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Fissure fillings from Finnsjön and Studsvik Sweden.

Identification, chemistry and dating

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Swedish Geological, Gothenburg, December 1982

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written:	corrected to:
p 14 .. the δ^2H axis of + 25%o.	.. the δ^2H axis of + 7 %o.
p 16 .. K_{CaCO_3} =	.. $pK_{HCO_3} - pK_{CaCO_3}$ =
p 27 .. The probable ages are, < 29000 years ..	.. The probable ages, < 29000 years ..
p 55 .. No relevant ages was ..	.. No relevant ages were ..
p 74 .. Helgesson et al., 19 : ..	.. Helgesson et al., 1969: ..

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FISSURE FILLINGS FROM FINNSJÖN AND STUDSVIK, SWEDEN. IDENTIFICATION, CHEMISTRY AND DATING

BY

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TABLE OF CONTENTS

1. SUMMARY........................ 2
2. INTRODUCTION................... 5
3. FINNSJÖN....................... 8
3.1. THE TEST SITE................ 8
3.2. EXTENT OF THE INVESTIGATION... 9
3.3. FISSURE FILLING MINERALS......10
3.3.1. CALCITE.....................10
3.3.1.1. STABLE ISOTOPE AND FLUID INCLUSION STUDIES.............13
3.3.1.2. DATING OF CALCITES............24
3.3.2. PREHNITE....................27
3.3.3. LAUMONTITE....................29
3.3.4. QUARTZ.........................32
3.3.5. WAIRAKITE - ANALCIME..........32
3.3.6. CHLORITE AND EPIDOTE..........33
3.4. WATER-ROCK INTERACTION........35
3.4. CONCLUSION.....................43
TABLES.........................45
4. STUDSVIK......................61
4.1. INTRODUCTION..................61
4.2. EXTENT OF THE INVESTIGATION...66
4.3. FISSURE FILLING MINERALS......67
4.4. CONCLUSION.....................69
TABLES.........................71
REFERENCES....................73

1. SUMMARY

To be able to find out frequency, equilibrium conditions and age of filling minerals, an identification and a chemical characterization of fissure fillings have been carried out. The sampling includes minerals from Finnsjön and Studsvik test sites respectively. The Studsvik investigations were also carried out in order to interprete results from the in situ migration experiments which have been made earlier. Samples were taken from cores and were collected at different levels.

The bedrock at Finnsjön is a Svecokarelian granite-granodiorite. The most frequent mineral in the fissures is calcite. Other common fissure fillings are laumontite, prehnite, quartz and chlorite. Other clay minerals, pyrite, wairakite-analcime, epidote and dolomite have also been recorded.

Three generations of calcite can be detected within one and the same fissure filling. Two texturally different types of calcite could have formed due to different stress regimes. A chemical difference is established for texturally different types.

Waters pumped from boreholes in Finnsjön have got a mean $\delta^{18}O$ value of -12 $^{o}/oo$. Most waters showed saturation in respect of calcite. To see if the calcites were crystallized or not from present waters a $\delta^{18}O$ value of calcites precipitated during present temperature conditions was calculated. The result shows that approximately 50% of calcites from open fissures could have been precipitated from present waters. In contrast, only a few calcites from sealed fissures were in isotopic equilibrium with the waters. Isotopically three different groups of calcite have been distinguished. One group contains calcites precipitated from a water richer than the present $\delta^{18}O$.

Another group, which contains most of the calcite fillings includes those calcites which are in isotopic equilibrium with sampled groundwaters. This group also contains cal-

cites precipitated by hydrothermal solutions. This is evident from fluid inclusion studies.

The third group represents calcites from sealed fissure fillings precipitated at temperature conditions similar to those required for prehnite and laumontite formation (hydrothermal conditions). Results from fluid inclusion studies show that temperatures from 175°C to < 50°C prevailed during formation of the crystals. That is, several events of fluid activation are responsible for the calcite fissure fillings.

