table 1 gives unweighted mean values of the potassium and argon contents. Ages were calculated using the decay constants of Steiger & Jäger (1977), with the uncertainty specified by $\pm 1\sigma$. The atmospheric contamination value is the higher of the values obtained in the duplicated argon analyses.

Interpretation of the potassium-argon ages of K-feldspars must be approached with caution. Conventional K-Ar ages of K-feldspars (including microcline) from plutonic rocks are generally regarded as unreliable (see, for example, Hart 1964, Dalrymple & Lanphere 1969). Interpreting such ages within the context of their geological setting and the ages of dated coexisting minerals demonstrates that the apparent age is invariably young. A mechanism of argon loss is now generally accepted as the explanation for these young ages.

Recent work (Berger & York 1981; Harrison & McDougall 1982; Zeitler & Fitz Gerald 1986), using the $^{40}\text{Ar}/^{39}\text{Ar}$ method, has shown that K-feldspars can be a useful low-temperature thermochronometer ($\approx 200^\circ\text{C}$). Zeitler & Fitz Gerald (1986) showed from stepwise heating that thermally disturbed K-feldspars have a complex argon release pattern. Their results show that part of the spectrum dates the cooling from the thermal event that causes the argon loss, and other parts of the spectrum indicate the presence of excess argon. Based on what has been learned from the $^{40}\text{Ar}/^{39}\text{Ar}$ method on the response of K-feldspars to elevated temperatures, we are interpreting the microcline K-Ar ages presented in this paper as mixed ages. The temperatures to which these ages correspond cannot be precisely determined.

Halliday & Mitchell (1976) have considered the criteria of suitability of adularias for K-Ar analysis and concluded that increasing triclinicity is associated with a progressive reduction in apparent age. The more monoclinic the adularia being studied, the most closely does the apparent age correspond to the crystallization age of the mineral, or, in other words, the higher the closure temperature of the adularia. However, even monoclinic adularia ages are regarded as cooling ages, recording cooling through an imprecisely determined closure temperature.

Fission-track dating

Annealing

Fission tracks disappear at elevated temperatures through a process known as *track annealing*. Heating a

mineral containing fission tracks allows ions displaced along the damage zone of the track to move back into normal crystallographic positions in the mineral. Repair of the damage zone leads to shortening and ultimately to the total disappearance of the fission track. The annealing of fission tracks is a time-temperature function. Short heating times at high temperatures can have the same effect on fission tracks as long heating times at lower temperatures. Over the periods of time that are usually required for geological processes ($> 10^5$ yr), total fission-track annealing will take place in apatite (fluorapatite) at temperatures between 100° and 150°C (Naeser 1979, 1981). The shorter the heating time, the higher the temperature required for total annealing.

Annealing temperatures of apatite are also affected by chemical composition (Green et al. 1989; Crowley et al. 1990). F-, Sr-F and OH-apatite anneal at very similar temperatures, but chlorine-rich apatite is significantly more resistant to annealing; at fixed heating times in the laboratory, Cl-apatites anneal at temperatures up to 30°C higher than other apatite varieties (Crowley et al. 1990). Similar variation in annealing temperatures related to Cl-content has been observed in a drill hole in the Otway Basin, Australia, where apatite grains low in chlorine are totally annealed at a present temperature of 92°C , but chlorine-rich apatite grains are not totally annealed until a temperature of $\approx 125^\circ\text{C}$ is reached (Green et al. 1989). Fortunately, apatite suites are typically so dominated by fluorapatite that most can be interpreted using fluorapatite annealing data. As a practical matter, evidence suggests that the presence or absence of significant concentrations of chlorine can be determined indirectly from the etching characteristics of fission tracks in apatite (Crowley et al. 1990). Chlorine-rich apatites etch faster than other apatite varieties, producing broader fission tracks.

Apatite fission-track ages are generally regarded as cooling ages that record the time since the apatite last cooled through its closure (blocking) temperature. The apatite closure temperature is commonly given as 100°C (Naeser 1979), but in reality the closure temperature (for fluorapatite) can range from 100° to 150°C or higher, depending on the rate of cooling (Naeser 1981). Slow uplift and/or cooling results in closure temperatures closer to 100°C , whereas the closure temperature for rapid uplift and/or cooling is closer to 150°C .

Unfortunately fission-track ages cannot always be interpreted simply as cooling ages because annealing is not a simple process in which the tracks are either totally retained or totally lost. There is a zone of partial annealing (Naeser 1979), which spans a temperature interval of about 30°C to 40°C (Naeser 1981). Apatite from surface samples that resided in the zone of partial annealing prior to cooling will yield a mixed age that is less than the primary age, but greater than the cooling age.

