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$^{40}Ar/^{39}Ar$ (adularia) and Rb-Sr (adularia, prehnite, calcite) ages of fracture minerals

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Abstract

This report presents the results obtained from geochronological studies of fracture minerals from drill cores from the Forsmark site investigation. Five adularia (low temperature K-feldspar) samples from both open and sealed fractures have been dated with the $^{40}Ar/^{39}Ar$ method and one fracture filling consisting of an assemblage of adularia, prehnite and calcite has been dated by the Rb-Sr method.

Fracture minerals have been selected to provide absolute geochronological constraints of the relative sequence of fracture mineralizations obtained by e.g. cross-cutting relations and stable isotope studies /Sandström and Tullborg 2006/. The sequence consists of 4 different generations of which Generation 2 and 3 have been dated during this study.

$^{40}Ar/^{39}Ar$ dating of Generation 2 minerals has given ages of 1,072 ± 3 and 1,034 ± 3 Ma for fracture filling adularia which correlate with the Rb-Sr reference age of an assemblage of adularia, prehnite and calcite which gave 1,096 ± 100 Ma. The ages are interpreted as being associated with a Sveconorwegian tectonothermal event. This event involved formation or reactivation of the fractures, during which the adularia has either crystallized, recrystallised or has been thermally reset.

The two minerals from Generation 3 give ages of 455.9 ± 1.5 and 276.9 ± 1.1 Ma by the $^{40}Ar/^{39}Ar$ method which are interpreted as crystallization ages, indicating that the precipitation of Generation 3 minerals was active at different episodes during the Paleozoic.

Sammanfattning

I denna rapport presenteras resultaten från geokronologiska studier av sprickmineral från borrkärnor från Forsmarks platsundersökning. Fem prover av adular har daterats med hjälp av $^{40}Ar/^{39}Ar$ metoden och en sprickläkning bestående av adular, prehnit och kalcit har daterats med Rb-Sr metoden.

Sprickmineral har valts ut för att ge absolut geokronologisk data till den relativa sekvensen av sprickmineraliseringar i Forsmark baserad på bl a klippande relationer och stabila isotoper /Sandström och Tullborg 2006/. Sekvensen består av fyra olika sprickmineralgenerationer varav Generation 2 och 3 har daterats i denna studie.

$^{40}Ar/^{39}Ar$ datering av adular från Generation 2 minerals har get åldrar på 1 072 ± 3 och 1 034 ± 3 Ma vilket stämmer överens med Rb-Sr referensåldern på 1 096 ± 100 Ma av en sprickfyllnad bestående av adular, prehnit och kalcit. Dessa åldrar tolkas som en Svekonorvegisk tektonotermal händelse, vilken antingen har genererat eller reaktiverat sprickor, samtidigt som adular har kristalliserats, omkristalliserats eller har blivit termalt nollställd.

De två adular-proverna från Generation 3 ger $^{40}Ar/^{39}Ar$ åldrar på 455,9 ± 1,5 och 276,9 ± 1,1 Ma, vilka tolkas som kristallisationsåldrar. Detta indikerar att utfällningen av Generation 3 mineral har ägt rum vid olika tidpunkter under Paleozoikum.

Contents

1 Introduction

This document reports the results gained by the geochronological study of fracture minerals, which is one of the activities performed within the site investigation at Forsmark. The work was carried out in accordance with activity plan AP PF 400-05-047. In Table 1-1 controlling documents for performing this activity are listed. Both activity plan and method descriptions are SKB's internal controlling documents.

A relative geochronological sequence of fracture minerals has been compiled by /Sandström and Tullborg 2006/ and consists of 4 distinguished fracture mineral generations. The sequence is based on e.g. cross cutting relations in about 100 drill core samples from more than 10 different drill cores. Stable isotope analyses of calcite and pyrite and geochemical analyses have further contributed to the subdivision into different fracture mineral generations. These generations grade from relatively high temperature (greenschist facies) to low temperature (zeolite facies and lower). The fracture mineral generations are summarized below, with decreasing relative age of formation:

Adularia from Generations 2 and 3 has been selected for dating by the $^{40}Ar/^{39}Ar$ method. Thermochronological studies in the Forsmark area by /Page et al. 2004/ show that cooling below 300°C took place between 1,704 and 1,635 Ma and cooling below 70–60°C between 630 and 250 Ma. This long period of low temperature conditions in the area is favourable for $^{40}Ar/^{39}Ar$ dating of adularia, since the closing temperature of radiogenic argon in K-feldspar can be as low as 130–150°C /Foland 1974, Harrisson and McDougall 1982/.

Table 1-1. Controlling documents for the performance of the activity.

Activity plan	Number	Version
Geokronologisk undersökning av sprickmineral	AP PF 400-05-047	1.0
Method descriptions	**Number**	**Version**
Sprickmineralogi	SKB MD 144.000	1.0
Åldersdateringar av mineral och bergarter	SKB MD 132.002	

Table 1-2. Relative sequence of fracture minerals in Forsmark from /Sandström and Tullborg 2006/.

Generation 1	Generation 2	Generation 3	Generation 4
consists mainly of epidote, quartz and Fe-rich chlorite. The deformation grades from semi-ductile to brittle.	is a sequence of hydrothermal minerals, probably extended in time. The sequence consists of a first phase of hematite stained *adularia*[1), 2)] (low temperature K-feldspar), albite and anhedral quartz, followed by *prehnite*[1)] and a later phase of hematite stained laumontite. Chlorite/corrensite and *calcite*[1)] have precipitated throughout this hydrothermal event.	consists of low temperature fracture minerals dominated by euhedral quartz and calcite together with pyrite, corrensite and analcime. Small amounts of *euhedral adularia*[2)], albite and other sulphide minerals also belong to this generation. Asphaltite occurs in the upper parts of many of the boreholes.	represents the latest fracture minerals and consists of clay minerals and calcite precipitated as an outermost layer in open fractures.

1) Rb-Sr dating

2) $^{40}Ar/^{39}Ar$ dating

Rb-Sr dating has been carried out on a sealed fracture filled with adularia, prehnite and calcite. The Rb-Sr method is more imprecise, but more resistant to elevated temperatures than $^{40}Ar/^{39}Ar$ dating. The Rb-Sr dating has been used to compare the ages obtained from two independent methods.