Dating of calcites were tried by the U-series method. Ages of $29 \pm 13 \times 10^3$ years to $79 \pm 25 \times 10^3$ years were estimated. It is reasonable to consider the ages as composite in the light of textural, fluid inclusion and isotopic data. Next to calcite is prehnite and laumontite the most common fissure fillings. Both minerals require hydrothermal temperature conditions and are mostly coprecipitated with the calcite group exhibiting lowest $\delta^{18}O$. Laumontite seems to be most frequent within the eastern part of the Finnsjön test area. At least two generations of quartz are recognized in the Finnsjön samples. Both granular as well as prismatic crystals appear.

Water analyses from Finnsjön show that laumontite is in chemical equilibrium with present waters. All waters analysed (from Finnsjön, Kråkemåla and Sternö) are saturated in respect of quartz. Feldspars are chemically unstable.

In Kråkemåla most waters are saturated in respect of fluorite. This is also the only place investigated where fluorite has been found as a fissure filling mineral.

Most fissure filling minerals identified have got cation exchange capacities (CEC) which are different from what has been established for the host granite. Thus e.g. quartz and calcite have got a very low CEC in contrast to zeolites and clay minerals.

The bedrock at Studsvik is a Svecokarelian gneiss of sedimentary type which is migmatized. Core mapping present calcite and chlorite as the most common fissure filling minerals. Clay minerals of smectite type are also frequent. This mineral type exhibits a high CEC. Feldspar, pyrite and palygorskite have also been identified. Most fissure fillings are thin and simple.

2. INTRODUCTION

The purpose of this study has been to investigate fissure filling minerals within test sites at Finnsjön and Studsvik (Fig. 1). The study was carried out at the request of KBS, department within the Swedish Nuclear Fuel Supply Company (SKBF). To be able to find out frequency, equilibrium conditions and age of filling minerals an identification and a chemical characterization of fissure fillings has been carried out.

As groundwater is transported within fissures and fractures in crystalline bedrock it will be in contact with the fissure walls which mostly are coated by filling minerals quite different from those minerals found in the bedrock itself. Thus it is necessary to find out what minerals appear on the fissure walls, their relations to the water present, and at what conditions they were deposited.

The sampling in the Finnsjön area includes several samples from boreholes Fi:7 and Fi:8 (Fig. 2). These samples will complement the sampling carried out earlier (Larson, et al., 1981) from boreholes Fi:5 and Fi:7 in order to find out if the chemical characteristics, methods and other results can be generalized for Finnsjön.

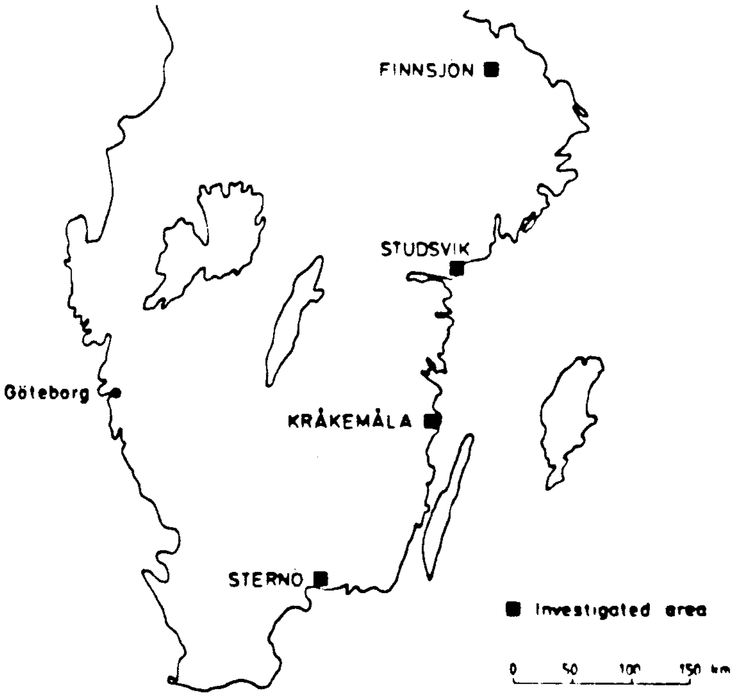


Fig. 1. Location of the test areas.