Apatite fission-track ages from surface samples will always be either equal to (for samples that cooled quickly through their partial annealing zone) or greater

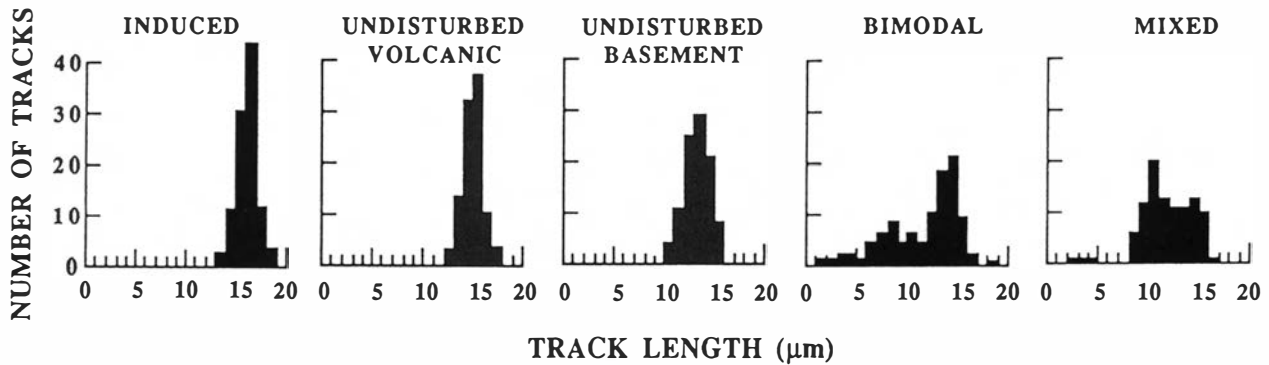


Fig. 2. Comparison of typical 'induced', 'undisturbed volcanic' (from rocks that have undergone rapid cooling and remained at low temperatures), 'undisturbed basement' (from rocks that have undergone slow continuous cooling from deep crustal to ambient temperatures), and 'mixed' (thermally disturbed) horizontal, confined track-length distributions in apatite. The 'bimodal' distribution is a special case of the mixed distribution in which two separate components, reflecting a two-stage thermal history, can be readily identified. All track lengths were measured on polished surfaces essentially parallel to the crystallographic c-axis and are not corrected for measurement bias (Laslett et al. 1982). Modified from Gleadow et al. (1986).

than (mixed age samples) the age of the last uplift/cooling event. Thus, the youngest apatite age out of a series of samples from the same structural block is a maximum age for the latest cooling event.

The fission-track annealing temperatures of zircon are less well known. It has been established through numerous studies (e.g. Harrison et al. 1979; Zeitler 1985; Hurford 1986) that fission tracks in zircon are more resistant to annealing than those in apatite. Several estimates have been made for the closure temperature for zircon; Harrison et al. (1979) estimated $\approx 175^\circ\text{C}$, and Hurford (1986) estimated $240^\circ\text{C} \pm 50^\circ\text{C}$. Hurford's estimate is based on data generated from rocks in the Lepontine Alps, Switzerland, in an area of relatively rapid cooling. Because of the rapid cooling in these rocks, Hurford's value should be considered as a maximum estimate of closure temperature. In areas of less rapid uplift/cooling, such as the present study area, zircon ages can probably be considered to indicate cooling of the rock below $\approx 200^\circ\text{C}$.

The annealing temperatures of fission tracks in sphene under geological conditions are poorly understood. Most estimates place the closure temperature for sphene between 200° and 300°C (Gleadow & Brooks 1979; Harrison et al. 1979). In studies where there has been slow cooling from temperatures $> 300^\circ\text{C}$, sphene fission-track ages are always older than zircon fission-track ages. This phenomenon has been observed in many fission-track studies, including the two cited above. For purposes of interpreting the data in this report, the following closure temperatures will be used: apatite (fluorapatite), $125^\circ \pm 25^\circ\text{C}$; zircon, $200^\circ \pm 50^\circ\text{C}$; sphene, $250^\circ \pm 50^\circ\text{C}$.

Fission-track lengths in apatite are also a sensitive recorder of thermal history because each track in a given apatite forms at a different time and thus is exposed to a different fraction of the apatite's thermal history (Gleadow et al. 1986). Apatites in volcanic and related rocks that cool rapidly and remain at low temperatures have a narrow, symmetric track-length distribution, with mean track length of $14.0\text{--}15.6\ \mu\text{m}$ and standard deviation

of the distribution of ≈ 0.8 to $1.2\ \mu\text{m}$. More complex thermal histories produce more complex distributions. In the progression from 'undisturbed volcanic' through 'undisturbed basement' to 'mixed' thermal histories, mean track length decreases, standard deviation of the track length distribution increases, and the form of the track-length distribution becomes increasingly complex (Figs. 2, 3; Gleadow et al. 1986).