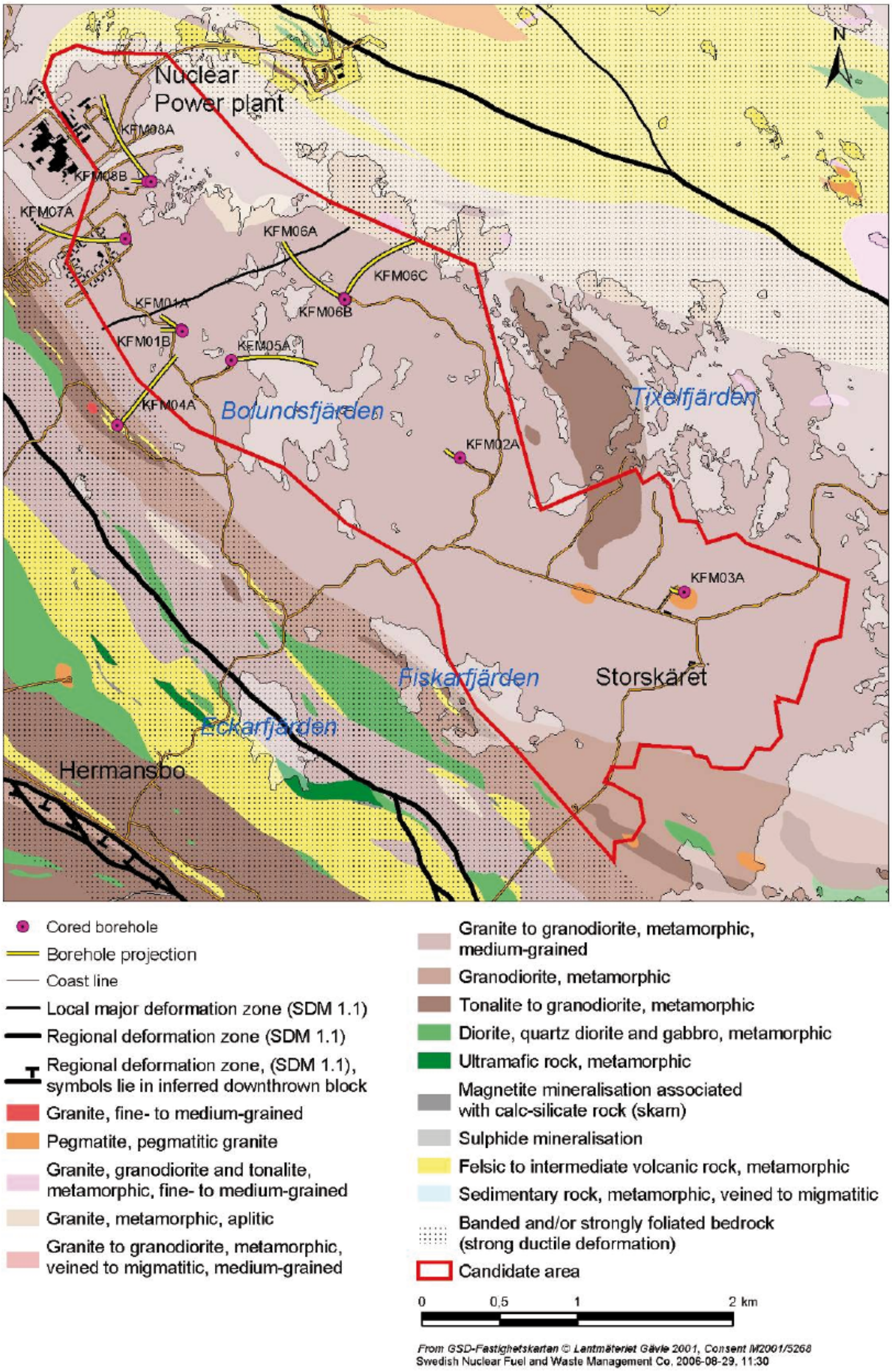

Figure 1-1. Geological map over the Forsmark site investigation area with projections of boreholes.

2 Objective and scope

The objective with this study is to provide absolute geochronological constraints on the relative sequence of fracture generations in Forsmark by /Sandström and Tullborg 2006/ and thereby contribute to the reconstruction of the low temperature geological evolution in the Forsmark area.

Two of the four fracture mineral generations in Forsmark /Sandström and Tullborg 2006/ have been sampled for geochronological work. Five adularia samples (from both sealed and open fractures) have been dated by the $^{40}Ar/^{39}Ar$ method and one sealed fracture filling consisting of an assemblage of coeval adularia, prehnite and calcite has been dated by the Rb-Sr method.

This report presents the data obtained from the geochronological study and links it to the relative geochronological model of fracture minerals by /Sandström and Tullborg 2006/.

3 Equipment

3.1 Description of equipment/interpretation tools

The following equipment was used for the selection of samples for geochronological analyses.

- Rock saw.
- Swing mill.
- Tweezers.
- Digital camera.
- Petrographic Microscope (Leica DMRXP).
- Binocular microscope (Leica MZ12).
- Digital microscope camera (Leica DFC 280).
- Scanning electron microscope (HITACHI S-3400N).
- EDS-detector (INCADryCool).

All the above described equipment is located at the Earth Sciences Centre at Göteborg University, Sweden. For the geochronological analyses the following equipment was used:

- Micromass 5400 mass spectrometer (Lund University, Sweden).
- New Wave Research 50W CO_2 laser facility (Lund University, Sweden).
- Thermal Ionization Mass Spectrometer (TIMS) (Activation Laboratories Ltd, Ancaster, Canada).
- Conventional cation exchange equipment (Activation Laboratories Ltd, Ancaster, Canada).

4 Execution

4.1 Selection of samples

To obtain useful geological knowledge from the geochronological data of fracture minerals, it is important to have detailed knowledge of the relative fracture mineral sequence and to select samples based on this sequence. The samples were selected from drill cores KFM05A, KFM07A and KFM08A. The individual samples were selected based on the relative fracture mineral sequence in Forsmark described by /Sandström and Tullborg 2006/. Before the selection of samples for geochronological analyses, detailed microscopy with binocular, petrographic and scanning electron microscope (SEM-EDS) was carried out to identify suitable fracture minerals.

4.2 Preparations

The drill core samples were documented using a digital camera.

To identify the fracture minerals, polished thin-sections with a thickness of 30 µm were prepared and analysed with optical microscope and scanning electron microscope (SEM) equipped with an energy dispersive spectrometer (EDS). Fracture surfaces were examined with binocular microscope and with SEM-EDS under low vacuum conditions. Low vacuum was used in order to avoid using gold coating on the fracture surface. The SEM-EDS analyses were carried out at Earth Sciences Centre, Göteborg University using a HITACHI S-3400N SEM equipped with an INCADryCool EDS detector.

From the open fractures, adularia was handpicked under a binocular microscope. From sealed fractures, the fracture filling was separated from the wall rock using a rock saw and then crushed manually with a hammer. The fragments were put in a swing mill for a few seconds to obtain small grains made up of individual mineral phases. The adularia was then handpicked with tweezers under a binocular microscope and washed in distilled water.

4.3 Execution of field work

Samples have been selected from drill cores KFM05A, KFM07A and KFM08A during the sampling for the detailed fracture mineralogy study (activity AP PF 400-04-32).

4.4 Analyses and interpretations

4.4.1 Rb-Sr dating

Rb-Sr dating was carried out at Activation Laboratories LTD, Canada, using thermal ionization mass spectrometry (TIMS). Fractions for Rb-Sr analysis were dissolved in a mixture of HF, HNO_3 and $HClO_4$. Before the decomposition, all samples were totally spiked with ^{85}Rb-^{84}Sr mixed solution. Rb and Sr were separated using conventional cation-exchange techniques. Total blank are 0.01–0.05 ng for Rb and 0.3–0.7 ng for Sr. During the period of work the weighted average of 15 SRM-987 Sr-standard runs yielded 0.71024 ± 2 (2) for $^{87}Sr/^{86}Sr$. Sr isotopic ratios were normalized to $^{88}Sr/^{86}Sr = 8.37521$.

The Rb-Sr geochronological data were calculated using the program Isoplot/Ex 3.00 /Ludwig 2003/ for Microsoft Excel.

4.4.2 $^{40}Ar/^{39}Ar$ dating

The adularia samples selected for $^{40}Ar/^{39}Ar$ geochronology were irradiated together with the 28.34 TCR sanidine standard (28.34 Ma recalculated following /Renne et al. 1998/, for 35 hours at the NRG-Petten HFR RODEO facility in the Netherlands. J-Values were calculated with a precision of 0.25%.

