Preliminary fission-track ages of fluorite mineralisation along fracture zones, inner Trondheimsfjord, Central Norway

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Grønlie, A., Harder, V. & Roberts, D.: Preliminary fission-track ages of fluorite mineralisation along fracture zones, inner Trondheimsfjord, Central Norway. *Norsk Geologisk Tidsskrift*, Vol. 70, pp. 173–178. Oslo 1990. ISSN 0029-196X.

Fluorite mineralisation occurring along two major faults in coastal areas of inner Trondheimsfjord has been dated by the fission-track method. Fluorite from the Ystad Fault near Hylla gave ages of 57.4 ± 31.6 and 64.8 ± 22.6 Ma, while a sample from the Slipra Fault near Mosvik gave a date of 76.1 ± 41.2 Ma. Although caution must be exercised in view of the large error margins, the dating provides a minimum age of Late Cretaceous/Early Tertiary for this hydrothermal activity. It is suggested that the fluorite mineralisation developed in Late Cretaceous time shortly before a phase of rapid crustal uplift recorded in the Early Tertiary. The ages broadly coincide with that of a phase of alkaline magmatic activity, with late fluorite-calcite veining akin to that described here, reported from areas in East Greenland and which is considered to be related to the rifting and opening of the northern part of the North Atlantic Ocean.

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In this account we present preliminary results of fission-track dating of fluorite from the Ystad Fault, Inderøy, and from the Slipra Fault, Mosvik, in inner Trondheimsfjord (Fig. 1). The fluorite mineralisation is closely associated with red, thorium-enriched, carbonate veins and breccias, several hundred of which have been located along fault zones around inner Trondheimsfjord (Grønlie & Torsvik 1989). The veins cut metasediments, metavolcanites and igneous rocks in the Caledonian nappes (Wolff 1979) and are clearly post-Caledonian in age. Apart from a high thorium content, the veins and breccias are characterised by abundant iron-carbonate mineralisation and strong potassic fenitisation and it has been proposed that the thorium-enriched veins may relate to a subcropping alkaline and/or carbonatite intrusion (Grønlie & Torsvik 1989). Late-stage fluorite mineralisation is abundant, either filling fractures or occurring as a matrix mineral.

The Møre–Trøndelag Fault Zone (MTFZ) (Fig. 1) (Gabrielsen & Ramberg 1979; Gabrielsen et al. 1984) represents a long-lived fault zone which has existed as a zone of crustal weakness since Caledonian time; and as a precursor fault possibly as far back as the Precambrian (Aanstad et al. 1981). The discovery of down-faulted Jurassic sediments in Beitstadfjord (Oftedahl 1975) indicated that important fault movements occurred along the Verran Fault (Fig. 1) in Mesozoic times, although opinions differ on whether this down-faulting occurred in an extensional dip-slip or strike-slip regime (Oftedahl 1975; Grønlie & Roberts 1989; Bøe & Bjerkli 1989). Studies of the subparallel Hitra–Snåsa Fault (Fig. 1), showing largely ductilely deformed fault rocks, have provided indications of an earlier, possibly Late Devonian, phase of sinistral strike-slip movement.

Apart from a few igneous dykes and sills, no post-Devonian rocks occur onshore in this part of Norway. The timing of faulting and hydrothermal activity within the MTFZ thus cannot be established on a stratigraphic basis. A programme of palaeomagnetic (Grønlie & Torsvik 1989) and isotopic dating of fault rocks has therefore been initiated in order to provide a more definitive time-frame for the faulting and hydrothermal activity.