Methods

Fission-track ages of apatite, zircon and sphene were determined using the external detector method (Naeser 1976, 1979). Apatite separates were mounted in epoxy,

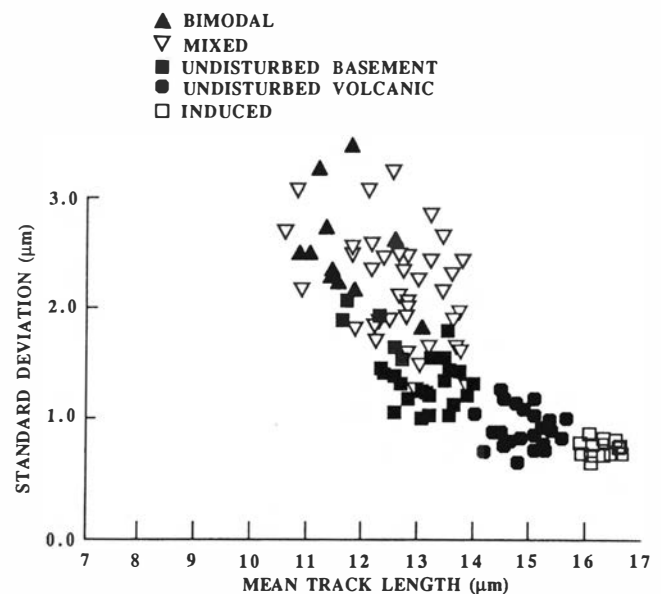


Fig. 3. Relationship between standard deviation and mean track length for the various track-length distributions shown in Fig. 2. Note that bimodal distributions are much broader (have a larger standard deviation) than distributions of undisturbed samples. The mean length and standard deviation of mixed distributions span the range of the bimodal and undisturbed basement samples. From Gleadow et al. (1986).

polished, and then etched in 7% HNO₃ at 21°C for 40 seconds. Zircon was mounted in teflon, polished, and etched in a eutectic melt of KOH-NaOH (Gleadow et al. 1976) at 217°C for times between 10 and 47 hours. Sphene was mounted in teflon, polished, and etched in an acidic solution (3 parts concentrated HNO₃, 2 parts concentrated HCl, 1 part concentrated HF, and 6 parts H₂O) at 21°C for between 10 and 20 minutes. The grain mounts were covered with low-uranium-content muscovite detectors and irradiated along with neutron dose monitors (U-doped glass SRM 962 for zircon and sphene; U-doped glass SRM 963 for apatite) (Carpenter & Reimer 1974). The samples were irradiated in the US Geological Survey reactor in Denver, Colorado. The thermal neutron dose was determined from the track density in calibrated muscovite detectors that covered the glass standards during the irradiations. Ages were calculated using the zeta method of calibration and calculation as recommended by Hurford & Green (1983). Zeta values used to calculate the ages are given in Table 2, along with the analytical data and calculated ages. Un-

certainty in the age was calculated by combining the Poisson errors on the spontaneous and induced track counts and on the track counts in the detector covering the dosimeter (McGee et al. 1985).

Apatites for track-length measurements were mounted in epoxy, polished and etched in 7% HNO₃ at 23°C for 60 seconds. Track lengths were measured in transmitted light at ×1500 magnification using a ×100 oil immersion lens and a Summagraphics MacTablet digitizing tablet and projection tube calibrated against a stage micrometer (1 unit = 0.01 mm). Only well-etched horizontal confined tracks in grains with polished surfaces approximately parallel to the crystallographic c-axis were measured. The track-length data (Table 3, Figs. 4, 5) are actual measurements, not corrected for length-measurement bias (Laslett et al. 1982). Track lengths were determined for six of the dated apatite samples; samples FT-1 and FT-2 did not contain sufficient apatite for length measurements.

A qualitative estimate of the chlorine content of the apatites used in this study was obtained by measuring the

Table 2. Fission-track data and ages.

Sample number	Mineral	Number of grains	$\rho_s \times 10^6$ t/cm ²	$\rho_i \times 10^6$ t/cm ²	χ^2 *	Dosimeter density × 10 ⁵ t/cm ²	Age ^a (Ma ± 2σ)
AG-1	Apatite	6	0.644 (364) ^b	1.25 (354) ^b	P	0.266 (3276) ^b	144 ± 22
	Sphene	6	12.3 (1759)	4.52 (324)	P	4.15 (2369)	338 ± 43
	Zircon	3	23.4 (710)	12.9 (196)	F	4.16 (2369)	235 ± 39
AG-2	Apatite	6	1.50 (555)	2.15 (398)	P	0.269 (3276)	197 ± 27
	Sphene	6	14.3 (3321)	4.55 (527)	P	4.17 (2369)	391 ± 40
AG-3	Apatite	6	0.935 (450)	1.33 (320)	P	0.272 (3276)	201 ± 30
	Zircon	6	20.4 (1414)	8.38 (291)	F	4.19 (2369)	315 ± 43
AG-4	Apatite	6	0.961 (623)	1.67 (542)	P	0.275 (3276)	167 ± 20
	Sphene	6	28.8 (2710)	10.5 (491)	P	4.20 (2369)	346 ± 37
	Zircon	5	18.2 (1181)	6.26 (203)	F	4.21 (2369)	377 ± 59
AG-5	Apatite	6	1.57 (682)	2.14 (465)	P	0.278 (3276)	214 ± 27
	Sphene	6	10.4 (1834)	2.94 (259)	P	4.22 (2369)	443 ± 62
	Zircon	6	15.8 (2115)	5.32 (357)	P	4.22 (2369)	385 ± 47
FT-2	Apatite	6	2.50 (636)	3.28 (417)	P	0.280 (3276)	224 ± 29
FT-5	Apatite	6	3.33 (848)	4.31 (549)	F	0.283 (3276)	229 ± 26
	Sphene	6	26.3 (1823)	13.2 (460)	P	4.24 (2369)	253 ± 28

