Fission-track dating of apatites in Swedish Precambrian apatite iron ores

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Fission-track ages have been determined on single crystals of apatite crystallized in open fabrics and on ore (rock) apatites formed in closed fabrics, both originating from Precambrian apatite iron ores from northern and central Sweden. With one exception, all specimens yield corrected fission-track cooling ages between 191 and 283 million years with corresponding temperatures of 149 and 153°C. The consequences for denudation and morphogenesis are discussed.

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Physical background and results

The fission-track age (FTA) of a mineral is known not to be the true age of the mineral; it represents instead a shorter period of time within which the tracks of ^{238}U fission events that are still observable today have been preserved. The fission tracks, under the influence of temperature, become partly or totally healed in the course of time. There are comprehensive investigations (see for instance Fleischer et al. 1975) concerning this thermally engendered annealing of the fission tracks, and particularly for apatites by E. Märk et al. (1973). Based on the results of the latter, it is possible to compare in apatite the fossil track lengths l_s with track lengths l_i caused by irradiation from a reactor as a ratio l_i/l_s and to use this ratio to correct the measured fission-track age. In addition, following E. Märk et al. (1973), it is possible to determine a temperature value T_w corresponding to the corrected fission-track age t_w in case the cooling rate has been linear. (Recent results see Bertel et al. 1978.)

The temperature for complete annealing of fission tracks in apatite is quite low. Hence in rock and mineral specimens, the age measurements are limited to the interval since the sample last reached a temperature $T < 200°C$. All older tracks have been completely annealed. Fission-track ages of rocks and minerals are thus only of service for establishing true geological ages in the volcanic range. On the other hand, for plutonites and metamorphic minerals, only cooling ages can be measured, never crystallization or metamorphism ages. Hence old fission-track ages obtained from apatites in Variscan or Caledonian samples can only be expected in crustal zones which have escaped more recent metamorphism or major vertical tectonic displacements, or in aged continental blocks.

In the present paper, FTA from apatites obtained from Sweden are reported for the first time. The age calculation was made by consideration of the decay of ^{238}U using the relationship (R. L. Fleischer et al. 1965 and Märk et al. 1973).

$$t_w = \frac{1}{\lambda_\alpha} \ln\left[1 + \frac{\lambda_\alpha \cdot \sigma_f \cdot I \cdot n}{\lambda_s} \frac{p_s}{p_i} \frac{\bar{l}_i}{\bar{l}_s}\right] \qquad (1)$$

where the symbols have the following meanings: $\lambda_\alpha = 1{,}54 \cdot 10^{-10} yr^{-1}$ and $\lambda_f = 0{,}84 \cdot 10^{-16} yr^{-1}$ (Spadavecchia & Hahn 1967), the time constants for α-decay or spontaneous fission, respectively of ^{238}U; $\sigma_f = 582$ barns (Hanna et al. 1969), the fission cross section of ^{235}U for thermal neutrons; $I =$ the isotope abundance ratio $^{235}U/^{238}U = 7{,}26 \cdot 10^{-3}$ (De Wet & Turkstra 1968); $n =$ the integrated neutron flux; p_s and $p_i =$ measured areal densities of spontaneous and induced fission tracks; $\bar{l}_i/\bar{l}_s =$ ratio of average lengths of induced tracks to spontaneous tracks (Märk et al. 1973); t_w = the corrected FTA. If the track-length ratio is omitted, i.e., if $\bar{l}_i/\bar{l}_s$ is set equal to 1, a value t_r is obtained, called the uncorrected FTA.

By contrast with other studies (e.g. Wagner 1968) in which separated rock-apatites were used and hence a large assortment of smaller single individuals, in the present work large single crystals of apatite were used. The examination of larger specimen areas permits a better evaluation of the homogeneity of the fission tracks, or correspondingly, of the uranium content in the sample. Samples with inhomogeneous track distribution can thus be eliminated. The disadvantage of this selection of specimens lies in their relatively rare occurrence so that a broad survey of fission tracks covering a large territory, as was originally planned, is not possible without gaps.