The $^{40}Ar/^{39}Ar$ geochronology laboratory at Lund University contains a Micromass 5400 mass spectrometer with a Faraday and an electron multiplier. A metal extraction line, which contains two SAES C50-ST101 Zr-Al getters and a cold finger cooled to ca –155°C by a Polycold P100 cryogenic refrigeration unit, is also present.

One or two grains of adularia were loaded into a copper planchette that consists of several 3 mm holes. Samples were step-heated using a defocused 50 W CO_2 laser. Sample clean-up time that made use of the two hot Zr-Al SAES getters and a cold finger with a Polycold refrigeration unit was five minutes. The laser was rastered over the samples to provide even-heating of all grains. The entire analytical process is automated and runs on a Macintosh-steered OS 10.2 with software modified specifically for the laboratory at Lund University. The software was originally developed at the Berkeley geochronology Centre (Al Deino). 18 Time zero regressions were fitted to data collected from 10 scans over the mass range of 40 to 36. Peak heights and backgrounds were corrected for mass discrimination, isotopic decay and interfering nucleogenic Ca-, K-, and Cl-derived isotopes. Isotopic production values for the cadmium-lined position in the Petten reactor are $^{36}Ar/^{37}Ar(Ca) = 0.000270$, $^{39}Ar/^{37}Ar(Ca) = 0.000699$, and $^{40}Ar/^{39}Ar(K) = 0.00183$. ^{40}Ar blanks were calculated before every new sample and after every three sample steps. ^{40}Ar blanks were between $6.0^{-3}\cdot10^{-16}$. Blank values for masses 39–36 were all less than $7\cdot10^{-18}$. Blank values were subtracted for all incremental steps from the sample signal.

The laboratory was able to produce very good incremental gas splits, using a combination of increasing time at the same laser output, followed by increasing laser output. Age plateaus were determined using the criteria of /Dalrymple and Lanphere 1971/, which specify the presence of at least three contiguous incremental heating steps with statistically indistinguishable ages and constituting greater than 50% of the total ^{39}Ar released during the experiment.

4.5 Nonconformities

The activity has been performed according to the activity plan without any nonconformities.

5 Results

5.1 $^{40}Ar/^{39}Ar$ dating

5.1.1 Sample KFM05A 395.75 m

Sealed fracture with hematite stained adularia, prehnite and calcite (Figure 5-1). The fracture filling belongs to an early phase of the sequence of hydrothermal fracture minerals classified as Generation 2 in Table 1-2. The adularia is red-stained by sub-microscopic grains of hematite. The fracture is surrounded by red-coloured altered wall rock. The analysed grain consists of the hematite stained adularia. The orientation of the fracture is 057/68°.

The plateau age defined on the $^{40}Ar/^{39}Ar$ step-heating spectrum is 1,072 ± 3 Ma (Figure 5-2).

Figure 5-1. *KFM05A 395.75 m. Fracture sealed with hematite stained adularia (red), prehnite (greenish) and calcite (white).The diameter of the drill core is c. 5 cm.*

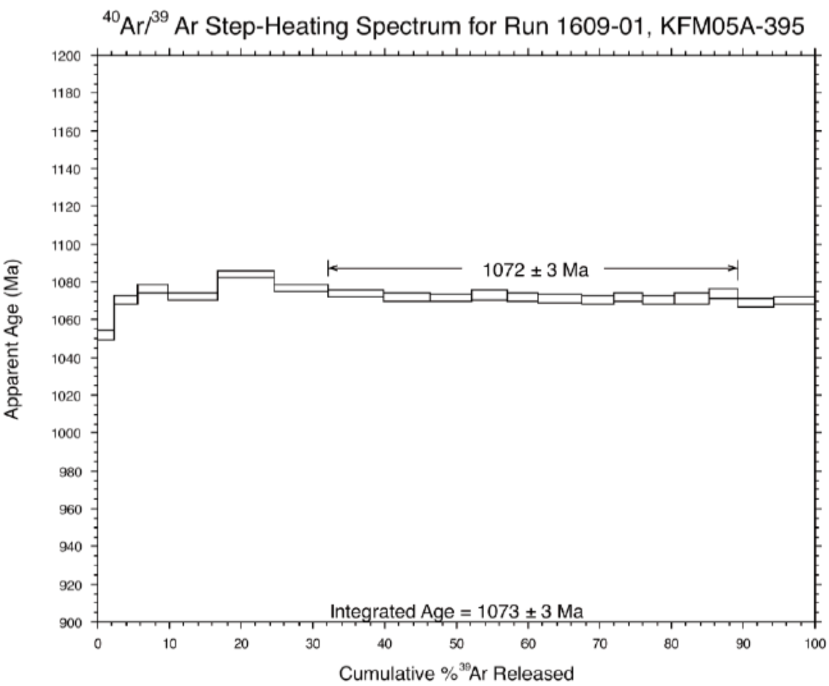

Figure 5-2. *$^{40}Ar/^{39}Ar$ adularia step-heating spectrum for sample KFM05A 395.75 m.*

5.1.2 Sample KFM05A 692.00 m

A thin adularia sealed fracture cutting an older epidote filled fracture. The adularia is red-stained due to sub-microscopic grains of hematite. The fracture is surrounded by red-coloured altered rock (Figure 5-3 and 5-4).The adularia filled fracture belongs to an early phase of the sequence of hydrothermal fracture minerals, classified as Generation 2 in Table 1-2. The analysed grain consists of the hematite stained adularia. The orientation of the dated adularia filled fracture is 032/86°.

The plateau age defined on the $^{40}Ar/^{39}Ar$ step-heating spectrum is 1,034 ± 3 Ma (Figure 5-5).

Figure 5-3. *Sample KFM05A 692.00 m. Sealed fracture with hematite stained adularia cutting an older epidote sealed fracture. The diameter of the drill core is ~ 5 cm.*

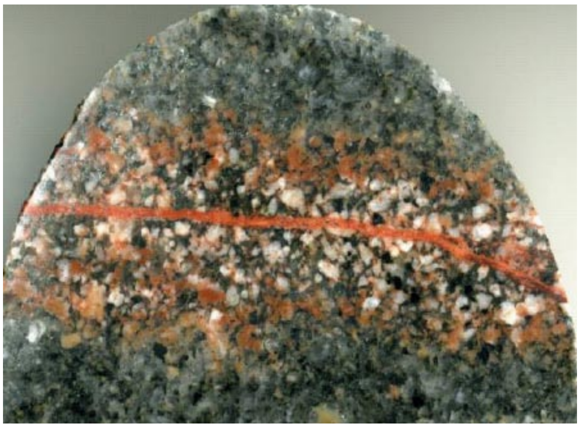

Figure 5-4. *Sample KFM05A 692.00 m. Sealed fracture with hematite stained adularia surrounded by altered wall rock. The diameter of the drill core is ~ 5 cm.*