ρ_s = fossil track density. ρ_i = induced track density; reported induced track density = twice measured value.

* χ^2 = pass (P) or fail (F) chi square test at 5%.

^a Calculated from the fission-track age equation (Hurford & Green 1983) using sums of fossil and induced track counts obtained for all grains counted in the sample. $\lambda_D = 1.551 \times 10^{-10}$ /yr. Zeta: zircon (SRM 962), 317.7; sphene (SRM 962), 306.8; apatite (SRM 963), 10,672. Standard deviation calculated by combining Poisson errors on fossil and induced counts and on counts in detector covering the dosimeter (McGee et al. 1985).

^b Number in parentheses is number of tracks counted.

Table 3. Confined fission-track lengths in selected apatite samples from the MTFZ.

Sample number	Mean track length ^a (μm)	Standard deviation ^b (μm)	Number of tracks measured
AG-1	13.17 ± 0.30	1.46	23
AG-2	13.73 ± 0.17	1.20	50
AG-3	13.64 ± 0.18	1.19	44
AG-4	13.95 ± 0.13	1.30	100
AG-5	13.62 ± 0.14	1.42	100
FT-5	13.19 ± 0.18	1.43	61

^a Standard error of the mean.

^b Standard deviation of the track-length distribution.

width of tracks in each of the dated grains and comparing the mean track width in each sample with mean track width in apatites of known chlorine content (Fish Canyon Tuff and Durango apatites) (Table 4). Track width was determined by measuring the maximum axis of the pit formed by the intersection of etched tracks with the polished surface of the apatite grain, using equipment similar to that described above for track-length measurements. All of the measured apatites were etched under identical conditions (21°C for 40 seconds), making it possible to directly compare pit widths from