Since the earlier investigation was carried out a new borehole was drilled. This is borehole Fi:8 which has been directed towards the Gåvastebo fault (Fig. 2).

The sampling at Studsvik has been carried out from the core drilled in borehole K:1. This investigation has been concentrated on the identification of fissure filling minerals. This is especially important to be able to interprete the results from the in situ migration experiments carried out at the test site.

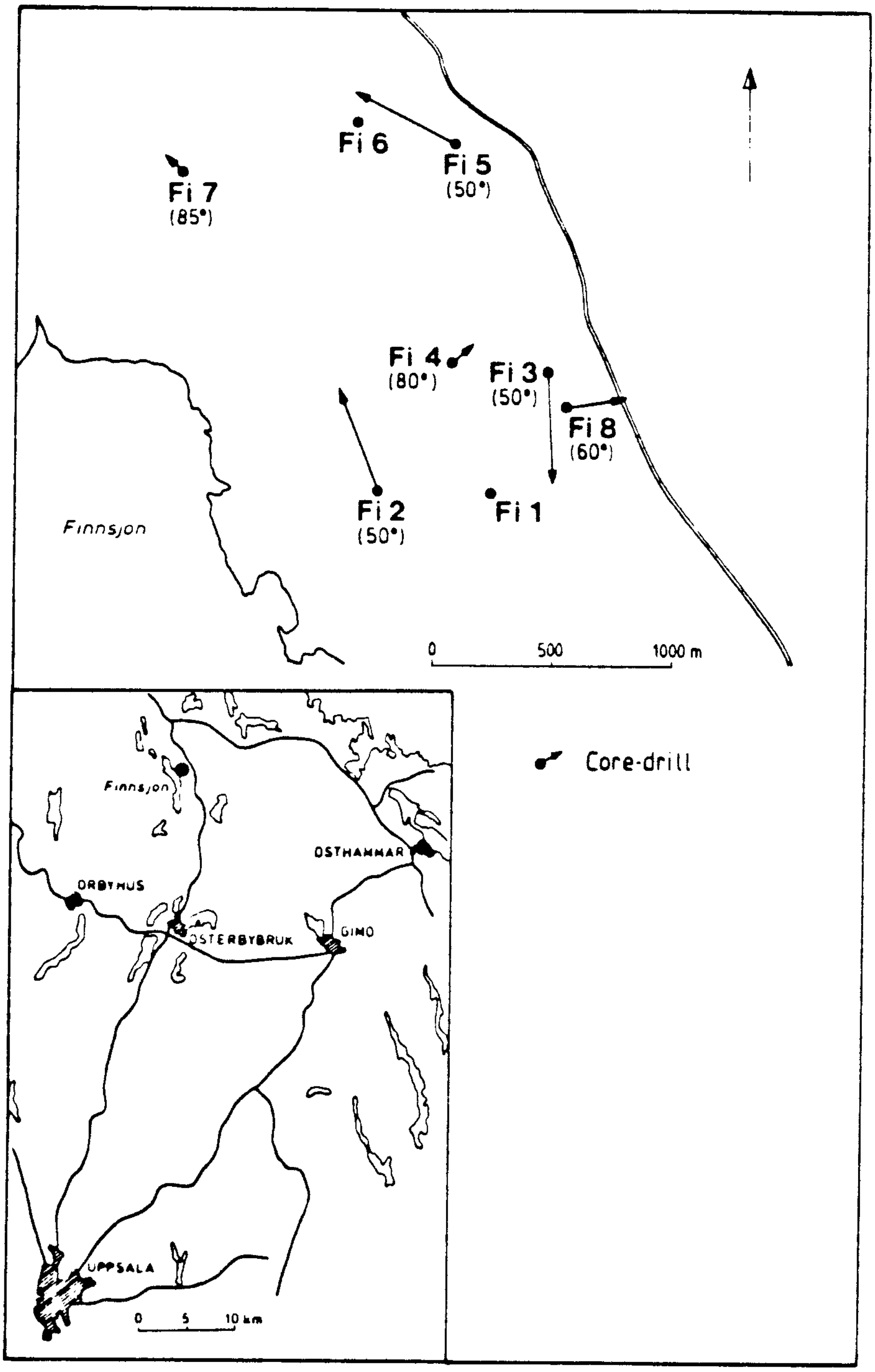


Fig. 2. The Finnsjön test site. Location and dip of boreholes.