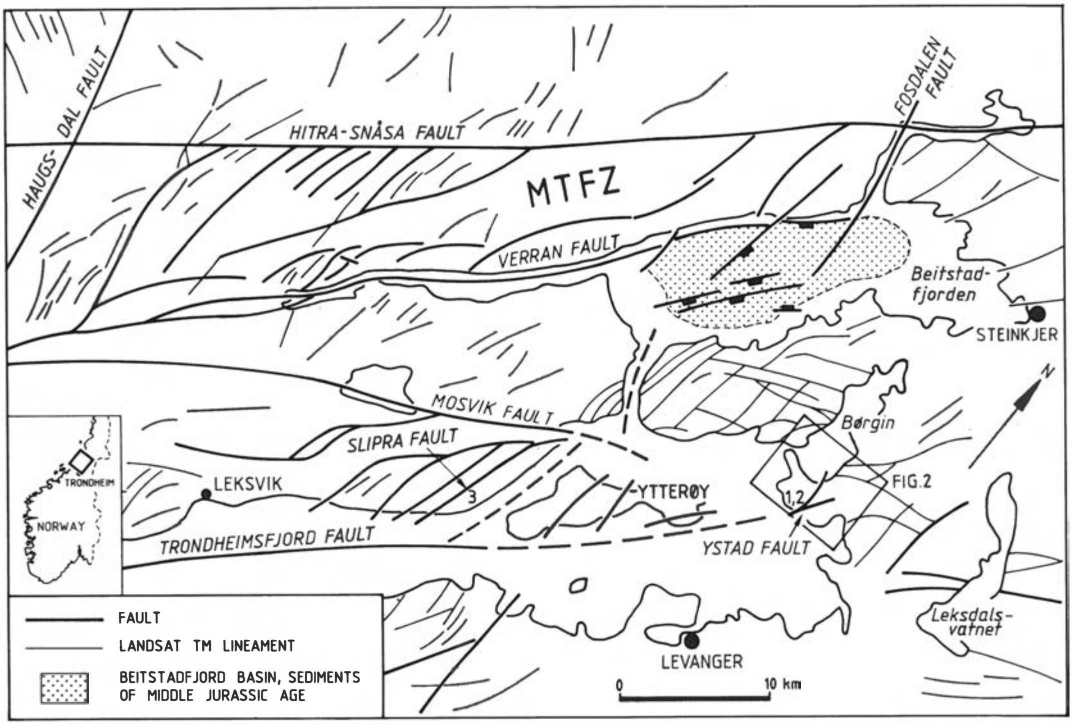

Fig. 1. Lineament and fault map of the inner Trondheimsfjord area. The map is based on available geological maps, as well as Landsat TM imagery and aerial photographs. Numbers 1–3 indicate locations of the dated fluorite samples.

In addition to the minerals commonly employed in fission-track dating (apatite, zircon and sphene (Naeser 1979)), fluorite has also been shown to be amenable to dating by this method (Harder 1986, 1987; Gilmer & Harder 1987). This is an important advance as fluorite is a common mineral in several geological environments. Fluorite will lose all fission-tracks in one million years at 90°C. This is a lower annealing temperature than for apatite, which loses all tracks at 135°C over one million years.

Geological setting

The geology of the coastal areas and islands of inner Trondheimsfjord is dominated by Caledonian nappe rocks and in particular by lithologies composing the Støren and Skjøtingen Nappes (Wolff 1979), part of the Upper Allochthon of Caledonide tectonostratigraphy. In this area the Støren Nappe comprises greenschist-facies metasediments and metavolcanic rocks of Ordovician age; this is in marked contrast to the amphibolite-facies garnet-mica schists, gneisses and amphibolites of the subjacent Skjøtingen Nappe.

Geology in the environs of the Ystad Fault

The Hylla peninsula to the south of Børgin (Fig. 2) exposes polydeformed low-grade metasediments and volcanic rocks of the Støren Nappe which generally dip at moderate angles to the southwest or west. Based on vergence of early, syn-schistosity folds in metasediments and pillow structures in basaltic greenstones, the lithostratigraphy indicated in the legend to Fig. 2 is, in reality, an inverted sequence. In its structurally lowermost part, in the thrust zone in contact with rocks of the Skjøtingen Nappe, the volcano-sedimentary sequence is strongly phyllonitic or mylonitic with a profusion of secondary quartz and local sheath folds.