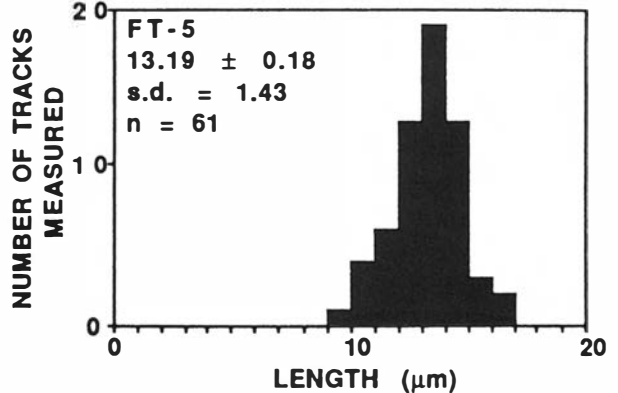
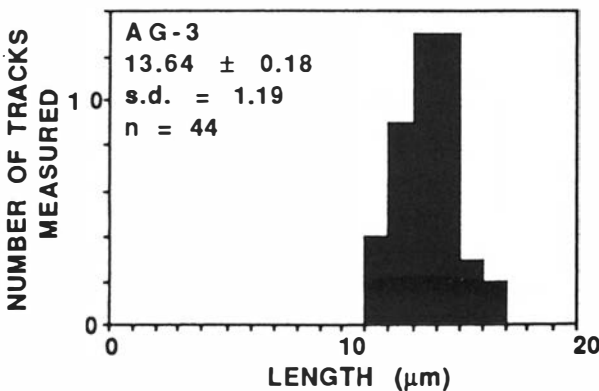
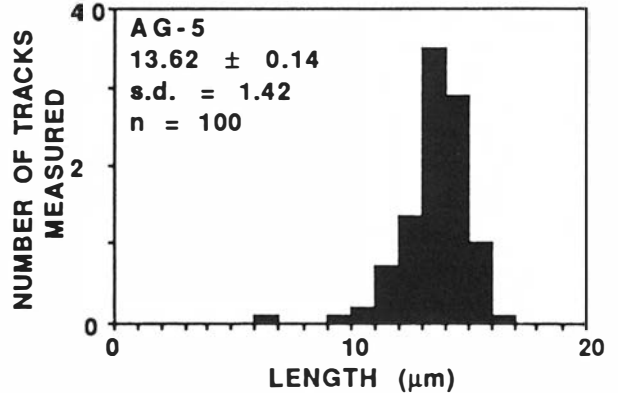
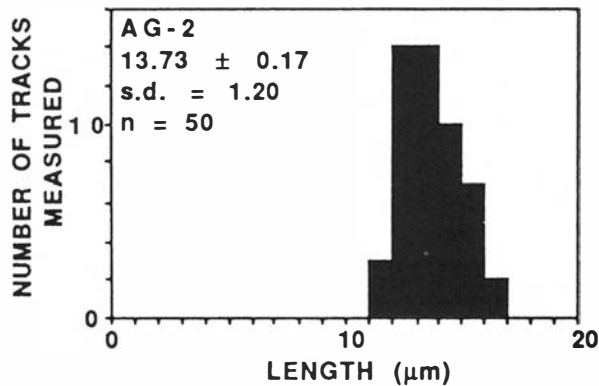
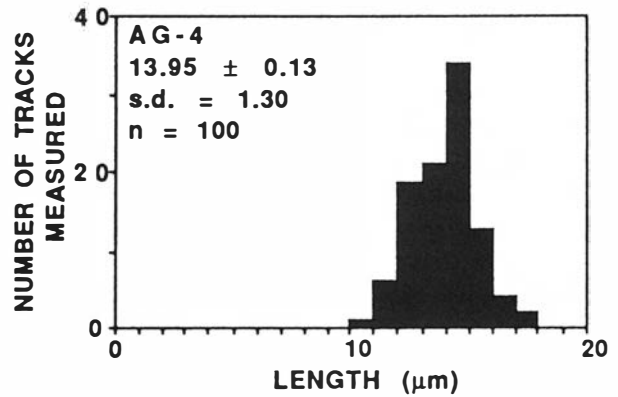
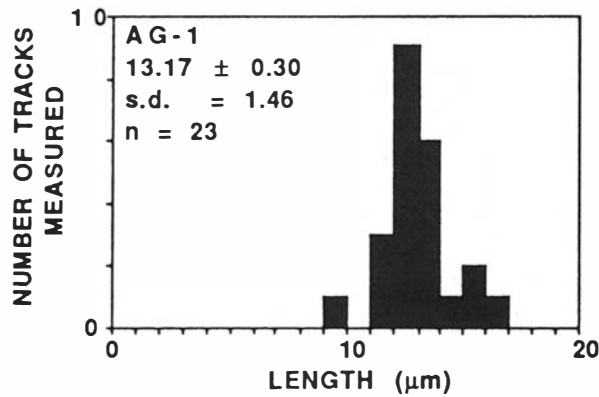


Fig. 4. Confined fission-track length distributions in selected apatite samples from the Møre-Trøndelag Fault Zone (Table 3). Each histogram shows (from top to bottom): sample number, mean track length ± standard error of the mean (in μm), standard deviation of the track-length distribution (in μm), and number of tracks measured.

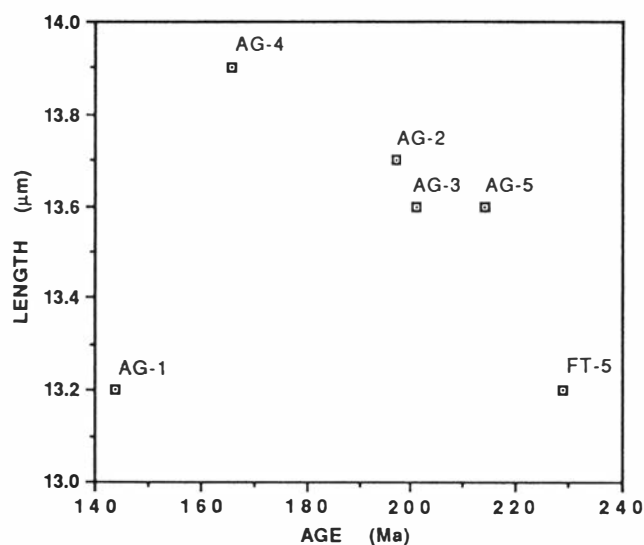


Fig. 5. Mean track length and fission-track age of selected apatite samples from the Møre-Trøndelag Fault Zone.

Table 4. Track (etch pit) width for apatites dated in this study.

Sample number	Number of measurements	Mean width (μm)	Range (μm)
AG-1	190	1.31 ± 0.03^a	0.6–2.6
AG-2	204	1.38 ± 0.03	0.6–2.6
AG-3	207	1.15 ± 0.02	0.6–2.0
AG-4	176	1.53 ± 0.03	0.6–2.7
AG-5	192	1.66 ± 0.03	0.6–3.2
FT-2	194	2.72 ± 0.05	0.9–4.1
FT-5	198	1.38 ± 0.04	0.6–2.9
Durango ^b	133	1.48 ± 0.04	0.6–2.7
Fish Canyon Tuff ^c	141	2.06 ± 0.05	0.9–3.5

^a Standard error of the mean.