The results of our FTA determinations are collected in Table A. Single samples were cut out of large single pieces of fissure apatites perpendicularly to the optic axis. The core drillings contain smaller apatite crystals anisotropically oriented. In order to have reproducible track criteria, microscopic observations in polarized light were made of the core drilling samples to establish that only those apatite crystals were used for track counts whose optic axes were perpendicular to the polished plane. The etching of the fission tracks was done for all samples under controlled conditions (65 % HNO_3, 20°C, 30 s). The uranium content of the samples used proved to be homogeneous. The reported error boundaries represent the uncertainties of the counting statistics combined with the error in the various constants in the formula for ages (Vartanian 1975).

Geological considerations

General tectonic emplacement

The apatites investigated by the fission-track method (FT-method) originate from Precambrian apatite iron ores from northern and central Sweden. This early-orogenic type of deposits, with its specific lithological and stratigraphical occurrence, is met with only in the Svecofennides within the Baltic Shield. The ore deposits are bound to the supracrustal rocks, which adjoin the ore-deficient central zone of Norrland on both sides. In the north, they are assigned to the ore-bearing subprovince of the Svecofennian in northern Norrland, and in the south to that of the similarly Svecofennian leptite complex in Bergslagen.

Description of the deposits

These apatite iron ores are stratified apatite-magnetite ores (more seldom stratified apatite-haematite ores and apatite-heamatite impregnations), which are mostly situated in keratophyric and quartz-keratophyric metavolcanics. Alongside these stratified ores, at the contacts but also isolated in the country rocks, there occurs brecciation of the metavolcanics, which are healed up with magnetite, haematite, and apatite ("ore breccias"). At first, the ores were interpreted as being exhalative-synsedimentary (Bäckström 1898; De Launay 1903) and then for a long time as being formed from phosphorous iron melts which had intruded near the surface and were split up by liquation (Stutzer 1907; Geijer 1910; Magnusson 1938). Recently, findings have again multiplied which furnish arguments in favour of syngenetic-volcanic interpretations (Koark 1952, 1970, 1973; Oelsner 1961; Parák 1975). There seems to be a certain relationship with apatite-magnetite lavas, which are known from Chile (Park Jr. 1961; Haggerty 1970) and Iran (Förster & Burundi 1971).

Metamorphism

The ores and country rocks were exposed to at least two phases of metamorphism — synorogenic regional metamorphism under the conditions of the amphibolite facies and late- to post-orogenic metamorphism with effects varying from migmatite-forming conditions to low-temperature metasomatism.

Genetic position of the apatite

The FT ages were determined partly on single crystals of apatite crystallized in open fabrics from Malmberget, Tuolluvaara and Grängesberg and partly on ore (rock) apatites formed in closed fabrics from Nakerivaara and Tjårrojåkka.

The ore apatites first crystallized approximately at the same time as the iron oxides. During later regional metamorphism(s), the apatite re-crystallized several times, together with the other primary minerals in the fabrics. The apatites in fissures resulted from isochemical remobilization in the syn- to late-orogenic stage.

Both ore and fissure apatites are without exceptions fluorine-dominated members of the fluorine-apatite- to hydro-apatite series. The minerals, determined in this case by the FT-method, were not chemically analyzed any further. Parák (1973) gives analyses of comparable materials from the deposits at Kirunavaara (ore and fissure apatites) and Malmberget (ore apatites).

Table A. The results of the FTA determinations.

Location		Tracks counted		t_r in 10^6 years	$\bar{I}_i/\bar{I}_s$	t_w in 10^6 years	T_w (°C)	Comments	
		Spontaneous	Induced						
Grängesberg		974	211	250 ± 52	1,14 ± 0,07	283 ± 73	150	Cluft-apatite	
Malmberget		820	245	158 ± 32	1,21 ± 0,08	191 ± 48	153	—„—	
Tuolluvaara		3398	1787	411 ± 65	1,19 ± 0,06	486 ± 95	149	—„—	
								Depth in m	Core drillings
Nakarivaara	(1)	1454	662	195 ± 35	1,15 ± 0,07	224 ± 51	152	26,80—26,88	
—„—	(2)	1227	744	221 ± 39	1,28 ± 0,07	281 ± 58	150	28,9—28,95	
Tjårrojåkka	(1)	1354	1155	181 ± 31	1,17 ± 0,07	212 ± 45	152	234,2—234,3	
—„—	(2)	1683	1230	225 ± 37	1,15 ± 0,06	258 ± 53	151	241,05—241,10	

Regional geology of the deposits

Tjårrojåkka. — 50 km WSW of Kiruna and about 20 km E of the edge of the Caledonides. Magnetite ores in the form of irregular bodies or porphyric breccias healed up with magnetite and apatite. The country rock is a syenite porphyry with intercalations of tuffs and tuffites (Grip & Frietsch 1973).