Faulting post-dating the nappe juxtaposition constitutes an important element of the geological

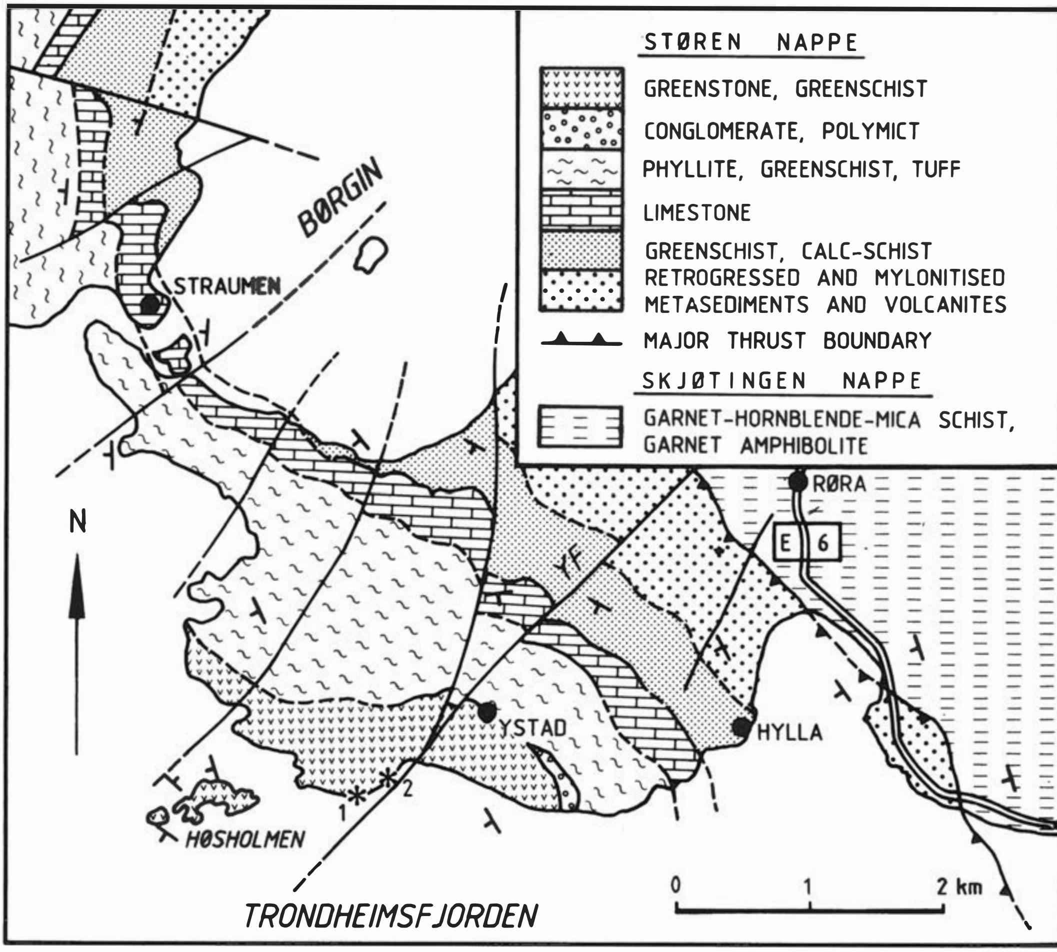

Fig. 2 Bedrock geology in the environs of the Ystad Fault (YF), inner Trondheimsfjord. Numbers 1 and 2 indicate locations of two of the dated samples. The location of this figure is shown in Fig. 1.

history of the area. The principal faults show a general NE–SW trend (Fig. 2), broadly parallel to that of thorium-enriched veins with local breccias. These vary in trend from ca. 035° to 060° with steep dips to the southeast; but some are oriented at ca. 015–020°, which is also parallel to a subsidiary and branching fault trend. Many of the hydrothermal alteration zones also carry similarly trending, thin, calcite-fluorite veins or veinlets.