^b Contains 0.16 atoms of chlorine per unit cell (K. D. Crowley, personal communication, 1991).

^c Contains 0.26 atoms of chlorine per unit cell (K. D. Crowley, personal communication, 1991).

one sample to another. The use of track width as a qualitative indicator of the relative amounts of F and Cl in apatite is currently being evaluated by CWN. The validity of this measurement is yet to be proven.

Results

Sixteen fission-track ages were determined during this study (Table 2): seven on apatite, four on zircon and five on sphene. Apatite ages range from 144 ± 22 Ma to 229 ± 26 Ma, zircon ages from 235 ± 39 Ma to 385 ± 47 Ma, and sphene ages from 253 ± 28 Ma to 443 ± 62 Ma.

In six of the dated apatites, track widths are similar to widths measured in the Durango fluorapatite, suggesting that apatites in these six samples are also fluorapatite containing little or no chlorine (Table 4). In sample FT-2, however, tracks are significantly wider than in the other samples and are even wider than in Fish Canyon Tuff apatite. This suggests that there may be a significant

component of chlorine in the apatite from FT-2, and thus it may have annealed at higher temperatures than the other apatites analysed in this study.

All samples have a mean track length greater than $13 \mu\text{m}$ and a relatively narrow track-length distribution (i.e. a relatively small standard deviation of the track-length distribution) (Table 3, Fig. 4). All of the length distributions fall into the field of 'undisturbed basement' distributions (Gleadow et al. 1986; Figs. 2, 3), suggesting that (1) below the closure temperature of apatite, these rocks underwent cooling at a relatively uniform rate and at a relatively slow rate (as compared with the rapid cooling of volcanic rocks); and (2) since the time of cooling there has been little if any thermal disturbance of these rocks.

There are, however, several possible complications in this relatively simple picture. There is a general trend towards shorter track lengths and more negatively skewed track-length distributions with increasing fission track age (Figs. 4, 5). This trend may indicate some increased degree of thermal disturbance in the older rocks (e.g. the rocks yielding older ages may have been higher in the crust, cooled earlier, and spent somewhat longer time in the partial annealing zone), but more samples would be needed to confirm this. On Fig. 5, sample AG-1, from the Verran Fault, appears to be anomalous. The data suggest a different thermal history for this sample.

In summary, the apatite track-length measurements suggest that the samples underwent relatively slow, uniform cooling below the temperature at which tracks are retained in apatite, and the samples appear to have undergone little if any thermal disturbance since cooling.

Discussion

The fission-track samples (Table 2) can be divided into two subsets: samples from rocks that are hydrothermally altered (samples FT-2, FT-5 and AG-1) and samples from fresh country rocks. Samples FT-5 and FT-2 were collected in strongly hydrothermally altered fault zones in the Trondheimsfjord area that are characterized by feldspathic fenitization, abundant iron carbonates, and, locally, highly thorium enriched breccias (TE-breccias) (Grønlie & Torsvik 1989). Grønlie & Torsvik proposed that the hydrothermal alteration is related to a buried carbonatite or alkaline rock body. Based on palaeomagnetic evidence, they suggested several stages of hydrothermal activity in these rocks, beginning with major hydrothermal alteration in the Permian, followed by formation of the TE-breccias in the Mesozoic, probably in the Late Jurassic.

There is evidence of Late Palaeozoic rift-related igneous activity along the MTFZ, including the presence of a Permian lamprophyre dyke on Ytterøy (Fig. 1; Torsvik et al. 1989) and a Late Carboniferous syenite sill at Stabben, southwest of the study area (Råheim 1974;

Sturt & Torsvik 1987). Late Palaeozoic–Mesozoic alkaline activity has been documented elsewhere in Norway. In southwest Norway, Færseth et al. (1976) found evidence for three episodes of alkaline dyke intrusion related to Permian (275 Ma), Triassic (220 Ma) and Jurassic (160 Ma) tectonic activity, and alkaline rocks of Permian age are known from the Oslo Graben (Ramberg & Larsen 1976).

Sphene separated from sample FT-5 yielded a significantly younger fission-track age (253 ± 28 Ma) than sphene from surrounding unaltered rocks (Table 2, Fig. 1), suggesting that the sphene age was partially to totally reset by the hydrothermal fluids. Compared with the surrounding area, this block underwent relatively rapid cooling from $>200^\circ\text{C}$ to $<125^\circ\text{C}$ during Late Permian–early Late Triassic time. The cooling may have been related to the hydrothermal activity or to regional cooling (uplift and erosion) along the MTFZ. Regional cooling is favoured by the concordance (at the 95% confidence level; Dalrymple & Lanphere 1969) of the apatite fission-track age (229 ± 26 Ma) and K-Ar adularia age (225 ± 4 Ma) of FT-5 with the apatite ages of nearby unaltered country rocks (e.g. AG-2 and AG-3; Table 2, Fig. 1), but available data do not allow us completely to rule out either interpretation.