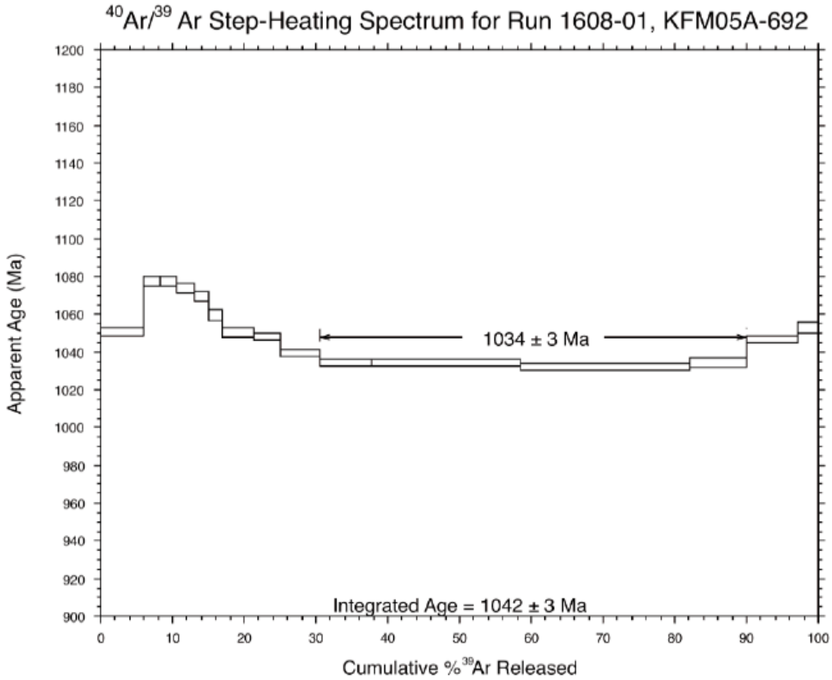

Figure 5-5. *$^{40}Ar/^{39}Ar$ adularia step-heating spectrum for sample KFM05A 692.00 m.*

5.1.3 Sample KFM07A 876.11 m

Euhedral adularia crystals have grown in an open void together with quartz crystals in this vuggy rock sample (Figure 5-6 and 5-7). The red colour is due to sub-microscopic grains of hematite. The sample has been interpreted as belonging to the early stage of Generation 2 (Table 1-2), the same quartz and adularia that commonly occur as thin fracture sealings (see Section 5.1.1 and 5.1.2). The sample consists of voids and no orientation has been obtained.

No reliable age was obtained from this sample and the character of the $^{40}Ar/^{39}Ar$ step-heating spectrum indicates a slow cooling of the sample (Figure 5-8). This result has therefore been excluded from the discussion since it does not provide useful geochronological information.

Figure 5-6. *Sample KFM07A 876.11 m. Euhedral quartz and adularia crystals in a large void in the rock. The reddish colour is due to sub-microscopic grains of hematite. The diameter of the drill core is ~ 5 cm.*

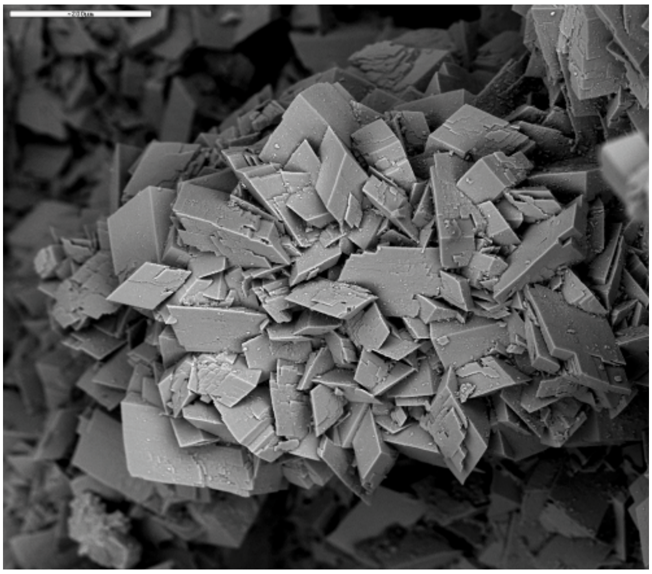

Figure 5-7. *Electron image of euhedral adularia crystals. The white bar is 200 µm.*

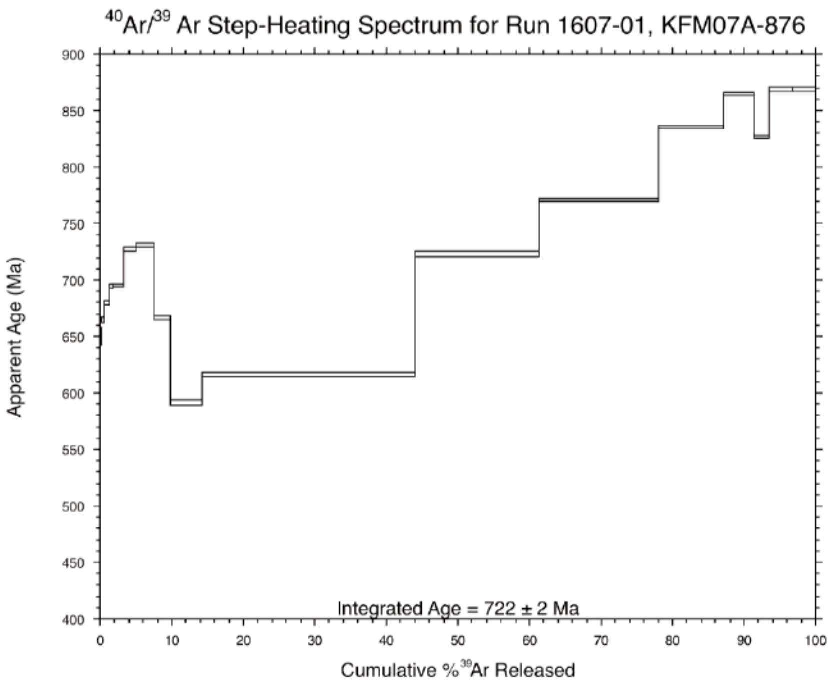

Figure 5-8. *$^{40}Ar/^{39}Ar$ adularia step-heating spectrum for sample KFM07A 876.11 m.*

5.1.4 Sample KFM07A 882.95 m

Open fracture with small euhedral adularia crystals together with quartz and pyrite (Figure 5-9 and 5-10). The small euhedral quartz and pyrite crystals that occur together with the adularia are typical for Generation 3 minerals (Table 1-2). The orientation of the fracture is 236/67°.

Figure 5-9. *Sample KFM07A 882.95 m. Open fracture coated with a thin layer of small euhedral quartz crystals together with minor occurrences of adularia and pyrite. The diameter of the drill core is ~ 5 cm.*

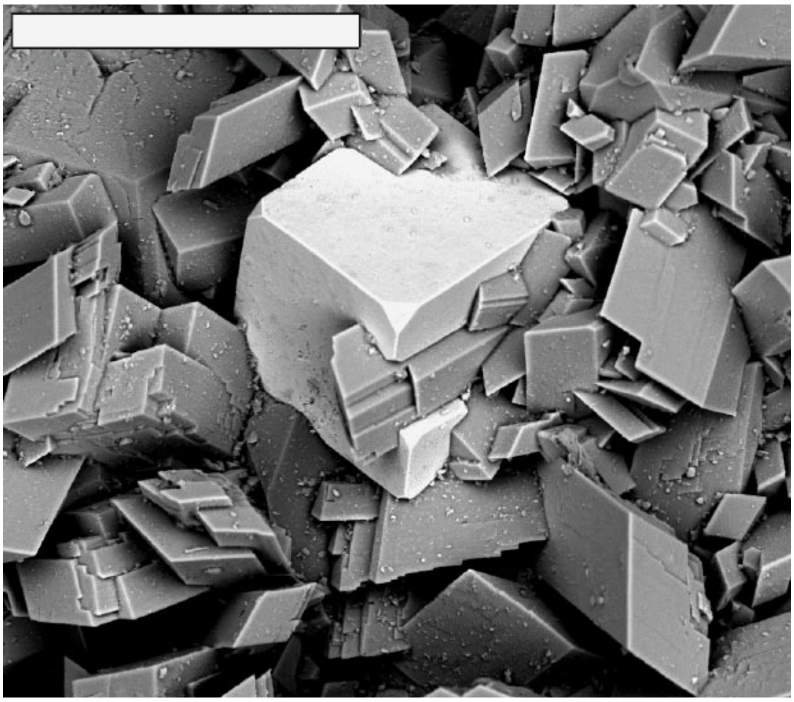

Figure 5-10. *Sample KFM07A 882.95 m, Backscattered electron image of pyrite (bright) intergrown with euhedral adularia crystals, the white bar is 200 µm.*