Nakerivaara. — 52 km NW of Kiruna and about 10 km E of the edge of the Caledonides. Schistose rocks of a dioritic composition (metavolcanics or metaintrusives) are brecciated and healed up with magnetite and apatite (Grip & Frietsch 1973).

Tuolluvaara. — 4 km E of Kiruna. Stratified apatite-magnetite and rarely apatite-haematite ores embedded in quartz keratophyres. The quartz keratophyres adjoining the ore layers are mostly volcano-tectonically brecciated and healed up with iron oxides and apatite. Comparable breccias are also to be found at varying distances from the ore layers, generally with the same strike. Now and then, these ore-consolidated breccias meet discordantly into the stratified ores. After regional metamorpism under the conditions of the amphibolite facies, which affected both the ores and the country rock, there was in addition to the penetration of small intrusions of potassium syenites, in places a radical late-orogenic potassium metasomatism in the quartz keratophyres (Geijer 1920; Koark 1970).

Malmberget. — 5 km N of Gällivare. The apatite iron ore deposit that has been most altered by foldings and recrystallizations. Late-orogenic intrusions of granite and pegmatite are frequently interspersed among the ores and country rocks. The stratified ores consist of coarse-grained and often greatly extended apatite-magnetite *B*-tectonites. Apatite-haematite ores are more rare. The supracrustal country rocks are mostly gneissic acid effusives, now and then also basic effusives (Geijer 1930; Koark 1952; Ljunggren 1960).

Grängesberg. — About 200 km WNW of Stockholm, the most important deposit of the central Swedish apatite-iron-ore district. Ores in the form of large irregular lenses and layers with stratified structures. The deposit consists mainly of magnetite, but now and then also of haematite. The contents of apatite vary greatly. The country rocks are metakeratophyre and metarhyolite, including tuffs, with successive transitions into the ore in places (Koark 1973). Dikes of metaandesite and metadacite are interspersed in the loops of the ores. The numerous late-Svecofennian pegmatites lie preferably in the *ac* plane of the columnar structure. The regional metamorphic minerals in country rocks and to some extent in the ores are amphibole, pyroxene, garnet, and epidote (Magnusson 1938).

Paragenesis of fissure apatite

Documentation on the association of the fissure apatite determined by us by the FT-method is available only for the Malmberget deposit (Flink 1924). Flink's information is based on specimens in collections and not on his own specimens selected in the field. The apatite-bearing cavities at Malmberget are preferably to be found in skarns and parts of the ore and the country rock which is rich in skarn minerals.

Flink distinguished seven types of fissure apatites. The distinctive features were colour, habit, mineralogical composition of the growth plane, and the relative age within the fissure mineralization. The apatite crystal investigated by us could not be assigned to any of the seven groups, as it was an individual crystal originating from a collection and had no growth plane. Without knowing its fissure associatioan it is impossible to establish a paragenetic age classification.

Table B. Fissure associations of the apatites of Malmberget, Tuolluvaara, and Grängesberg.

Malmberget	*Tuolluvaara*	*Grängesberg*
Apatite, magnetite, haematite, quartz, amphibole, albite, pyroxene, muscovite, scapolite, titanite, desmine, epidote, stilbite, chabasite	Apatite, magnetite, amphibole, talc, albite, titanite, calcite, dufrenite, strengite, wavellite, cacoxenite, eleonorite, dahlite	Apatite, haematite, quartz, pyrite, asphalt, chlorite, (feldspar, epidote, hedenbergite)

The fissure associations of the apatites of Malmberget, Tuolluvaara and Grängesberg are given in summary form in Table B.