The other hydrothermally altered sample (FT-2), collected in a zone of strong feldspathic fenitization, yielded an apatite age (224 ± 29 Ma) concordant with the apatite age determined for FT-5. Apatite in FT-2 has anomalously wide tracks (Table 4), suggesting it has a higher Cl-content, and thus a higher closure temperature than the other dated apatites. If so, the concordance of apatite ages in FT-2 and FT-5 indicates that cooling in these rocks was sufficiently rapid that differences in the closure temperatures of the apatites did not result in significant differences in fission-track age, again supporting the interpretation of relatively rapid cooling in the hydrothermally altered rocks.

The third fission-track sample from altered rock, AG-1, was collected in a strongly hydrothermally altered zone with abundant stilbite and laumontite mineralization within the Verran Fault zone (Grønlie et al. 1991). According to Kristmannsdottir & Tomassen (1978), stilbite and laumontite are stable at temperatures of $70^\circ\text{--}170^\circ\text{C}$ and $110^\circ\text{--}230^\circ\text{C}$, respectively. Field evidence shows that, in some veins, laumontite was formed after crystallization of the stilbite, and thus formation of laumontite is likely to have taken place in the upper range of the stilbite stability field. The sphene fission-track age of AG-1 (338 ± 43 Ma) is concordant with the sphene age of nearby unaltered rocks and shows that the hydrothermal activity did not heat the rocks along the Verran Fault zone above approximately 200°C . The zircon age of this sample (235 ± 39 Ma) is younger than zircon ages determined on nearby fresh country rocks and may represent a partially annealed age. The apatite fission-track age of AG-1 (144 ± 22 Ma) is significantly younger than apatite ages of nearby unaltered rocks

(Table 2, Fig. 1), indicating that the altered rocks of the Verran Fault zone cooled through $\approx 125^\circ\text{C}$ at a later time than the surrounding fresh country rocks. Cooling in the fault zone most likely occurred after the zeolite mineralization. The 144 Ma (Jurassic/Cretaceous) apatite age suggests, therefore, that the major zeolite mineralization along the Verran Fault was related to the post-Mid Jurassic downfaulting of the Beitstadfjord half-graben.

The remaining fission-track samples are from fresh country rocks. They yielded apatite ages ranging from 214 ± 27 Ma (AG-5) to 167 ± 20 Ma (AG-4) and sphene ages ranging from 443 ± 62 Ma (AG-5) to 346 ± 37 Ma (AG-4) (Table 2, Fig. 1). In the case of both the apatite and sphene ages, the oldest ages (from AG-5) and the youngest ages (AG-4) are discordant at the 95% confidence level, but the two extremes are concordant with intermediate apatite and sphene ages determined on AG-2 and AG-3. It could be argued, therefore, that on a regional scale this entire area underwent two periods of relatively uniform uplift and cooling, passing through the sphene closure temperature in the Early Devonian and through the apatite closure temperature in the Early Jurassic.

However, within both the apatite and the sphene data there are consistent SE to NW trends of decreasing age across the study area (Table 2, Fig. 1). This trend is paralleled by a SE to NW trend of longer apatite track lengths and more positively skewed track-length distributions (Figs. 4, 5). If these trends are real, they indicate differential movement in the MTFZ both during the Late Ordovician–Early Carboniferous, when the rocks were cooling through the sphene and zircon closure temperatures, and during Late Triassic–Middle Jurassic time, when they cooled through the apatite closure temperature. During these two periods of cooling, the rocks may have been uplifted and cooled as:

- an essentially coherent block with greatest uplift in the northwest, or
- a series of structural blocks that came up at different times, with the oldest uplift in the southeast and the youngest in the northwest.

The existing data set does not permit the selection of one hypothesis over the other, although, at least for the Palaeozoic cooling, there is evidence supporting interpretation (b). North of the Hitra-Snåsa Fault (Fig. 1), sample AG-4 yields concordant, at the 95% confidence level, sphene (346 ± 37 Ma) and zircon (377 ± 59 Ma) fission-track ages, suggesting significant Middle Devonian–Early Carboniferous tectonic activity (cooling) in this area, whereas, to the southeast, concordant sphene (443 ± 62 Ma) and zircon (385 ± 47 Ma) ages for AG-5 suggest Late Ordovician–Middle Devonian cooling.

To summarize, the large analytical uncertainty on the fission-track ages and the small number of samples do not allow us to rule out the possibility that, on a regional scale, the MTFZ underwent two periods of essentially uniform cooling, in Early Devonian and Early Jurassic

times. However, the consistent SE to NW trends of the sphene and apatite ages and apatite track lengths across the study area suggest that differential uplift and cooling within the MTFZ are more likely. Faulting continued into the Late Jurassic along the Verran Fault, as shown by the apatite age of AG-1 (144 ± 22 Ma).