Fluorite vein mineralisation and coatings of fluorite along NE–SW joint surfaces are particularly common along the coastal exposures along and in the vicinity of the Ystad Fault (Fig. 2) and westwards to Høsholmen. Kink bands parallel to the fault trace point to a component of dextral movement, which accords with the offset revealed by geological mapping. Although the kinks, red alteration zones and calcite–fluorite veins are essentially parallel, there are examples where kink bands displace the locally brecciated alteration zones but are themselves cut by 0.5–2 cm-thick calcite-fluorite veins.

Geology in the environs of the Slipra Fault

The geology of this area, on the mainland west of Ytterøy (Fig. 1), is known only through reconnaissance mapping and compilation at 1:250,000 scale, by Wolff (1979). Rocks of the Støren and Skjøtingen Nappes are again in evidence, with the NNE–SSW trending Slipra Fault cutting mainly garnet-mica schists in the south and low-grade greenschists and greenstones in the north.

Aerial photographs and Landsat TM studies, with selected field observation, have shown that this particular area between the Mosvik Fault and Trondheimsfjord is strongly faulted (Fig. 1) and registers a fault pattern which is reminiscent of a strike-slip duplex (cf. Woodcock & Fischer 1986; Grønlie & Roberts 1989). Examination of the Slipra Fault has shown that this fault has been reactivated several times. Fluorite occurs as a matrix mineral in a 5 m-wide breccia zone where the fragments consist of red, hydrothermally altered rock.

Fluorite dating: methods and results

Fission-track ages were measured by the population method. Fluorite was hand separated from the rock and the sample was split into two groups. One group was heated at 300°C for one week to remove the fossil tracks. This annealed split was irradiated at the nuclear reactor at Georgia Technical Institute, Atlanta, Georgia. Thermal neutron fluences were monitored by apatite from the Fish Canyon tuff. The fluorites were mounted in epoxy resin, ground to reveal an internal surface, polished, and then etched for three minutes at 20°C in 14% HNO_3 to reveal the fission tracks. The Fish Canyon tuff apatites were also split into two groups. One group was heated at 500°C for two hours to remove the fossil tracks. The apatites were mounted in epoxy, ground, polished and then etched to reveal tracks in 7% HNO_3 for 30 s.

The mounts were counted at a magnification of 1368×, under an oil 90× objective with a 1.52× magnifier and 10× oculars, and only fluorite or apatite grains displaying sharp polishing scratches were counted in order to ensure that only well-etched grains were used. Fifty fluorite grains were counted in each age determination. Errors were determined by combining the assumed Poisson errors of the fossil and induced counts (Lindsey et al. 1975). The counting parameters are shown at the foot of Table 1. The error equation is as follows:

$$\%\ \text{Error} = \sqrt{(1/N_f + 1/N_i + 1/N_r)} \times 100$$

N_f = number of spontaneous fission tracks
N_i = number of induced fission tracks
N_r = number of tracks counted in standard

The induced and standard fission tracks can, to some extent, be controlled by the irradiation. The spontaneous fission-track contribution to the error can be reduced by counting as many areas as possible, which is what was done in this case. The same number of areas in the induced fission-track sample then have to be counted. The nature of the fluorites in the actual samples made counting difficult as they did not contain many clear areas amenable to counting.

Fluorite dating results are given in Table 1. The two samples from the Ystad Fault gave ages of 64.8 ± 31.6 Ma and 57.4 ± 22.6 Ma, whereas the sample from the Slipra Fault gave an age determination of 76.1 ± 41.2 Ma.

Interpretation and discussion

In inner Trondheimsfjord (Fig. 1), red thorium-enriched carbonate veins associated with fluorite-mineralised joints show a magnetic remanence component indicative of a Late Jurassic to Early Cretaceous emplacement age when plotted on the apparent polar wander path (APWP) (Grønlie & Torsvik 1989). The same veins also show another remanence component indicating a Late Cretaceous/Early Tertiary age of faulting and hydrothermal activity. Recent K/Ar-dating of

Table 1. Fluorite fission-track data.