The integrated age defined on the minima of the u-shaped $^{40}Ar/^{39}Ar$ step-heating spectrum is 455.9 ± 1.5 Ma (Figure 5-11). The u-shaped $^{40}Ar/^{39}Ar$ step-heating spectrum is typical for samples with excess argon, i.e. radiogenic argon present during crystallization in e.g. natural brines or metamorphic fluids. This argon is often trapped in fluid inclusions and released at both low temperatures and at high temperatures when the mineral disintegrate. The maximum age is thus represented by the lowest ages in the step-heating spectrum /Kelley 2002 and references therein/.

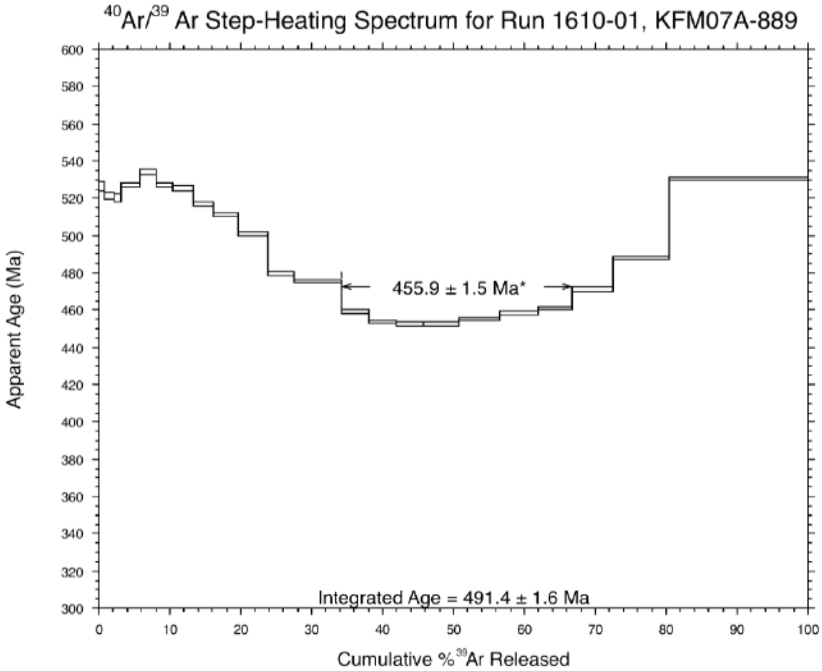

Figure 5-11. *$^{40}Ar/^{39}Ar$ adularia step-heating spectrum for sample KFM07A 882.95 m.*

5.1.5 Sample KFM08A 245.47 m

Open fracture coated with adularia, calcite, pyrite and analcime (Figure 5-12 and 5-13). The adularia has crystallized over the pyrite together with analcime and belongs to a late phase of Generation 3 (Table 1-2). The orientation of the fracture is 039/84°

The plateau age defined on the ^{40}Ar/^{39}Ar step-heating spectrum is 276.9 ± 1.1 Ma (Figure 5-14).

Figure 5-12. *Sample KFM07A 245.47 m. Open fracture coated with adularia, calcite, pyrite and analcime. The diameter of the drill core is ~ 5 cm.*

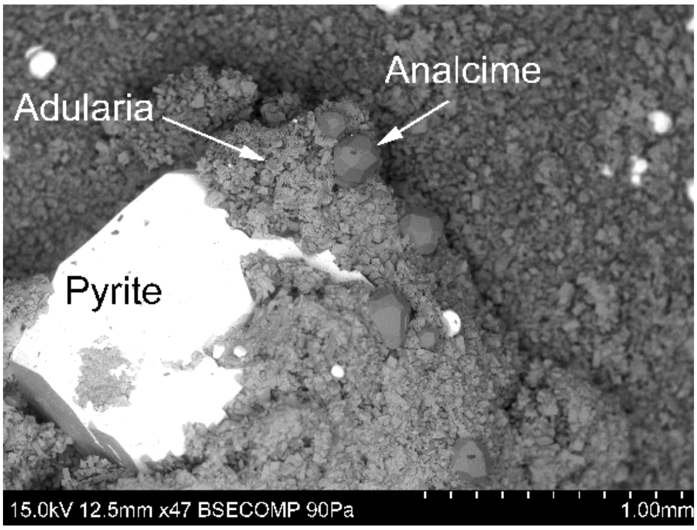

Figure 5-13. *Sample KFM07A 245.47 m. Backscattered electron image of pyrite crystal covered with adularia and analcime.*

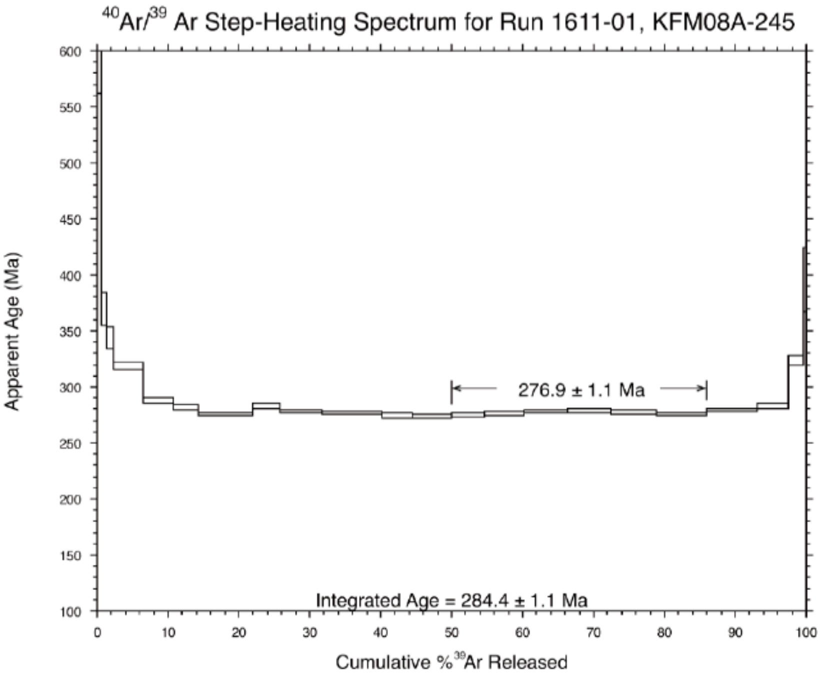

Figure 5-14. *$^{40}Ar/^{39}Ar$ adularia step-heating spectrum for sample KFM07A 245.47 m.*

5.2 Rb-Sr dating

Sample: KFM05A 395.75 m

The results from the Rb-Sr analyses are presented in Table 5-1 and Figure 5-15.