There are no special studies of the fissure paragenesis at Tuolluvaara. This is regrettable, not only because it is relatively rich in minerals but also because it is not out of the question that the very different fission-track value is to be explained by nuclear processes resulting from fissure associations. However, the fissure minerals already known (Table B) yield no relevant clues.

The fissure paragenesis of the Grängesberg deposit could only be reconstructed from specimens in the Gränges Gruvor AB museum. The most common mineral associated with apatite would seem to be haematite. Quartz, pyrite, and asphalt are less frequent. Moreover, feldspar, epidote, and hedenbergite also appear as fissure minerals, though the presence of apatite could not be verified in the available material.

Physical-age determinations by the Rb-Sr and K-Ar methods with a geological interpretation

There are no physical age determination of these ores. However, there are datings of the country rocks and the rocks in the immediate surroundings of the deposits in northern Norrland (Welin, Christiansson & Nilsson 1971).

Regarding the deposits at Kiruna (Kirunavaara and Luossavaara), there are Rb-Sr datings made on neighbouring acid metavolcanics. The whole rock analysis yield an isochron of $1605 \pm 65 \times 10^6$ years, with an initial Sr^{87}/Sr^{86} ratio of $0{,}705 \pm 0{,}003$. The authors interpreted this model age as the age of formation of the Kiruna volcanic-rock complex and its ores and concluded, on the basis of the diverging position in the time scheme of the Svecofennian supracrustal development, that it was a question of post-orogenic formation. This interpretation contradicts, inter alia, the tectonic facts, which show isoclinal fold structures with steep-axis re-folding in places. The fact that the metavolcanic rocks have been repeatedly metamorphosed and in places display a strong metasomatism of potash was not taken into account in the geological interpretation of the model age.

There are no datings from Tuolluvaara, which is only 4 km from Kiruna. As the geology, type of deposit, and age position are comparable with those of the nearby Kiruna deposits, recent Rb-Sr datings were assumed to be valid also for Tuolluvaara.

From Malmberget/Gällivare, there are so far only age determinations made on the late-orogenic Lina granites. They penetrate the ores and supracrustal country rocks and are consequently younger. For samples of Lina granite from Malmberget, the whole rock isochron yields a value of $1565 \pm 35 \times 10^6$ years at an initial Sr^{87}/Sr^{86} ratio of $0{,}712 \pm 0{,}003$ (Welin, Christiansson & Nilsson 1971).

However, there is a K-Ar dating made on amphibole from Malmberget (Welin, Lundström & Åberg 1972). The same sample and an additional crystal of the same specimen were also investigated by the fission-track method. The K-Ar age was determined as 1875×10^6 years. It can only be assumed that the two amphiboles originate from a skarn lens or druse, perhaps even associated with apatite. In that case, the age given must be the age of metamorphism.

There are no physical datings from the Grängesberg district in central Sweden.

As has already been stated above, the stratigraphic and tectonic conditions argue in favour of an early-orogenic classification of the apatite iron ores. This applies both to the deposits in central Sweden and to those in northern Norrland. On the basis of the Svecokarelian time scale, this early-orogenic phase would seem to have occurred in the time interval $2200—1900 \times 10^6$ years, while the different metamorphic and metasomatic processes which affected the ores and their country rocks would seem to have been active in the time interval $1950—1500 \times 10^6$ years, perhaps even later.

Geological and morphological interpretation

The measured (corrected) FT ages t_w of the apatites are cooling ages. Beside those datings the cooling temperatures T_w (°C) were resonstructed. As is shown in Table A, the FT ages (excluding error deviation) all gather in the interval $191—283 \times 10^6$ years. The calculated temperatures T_w were 149 to 153°C at the above mentioned ages, assuming linear cooling conditions.

An exception is made by the apatite of Tuolluvaara, which, with a temperature of $T_w = 149°C$, shows a cooling age t_w of $486 \pm 95 \times 10^6$ years.

The values for t_w between 191 and 283×10^6 years (see above) are spreading geologically from late Carboniferous (Stephanian) through Permian to Triassic time.