Below the apatite closure temperature, track-length distributions indicate that both the altered and the unaltered rocks have undergone relatively slow, uniform cooling, with little if any recent thermal disturbance in the region.

The timing of tectonic activity (cooling) in this part of the MTFZ indicated by the fission-track and K-Ar data is consistent with the timing of activity previously suggested for this area and elsewhere in Norway and Sweden. In studying the Old Red Sandstone at Ørlandet, west of the study area, Siedlecka (1975) maintained that crustal movement with a break in the deposition and erosion occurred at the Silurian–Devonian boundary in the whole of the Fosen region. K-Ar dating of white micas from the Edøyfjord region, just southwest of the study area, shows that uplift and cooling took place in Late Devonian time (Bøe et al. 1989). Tucker & Krogh (1988) found by U-Pb dating of zircon and sphene from the Ingdal granite gneiss that the area suffered a short-lived Scandian metamorphic event at 396 ± 5 Ma, and final cooling through 300° – 350°C occurred rapidly thereafter, as shown by a 372 ± 4 Ma Rb-Sr biotite age. Andriessen & Bos (1986), on the basis of apatite and zircon fission-track dating, maintain that rocks of the Eidfjord region of southwestern Norway were rapidly uplifted 390–306 Ma ago.

Zeck et al. (1988) determined apatite fission-track ages of about 220 Ma and sphene ages of the order of 680 Ma on basement granites of the Lake Vänern area in southern Sweden. The apatite and sphene ages, together with apatite track length data, suggest that the Precambrian basement was buried under a cover of 3–4 km of Palaeozoic supracrustals and subsequently underwent uplift and erosion (cooling) in the Late Triassic. In southern Rogaland, apatites from Precambrian intrusive rocks yield ages of 222 to 258 Ma (mean age = 241 Ma), again suggesting burial of the basement under 3–4 km of sediment followed by uplift and cooling in the Permo-Triassic (van den Haute 1977), possibly somewhat earlier than in the Lake Vänern area. Andriessen (1990) interpreted 160–260 Ma apatite ages from the Precambrian basement in the Hunnedalen region of southwestern Norway as recording post-Caledonian cooling. The reason for the large spread in ages is uncertain, but may be attributed to a rapid post-Caledonian uplift that left the rocks near the top of the partial annealing zone where minor differences in depth, rate of uplift, geothermal gradient or composition could produce significant differences in fission-track ages prior to final cooling.

In northern Norway, at Andøya, a 32 m thick weathering profile developed on metamorphosed granitic base-

ment is unconformably overlain by Mid Jurassic sediments. Sturt et al. (1979) considered the weathering profile to be Early Carboniferous in age. Whole-rock K-Ar dating of the weathering profile yields ages that indicate Late Palaeozoic burial and heating. By the end of the Triassic period, rapid uplift and erosion took the weathering profile back up through the blocking temperature for kaolinite and closed the system for ^{40}Ar diffusion.

The similarity of K-Ar and apatite fission-track ages in the MTFZ to other fission-track ages from southern Norway and Sweden and K-Ar ages in northern Norway indicates the presence of a widespread, Fennoscandian, Late Palaeozoic to Middle Mesozoic period of uplift (cooling). The Triassic was a period of major rifting and faulting in NW Europe (Ziegler 1981), involving many long-lived fault zones, such as the Great Glen Fault (Frostick et al. 1988) and the MTFZ (Doré & Gage 1987). On the Trøndelag Platform the accumulation of Triassic sediments was accompanied by syndepositional tensional faulting (Bucovics et al. 1984). On a global scale, the Middle/Late Triassic boundary (230 ± 5 Ma) marks the incipient dispersal of Pangea by the onset of continental rifting (Veevers 1989).

Conclusions

The geochronological data presented in this report indicate Late Ordovician–Early Carboniferous and Late Triassic–Late Jurassic periods of tectonic activity in central Norway. There was widespread Late Triassic–Middle Jurassic uplift/cooling in the Trondheimsfjord area and Late Jurassic activity is indicated along the Verran Fault.

The rocks currently exposed in the study area were at a temperature of $>100^\circ\text{C}$ during the Late Palaeozoic. Assuming normal geothermal gradients of 25° – $30^\circ\text{C}/\text{km}$, there was at least 3 km of supracrustal cover over these rocks prior to the Late Triassic–Middle Jurassic uplift and cooling. Additional data are needed for a more detailed picture of regional patterns of Mesozoic uplift and cooling.

The K-Ar and fission-track data do not provide conclusive evidence for the age of feldspathic fenitization and formation of TE-breccias in the MTFZ. Ages determined on rocks from alteration zones cannot be distinguished from the regional pattern of uplift and cooling ages in the region. As of now, the best evidence for the age of the Trondheimsfjord hydrothermal alteration remains the palaeomagnetic data (Grønlie & Torsvik 1989), which indicate a Permian age for the initial hydrothermal alteration and a Late Jurassic/Early Cretaceous age for the late TE-breccias.

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