To obtain an Rb-Sr isochron, which slope yields an age, a number of conditions should be fulfilled; 1) the initial $^{87}Sr/^{86}Sr$ ratio should have been the same for the whole system, and 2) the system should have been closed to Rb and Sr mobility from the formation until the present. These conditions are difficult to obtain in a hydrothermal fracture system which persistence and composition are not well defined. When the fit of the straight line is worse than MSWD ~ 2, the line is called an errochron. An errorchron does not lack geological significance, but the age obtained must be handled with caution /e.g. Dickin 1995/.

Table 5-1. Results from Rb-Sr dating of fracture filling. The different mineral fractions do not exclusively contain only one mineral phase and have been separated by tweezers under binocular microscope.

Sample KFM05A 395.75						
Sample	**Rb (ppm)**	**Sr (ppm)**	**$^{87}Rb/^{86}Sr$**	**$^{87}Sr/^{86}Sr$**	**Error**	**Dominating mineral**
YK-378 A	535	69,4	23.2	1.100388	5	Adularia
YK-378 C	20.2	123.1	0.477	0.735459	10	Calcite
YK-378 P	19.2	29.1	1.921	0.753845	13	Prehnite
YK-378 F	257	98.6	7.640	0.841255	10	Bulk fracture filling
YK-378 WR	45.1	68.5	1.913	0.756525	10	Wall rock

Errors for isochron calculation are: $^{87}Rb/^{86}Sr$ - 05%, $^{87}Sr/^{86}Sr$ - 0.05% (2σ)

The result from the adularia-prehnite-calcite fracture filling yields an errorchron with a very high MSWD (179). Included in the errorchron diagram are also one sample of the bulk fracture filling consisting of all three mineral phases and one sample consisting of altered, red-stained wall rock (Figure 5-15). All samples fits relatively well on a straight line. The high MSWD may be due to precipitation of the fracture minerals during an extended period of hydrothermal activity and not during one well defined event giving a fluctuation in the initial $^{87}Sr/^{86}Sr$ ratio of the minerals. The obtained reference age may possibly also be the result of recrystallization causing homogenisation of the Rb-Sr system in the fracture minerals and the wall rock.

Even though the Rb-Sr dating has a very high error, the age of 1,096 ± 100 Ma is interpreted as geologically significant. A similar Rb-Sr age (1,096 Ma, no error given) has been obtained from a prehnite filled vein by /Wickman et al. 1983/ c. 30 km SW of Forsmark.

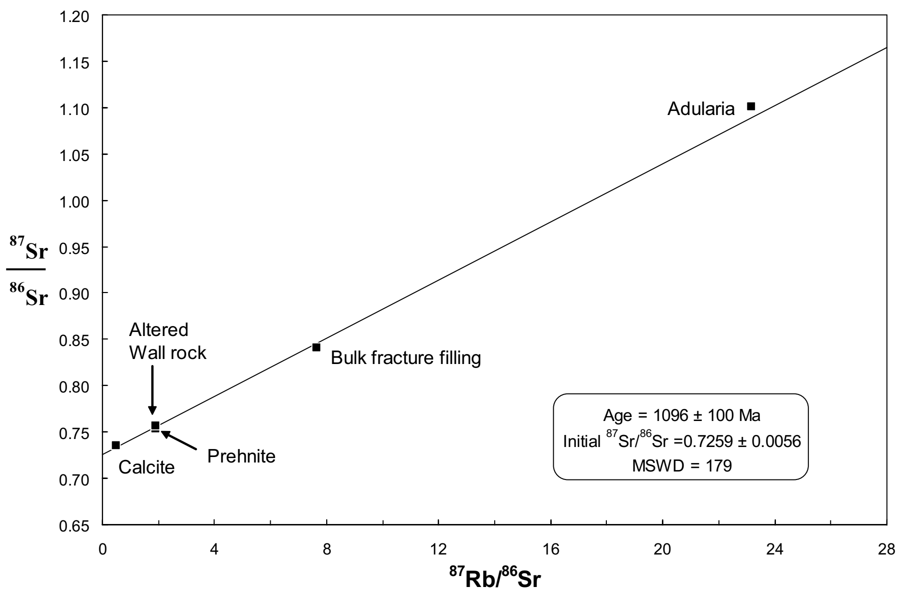

Figure 5-15. *Rb-Sr errorchron diagram.*

6 Summary and discussions

The fracture mineral studies /Sandström et al. 2004, Sandström and Tullborg 2005, 2006/ have resulted in a suggested sequence of different fracture mineralizations separated in time. The obtained geochronological results of fracture minerals confirm the established sequence.

In the Rb-Sr errorchron diagram (Figure 5-15), adularia, prehnite, calcite and the altered wall rock plot on a straight line, indicating an approximate coeval crystallization of the fracture minerals or a coeval resetting of the Rb-Sr isotopic system in both the fracture minerals and the wall rock.

It is worth noting that the two $^{40}Ar/^{39}Ar$ adularia ages from the same drill core (KFM05A) yield an older age closer to the surface and a younger age deeper down, suggesting that the ages show when different levels of the bedrock passed the closing temperature for adularia. If this is coincidental or has real geological significance, is not possible to determine with only two samples.

These obtained ages correspond to the Sveconorwegian reworking in western Sweden /Gorbatschev and Bogdanova 1993/. U-Pb dating of titanite shows a Sveconorwegian disturbance in the U-Pb system, with lead-loss at 909 ± 200 Ma in the Forsmark area /Page et al. 2004/ further supporting the significance of the obtained fracture mineral ages.

The Sveconorwegian adularias can be interpreted as crystallization ages during a Sveconorwegian tectonothermal event, or a total thermal resetting during the same period. Another possibility is that the precipitation may have taken place during reactivation of older fractures when older adularia may have been dissolved and recrystallised. However, the dated sealed fractures show neither macroscopically, nor microscopically signs of later reactivation. Furthermore, no sign of partial resetting can be observed in the $^{40}Ar/^{39}Ar$ step-heating spectrums of the adularia.

The $^{40}Ar/^{39}Ar$ dating of the Generation 2 adularia only provides an absolute age for the early phase of this generation of mineral growth /Sandström and Tullborg 2006/, if the adularia represents a neo-crystallization event. In such a situation, the $^{40}Ar/^{39}Ar$ ages of 1,034 ± 3 and 1,072 ± 3 Ma can be interpreted as the onset of the Generation 2 hydrothermal event. The obtained ages are in agreement with an older Rb-Sr age (1,096 Ma, no error given) from a prehnite filled vein by /Wickman et al. 1983/ c. 30 km SW of Forsmark.

Table 6-1. Ages of fracture minerals at the Forsmark site.

Sample	Minerals	Method	Age	Position in the relative fracture mineral sequence by /Sandström and Tullborg 2006/
KFM05A 395.75 m	Adularia	40Ar/39Ar	1,072 ± 3 Ma	Generation 2
KFM05A 395.75 m	Adularia, prehnite, calcite	Rb-Sr	1,096 ± 100 Ma	Generation 2
KFM05A 692.00 m	Adularia	40Ar/39Ar	1,034 ± 3 Ma	Generation 2
KFM07A 889.95 m	Adularia	40Ar/39Ar	455.9 ± 1.5 Ma	Generation 3
KFM08A 245.47 m	Adularia	40Ar/39Ar	276.9 ± 1.1 Ma	Generation 3

The analysed adularia samples belonging to Generation 3 in /Sandström and Tullborg 2006/ give $^{40}Ar/^{39}Ar$ ages of 455.9 ± 1.5 and 276.9 ± 1.1 Ma. This large difference in ages of fracture minerals interpreted as belonging to the same generation, suggests that the precipitation of Generation 3 minerals was active during a long time span or during different episodes of more intense precipitation. Adularia from KFM07A 889.95 m (455.9 ± 1.5 Ma) is coeval with pyrite and over-grows small euhedral quartz crystals, characteristic for an early phase of Generation 3. The adularia from KFM08A 254.47 m (276.9 ± 1.1 Ma) co-exists with analcime, and over-grows pyrite crystals. In most Generation 3 fractures, pyrite is found as one of the latest precipitated mineral, thus the dated adularia occurring over pyrite is interpreted as belonging to a late stage of Generation 3.