Any estimate of the thickness of the overburden in these special regions is prevented by the lack of data concerning the climate at that time as well as by the question of the lithological character of the overlying rocks. The latter implies the question as to whether basement rock or cover have been participants in the processes, and if both, in what proportions. The statistical mean value of the geothermal gradient for metamorphic basement in continental blocks is 67 m $deg.^{-1}°C$, and that for successions of basin sediments is 29 m $deg.^{-1}°C$ (Egyed 1969). On the basis of those data and assuming different annual temperature-mean values, $\bar{T}$, where 10°C and 25°C are taken as minimum and maximum, respectively, it is possible to make an estimate of the overburden thickness for basement and cover rock, respectively:

$\bar{T}$ (°C)	Difference $T_w - \bar{T}$ (°C)	Basement (m)	Cover (m)
10	139—143	~9400	~4100
25	124—128	~8400	~3700

These values should only be seen as indications of the magnitude.

The reporting on magnitude of denudation varies considerably corresponding to the different climatical and geological conditions. There is no literature known to the authors, which gives any valid magnitude of denudation for the Fennoscandian basement complex. However, for our purpose it is possible to use the metamorphic rank.

The last progressive phase of the regional metamorphic crystallization, which is mostly posttectonial, gives rise to cordierite, anthophyllite, sillimanite, almandine, phlogopite, and muscovite. They are constituents, which, formed by regional metamorphism, need pT-conditions around 0,4—0,5 GPa and 550—600°C. This means, that the present denudation surface now shows a level in the crust, which should have received its highest metamorphic character at a depth of 15—20 km. In other words, about 15—20 km of the basement surface should have been removed after the mentioned crystallizations.

As mentioned on page 106, we can assume that regional metamorphism was active in the period $1950—1500 \times 10^6$ years. Since this time 15—20 km of basement has been eroded, according to the above calculations. This corresponds to a denudation rate of approximately 10 $m/1 \times 10^6$ years, if uplift and erosion were acting continuously. However, it is known that the denudation was much more intensive during Precambrian time than after that. It can be supposed that the denudation rate during periods of the prekratogenic stage was of an order of magnitude comparable with that of the Alps (1000 $m/1 \times 10^6$ years).

If we accept a linear denudation rate of 10 $m/1 \times 10^6$ years the effect would be, that — in relation to our fission-track ages — a rock overburden with a thickness of the magnitude of 1900—2800 m has been carried away since the fixation of the t_w-ages in the apatites. These values stand against the above calculated overburden thicknesses. As mentioned above, the thickness of overlying basement rocks is calculated to be 8400—9400 m or, of cover rocks, 3700—4100 m. The resulting denudation rate would be 35—39 $m/10^6$ years for overlying basement and 15—17 $m/10^6$ years for cover. These rates deviate more or less from 10 $m/10^6$ years, the value calculated from the relation between the PT-conditions of the last progressive crystallization, their age, and the present surface. Consequently, the deviation above for the calculated rate value for cover is 68 % less than that for overburden basement. This supports the opinion that the overburden consisted dominantly of cover rocks at the time indicated by the fission-track ages.

In the Alps the fission-track ages have been used with success for the reconstruction of tectonial events and of the morphogeny, especially that of the history of upheaval (Wagner 1973). We had a similar aiming for the Fennoscandian part of the Baltic Shield. Those first few measurements are just a primary approach and they do not give enough space for conclusions about the different tectonial and morphological developments.

The reason why the t_w and T_w values of the apatite from Tuolluvaara diverge cannot be verified for the time being. The t_w age $486 \pm 95 \times 10^6$ years would suggest that the area around Tuolluvaara had reached its actual cooling level 200×10^6 years earlier than, for example, Nakerivaara, which is only 55 km away. For this reason, the mineralogical-petrological, stratigraphical, or tectonical differences are not enough pronounced.

The resulting denudational difference of approximately 280—1660 m could in some cases be lowered considerably by exogenic influence as deeply penetrating cooling processes caused by ground-water circulation in connection with fracturing/faulting. On the other hand, it is as well believable that a block movement of tectonical origin may create a vertical difference of 280—1660 m. This is especially true if "Staffelung" and combined up- and down-thrusting were in action. From areas where this can be shown, i.e. where late-Precambrian or younger sediments are existing, vertical fault movements of at least 1000 m are known (Visingsö Formation; Collini 1951).

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