		ρ_s		ρ_i		ϕ			
Sample no.	Location	Tracks/cm² (×10³)	No. of tracks counted	Tracks/cm² (×10³)	No. of tracks counted	Neutrons/cm² (×10¹⁴)	No. of tracks counted	T (Ma)	1 s.d. (Ma)
1	Ystad Fault	3.2	9	3.2	8	9.53	1000	64.8	31.6
2	Ystad Fault	5.2	13	5.2	13	9.49	1000	57.4	22.6
3	Slipra Fault	3.2	8	2.4	6	9.45	1000	76.1	41.2

$^{235}U/^{238}U = 7.2527 \cdot 10^{-3}$, $\sigma_f = 580.2 \cdot 10^{-24}\ cm^2$, λ_f (fission decay constant) $= 7.03 \cdot 10^{-17}\ yr^{-1}$ (Roberts et al. 1968).

adularia and microcline from the same veins shows Late Triassic ages (J. G. Mitchell, pers. comm. 1989). The K-feldspars clearly crystallised before calcite and fluorite in the paragenetic sequence of minerals (Grønlie & Torsvik 1989, Fig. 3).

Field mapping shows that the fluorite mineralisation records the latest hydrothermal event along both the Ystad and the Slipra Faults. The fission-track dating of fluorite, with a blocking temperature of approximately 90°C, provides a minimum age for the latest hydrothermal activity, i.e. Late Cretaceous/Early Tertiary times (Table 1). Because of the low annealing temperature of fluorite we consider it highly unlikely that the dates in question are emplacement ages. We interpret the dates as cooling ages; thus, the fluorite mineralisation could, in principle, have developed at any time during the period between the Caledonian metamorphism of the rocks and Early Tertiary times.

Bearing in mind the Late Triassic, K/Ar, K-feldspar ages, this in fact restricts the fluorite mineralisation to the time interval Late Triassic/Early Tertiary. Furthermore, palaeomagnetic dating of late thorium-enriched breccias by Grønlie & Torsvik (1989) has indicated that important hydrothermal activity and faulting took place in Late Jurassic/Early Cretaceous time. Late Cretaceous/Early Tertiary hydrothermal activity is also indicated by the palaeomagnetic data. We thus argue that the fluorite mineralisation formed in Late Cretaceous times and that it passed the annealing temperature relatively shortly afterwards due to rapid Early Tertiary uplift (Torske 1972; Talwani & Eldholm 1977).

In connection with Permian rifting there was a significant period of mineralisation at 280 Ma in Norway and Britain, and many of the ores include fluorite (Russell & Smythe 1978). Well-known fluorite deposits occur at Lassedalen and at Gjerpen (Ihlen & Vokes 1978) close to the Oslo Graben. From Lassedalen, Late Permian to Early Triassic K/Ar clay alteration ages have been reported by Ineson et al. (1975), thus providing a minimum age for this fluorite deposit. The Trondheimsfjord fluorite veins appear to be unrelated to this earlier, Permian mineralisation. On the contrary, the fluorite veining has much in common with that associated with a phase of earliest Tertiary alkaline magmatic activity reported from areas in East Greenland (Bearth 1958; Nielsen 1987).

Conclusions

Fission-track dating of fluorite from late, hydrothermal veins occurring along two major faults in inner Trondheimsfjord has yielded ages of 57.4 ± 22.6 and 64.8 ± 31.6 Ma in the case of the Ystad Fault, Hylla, and 76.1 ± 41.2 Ma from the Slipra Fault, Mosvik. Although the large error margins call for caution in interpreting these dates, they are here considered to represent cooling ages and provide a minimum age of Late Cretaceous/Early Tertiary for the hydrothermal activity. It is suggested that the fluorite mineralisation developed in Late Cretaceous time shortly before or in the initial stages of a phase of rapid crustal uplift which is known to have occurred in Early Tertiary time in this part of Scandinavia.

Acknowledgements. – We are grateful to C. Naeser, N. Naeser, B. Sturt, P. Ihlen, and T. Nielsen for invaluable criticism and comments on an earlier version of the manuscript. O. Skarpnes and H. Qvale reviewed the final manuscript. G. Grønli drafted the figures.

Manuscript received February 1990

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