Fission track analyses of apatite show that the Forsmark area has not experienced temperatures above 100°C during the Phanerozoic /Cederbom et al. 2000/, therefore is it unlikely that the obtained $^{40}Ar/^{39}Ar$ ages are resetting or cooling ages. The obtained ages thus suggest that the precipitation of Generation 3 fracture minerals was active during different episodes of the Palaeozoic.

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Appendix 1

$^{40}Ar/^{39}Ar$ data

Run ID	Pwr/T°C	Ca/K	36Ar/39Ar	40*Ar/39Ar	Mol 39Ar	% Step	Cum. %	%40Ar*	Age (Ma)	± Age
KFM07A-876, Run ID# 1607-01 (J = 0.01066 ± 0.000019):										
1607-01A	1.9	0.0259	0.007976	40.47554	0.0611	0.1	0.1	94.5	647.12497	2.13572
1607-01B	2	0.00518	0.006953	41.61831	0.0793	0.1	0.3	95.3	662.41285	1.8267
1607-01C	2.2	0.00174	0.00524	41.76728	0.2189	0.4	0.7	96.4	664.39627	1.16826
1607-01D	2.4	0.0027	0.007563	42.94414	0.3474	0.6	1.3	95.1	679.98885	0.94427
1607-01E	2.6	0.0044	0.001778	44.07676	0.211	0.4	1.7	98.8	694.86911	0.8578
1607-01F	2.9	0.00078	0.01229	44.12069	0.8778	1.6	3.3	92.4	695.44389	0.61495
1607-01G	3.2	0.00028	0.004285	46.61997	0.9146	1.7	4.9	97.4	727.84107	0.84377
1607-01H	3.5	0.000001	0.005465	46.84525	1.3837	2.5	7.4	96.7	730.73295	0.89033
1607-01I	3.8	0.00063	0.001054	41.87739	1.3095	2.4	9.8	99.3	665.86083	0.91708
1607-01J	4.2	0.00174	0.000658	36.39271	2.4098	4.4	14.2	99.5	591.42191	0.9425
1607-01K	4.5	0.00035	0.000812	38.22696	16.4449	29.8	44	99.4	616.65997	0.85399
1607-01L	4.6	0.00061	0.00089	46.2592	9.6072	17.4	61.4	99.4	723.20037	1.15509
1607-01M	4.8	0.00067	0.000978	50.01265	9.1943	16.7	78	99.4	770.90841	0.77144
1607-01N	5	0.00052	0.001067	55.2628	4.9984	9.1	87.1	99.4	835.59212	0.60794
1607-01O	5.2	0.00039	0.001275	57.6845	2.3912	4.3	91.4	99.4	864.66432	0.72733
1607-01P	5.5	0.00008	0.001063	54.52204	1.13	2	93.5	99.4	826.60499	0.78203
1607-01Q	5.8	0.00005	0.00121	58.08434	1.752	3.2	96.6	99.4	869.41962	0.95208
1607-01R	6.2	0.00076	0.001065	58.07634	1.8498	3.4	100	99.5	869.32451	0.99517
Integ. Age =									722	2

Run ID	Pwr/T°C	Ca/K	36Ar/39Ar	40*Ar/39Ar	Mol 39Ar	% Step	Cum. %	%40Ar*	Age (Ma)	± Age
KFM05A-692, Run ID# 1608-01 (J = 0.01066 ± 0.000019):										
1608-01A	2.2	2.74722	0.008114	74.12492	0.817	5.9	5.9	97	1050.53497	1.12653
1608-01B	2.4	2.58907	0.001176	76.64172	0.3324	2.4	8.3	99.7	1077.37178	1.24967
1608-01C	2.6	0.63347	0.000527	76.63185	0.3131	2.3	10.6	99.8	1077.26732	1.32792
1608-01D	2.8	0.4315	0.000808	76.27833	0.3443	2.5	13.1	99.7	1073.52157	1.32247
1608-01E	3	0.37616	0.001187	75.87101	0.2646	1.9	15	99.6	1069.19601	1.3483
1608-01F	3.2	0.44511	0.00163	74.96555	0.2735	2	17	99.4	1059.54311	1.37477
1608-01G	3.4	0.48295	0.002833	74.11325	0.6107	4.4	21.4	98.9	1050.40957	1.13102
1608-01H	3.6	0.23597	0.003013	73.89874	0.486	3.5	25	98.8	1048.10349	1.0057
1608-01I	3.8	0.19108	0.003546	73.10225	0.7651	5.5	30.5	98.6	1039.51495	1.00714
1608-01J	•4.0	0.12901	0.003488	72.61768	1.0032	7.3	37.8	98.6	1034.26989	0.73912
1608-01K	•4.2	0.1005	0.003556	72.59094	2.8623	20.8	58.5	98.6	1033.97998	0.94312
1608-01L	•4.4	0.04699	0.003894	72.43289	3.2528	23.6	82.1	98.4	1032.26559	0.86123
1608-01M	•4.6	0.07161	0.004123	72.60092	1.0789	7.8	89.9	98.4	1034.0881	1.29784
1608-01N	4.8	0.08095	0.003303	73.77261	0.9991	7.2	97.2	98.7	1046.74618	0.97161
1608-01O	5.5	0.0088	0.002772	74.32973	0.3869	2.8	100	98.9	1052.73383	1.46617
Integ. Age =									1042	3
(•) Plateau Age =						59.4			1034	3

Run ID	Pwr/T°C	Ca/K	36Ar/39Ar	40*Ar/39Ar	Mol 39Ar	% Step	Cum. %	%40Ar*	Age (Ma)	± Age
KFM05A-395, Run ID# 1609-01 (J = 0.01066 ± 0.000019):										
1609-01A	2.2	4.89715	0.001082	74.2499	0.1317	2.3	2.3	99.8	1051.87706	1.2562
1609-01B	2.4	7.47629	0.000687	75.96818	0.1778	3.2	5.5	100	1070.22885	1.1282
1609-01C	2.6	9.06542	0.002128	76.54453	0.2356	4.2	9.7	99.7	1076.34283	1.09636
1609-01D	2.8	7.1622	0.001429	76.16208	0.3923	7	16.7	99.8	1072.28804	0.97724
1609-01E	3	3.85891	0.000752	77.27881	0.4384	7.8	24.5	99.9	1084.10227	0.92739
1609-01F	3.2	1.44547	0.000188	76.59584	0.4199	7.5	32	100	1076.88612	0.95428
1609-01G	•3.4	0.14602	0.000014	76.29047	0.4328	7.7	39.7	100	1073.65029	0.9924
1609-01H	•3.6	0.03457	0.000023	76.1446	0.3712	6.6	46.4	100	1072.10249	1.02584
1609-01I	•3.8	0.02691	0.000009	76.08275	0.328	5.8	52.2	100	1071.4458	1.02617
1609-01J	•4.0	0.02766	0.000026	76.24011	0.2718	4.8	57.1	100	1073.1161	1.22148
1609-01K	•4.2	0.01421	0.000003	76.13332	0.2419	4.3	61.4	100	1071.98274	1.17435
1609-01L	•4.4	0.03149	0.000264	76.06532	0.3445	6.1	67.5	99.9	1071.2608	1.07718
1609-01M	•4.6	0.01527	0.000046	76.00824	0.2476	4.4	71.9	100	1070.65441	1.18352
1609-01N	•4.8	0.01351	0.00002	76.13011	0.2226	4	75.9	100	1071.94873	1.0824
1609-01O	•5.0	0.01462	0.000089	75.99281	0.2556	4.6	80.4	100	1070.49048	1.03985
1609-01P	•5.2	0.01142	0.000354	76.04562	0.2671	4.8	85.2	99.9	1071.05153	1.43963
1609-01Q	•5.4	0.00327	0.000102	76.31322	0.2298	4.1	89.3	100	1073.8915	1.15713
1609-01R	5.6	0.00326	0.000427	75.86268	0.2724	4.9	94.2	99.8	1069.10742	1.13911
1609-01S	5.8	0.02077	0.000841	75.93787	0.3271	5.8	100	99.7	1069.9067	0.90528
Integ. Age =									1073	3
(•) Plateau Age =						57.3			1072	3

Run ID	Pwr/T°C	Ca/K	36Ar/39Ar	40*Ar/39Ar	Mol 39Ar	% Step	Cum. %	%40Ar*	Age (Ma)	± Age
KFM07A-889, Run ID# 1610-01 (J = 0.01066 ± 0.000019):										
1610-01A	2.2	0.02007	0.000326	31.78106	0.0587	0.7	0.7	99.7	526.36357	1.26614
1610-01B	2.4	0.00067	0.000052	31.43233	0.1208	1.4	2.1	100	521.34708	1.08063
1610-01C	2.6	0.00498	0.000025	31.33284	0.0809	0.9	3	100	519.91338	1.09027
1610-01D	2.8	0.01488	0.000252	31.82816	0.2346	2.7	5.8	99.8	527.04005	0.6076
1610-01E	3	0.00158	0.000035	32.30542	0.201	2.3	8.1	100	533.88024	0.7242
1610-01F	3.2	0.01178	0.000027	31.83778	0.1939	2.3	10.4	100	527.17808	0.64376
1610-01G	3.4	0.01718	0.000167	31.71165	0.2471	2.9	13.3	99.8	525.36625	0.58862
1610-01H	3.6	0.01396	0.000023	31.11798	0.24	2.8	16.1	100	516.81324	0.62653
1610-01I	3.8	0.01136	0.00014	30.72594	0.3083	3.6	19.7	99.9	511.14293	0.47799
1610-01J	4	0.00894	0.000035	30.02488	0.3554	4.1	23.8	100	500.9583	0.50661
1610-01K	4.2	0.00083	0.000037	28.56127	0.3113	3.6	27.4	100	479.50848	0.53255
1610-01L	4.4	0.01045	0.000027	28.27731	0.5748	6.7	34.2	100	475.31729	0.38768
1610-01M	•4.6	0.0126	0.000086	27.18732	0.3297	3.8	38	99.9	459.13799	0.69837
1610-01N	•4.8	0.0083	0.000229	26.81405	0.3313	3.9	41.9	99.7	453.56397	0.45769
1610-01O	•5.0	0.01104	0.000262	26.73693	0.3408	4	45.8	99.7	452.4101	0.62006
1610-01P	•5.2	0.01018	0.000248	26.75044	0.4274	5	50.8	99.7	452.61221	0.50836
1610-01Q	•5.4	0.01367	0.000206	26.90244	0.4961	5.8	56.6	99.8	454.88541	0.42891
1610-01R	•5.6	0.00619	0.00022	27.12089	0.46	5.4	62	99.8	458.14729	0.51343
1610-01S	•5.8	0.00342	0.000276	27.30384	0.4062	4.7	66.7	99.7	460.87449	0.46786
1610-01T	6	0.01253	0.00033	28.01274	0.5008	5.8	72.6	99.7	471.40346	0.69717
1610-01U	6.3	0.02017	0.000358	29.14467	0.6656	7.8	80.3	99.6	488.08901	0.50558
1610-01V	6.8	0.03217	0.000362	32.05983	1.6838	19.7	100	99.7	530.36365	0.40959
Integ. Age =									491.4	1.6
(•) Plateau Age =						32.6			455.9	1.5

Run ID	Pwr/T°C	Ca/K	36Ar/39Ar	40*Ar/39Ar	Mol 39Ar	% Step	Cum. %	%40Ar*	Age (Ma)	± Age
KFM08A-245, Run ID# 1611-01 (J = 0.01066 ± 0.000019):										
1611-01A	2.2	0.51845	0.278905	35.95343	0.0071	0.6	0.6	30.4	585.32498	11.39041
1611-01B	2.4	0.17969	0.088648	21.32542	0.0088	0.7	1.3	44.9	369.54758	7.24812
1611-01C	2.6	0.35696	0.061718	19.66677	0.0123	1	2.4	51.9	343.36856	4.86148
1611-01D	2.9	0.28288	0.017335	18.15454	0.0494	4.1	6.5	78	319.16494	1.6427
1611-01E	3.2	0.13358	0.006365	16.21323	0.0518	4.3	10.8	89.6	287.61002	1.17354
1611-01F	3.4	0.12179	0.005361	15.85987	0.0416	3.5	14.3	90.9	281.8065	1.37216
1611-01G	3.7	0.03228	0.003462	15.48264	0.0918	7.7	21.9	93.8	275.59025	0.76866
1611-01H	4	0.00328	0.000952	15.91248	0.0456	3.8	25.7	98.3	282.67178	1.19576
1611-01I	4.3	0.000001	0.001016	15.63426	0.072	6	31.7	98.1	278.09136	0.77667
1611-01J	4.5	0.02034	0.001158	15.54989	0.1004	8.4	40.1	97.9	276.69999	0.69825
1611-01K	4.7	0.000001	0.001294	15.4215	0.0505	4.2	44.3	97.6	274.58071	1.11437
1611-01L	4.9	0.04772	0.001581	15.38898	0.0683	5.7	50	97.1	274.04351	0.82138
1611-01M	•5.1	0.06099	0.002309	15.43801	0.056	4.7	54.7	95.8	274.85329	1.02675
1611-01N	•5.3	0.00912	0.001619	15.49781	0.0651	5.4	60.1	97	275.84062	0.86198
1611-01O	•5.5	0.02818	0.002708	15.62808	0.0745	6.2	66.4	95.1	277.98948	0.77941
1611-01P	•5.7	0.00255	0.002738	15.6555	0.073	6.1	72.4	95.1	278.44145	0.8476
1611-01Q	•5.9	0.02982	0.00327	15.60353	0.076	6.3	78.8	94.2	277.5847	0.77953
1611-01R	•6.1	0.04233	0.005226	15.50835	0.0865	7.2	86	91	276.01459	0.68111
1611-01S	6.3	0.04401	0.009924	15.69858	0.0849	7.1	93.1	84.3	279.1513	0.80996
1611-01T	6.5	0.03371	0.020767	15.917	0.0518	4.3	97.4	72.2	282.74603	1.38092
1611-01U	6.7	0.000001	0.033154	18.43976	0.0274	2.3	99.7	65.3	323.7548	2.32173
1611-01V	6.9	1.18487	0.207649	23.03662	0.0036	0.3	100	27.3	396.16372	14.37475
Integ. Age =									284.4	1.1
(•) Plateau Age =						36			276.9	1.1