3. FINNSJÖN

3.1. THE TEST SITE

The bedrock at Finnsjön belongs to the Svecokarelian belt of Sweden. The rocks have been subjected to deformation and metamorphism. The dominating metamorphic event is the Svecokarelian mountain folding which was ended approximately 1750 Ma ago (Lundqvist, 1979). The oldest rocks in the Finnsjön area are supracrustals of sedimentary as well as volcanic origin. Acid, intermediate and basic volcanics as well as limestones are included. Dominating rocks at the borehole sites are a granodioritic to granitic gneiss formed during the Svecokarelian event. East of this area appears a somewhat younger red granite (Olkiewicz and Arnefors, 1981).

From the core mapping it is evident that borehole Fi:5 is dominated by a grey to red, medium grained, foliated granodiorite. Solitary sills of granite and metabasite appear. The length of the borehole is 750.5 metres and has a dip of 50° at the surface.

Borehole Fi:7 is dominated by the same grayish to red, medium grained, foliated granodiorite. Elements of pegmatite and metabasite appear as sills. The length of borehole Fi:7 is 552.7 metres and has a dip of 85° at the surface. The bottom of the hole is 530 metres below the surface. A specification of fissures, fractures and rock types from cores drilled from boreholes Fi:5 and Fi:7 is published in Olkiewicz et al. (1979).

Borehole Fi:8 contains approximately 50% of the same granodiorite as found in Fi:7 and 50% of a younger red granite with an aplitic look, which is outcropping to the east of the borehole (Arnefors pers. com., 1981). The borehole Fi:8 has a length of 465 metres and has a dip of 60° at the surface. The hole was drilled in order to investigate the character of the so called Gåvastebo fault at depth.

3.2. EXTENT OF THE INVESTIGATION

In an earlier investigation of the appearance and character of fissure filling minerals in Finnsjön the filling material from cores from boreholes Fi:7 and Fi:5 were preferably studied (Larson, et al., 1981). The reason for this was the extreme chemical variations of the borehole waters. Thus at equilibrium conditions, variations in the chemistry of the water should be mirrored by the chemistry of the filling minerals. However, no evident connection is found between the chemistry of the fluid and the filling minerals. At the earlier investigation it was also evident that the ocular inspection not made it possible to identify some of the fissure filling minerals. Thus, laumontite and prehnite are some dominating minerals hard to identify by ocular inspection. Other phases which are hard to identify by ocular inspection are dolomite and clay minerals. When checking, also some indications on wairakite were recorded on the XRD.

To be able to estimate the general applicability of the results from this earlier investigation the sampling was extended to embrace filling materials from borehole Fi:8 as well as complementary samples from borehole Fi:7. Particularly calcite fillings were sampled from borehole Fi:7 in order to confirm the chemical trends of oxygen isotopes which were indicated by the earlier investigation.

Table 1 shows identified phases, sites within boreholes, character of the filling material and methods used for the identification. The material was scraped from the fissure walls by knife for the chemical analyses. When separation of phases was applied, heavy liquids as well as a Frantz magnetic separator were used.

For identification and for analyses of fissure filling minerals following methods were applied:

Mineral identification - XRD, DTA and microscopy (SGU laboratories and the laboratory at Dept. of Geology, Chalmers, Göteborg).

Chemical analyses - XRF, emission spectroscopy and electron micro probe (SGU laboratories).

Stable isotope analyses - Mass spectroscopy (Dept. of Marine Geology, University of Göteborg).

3.3. FISSURE FILLING MINERALS

From the core mapping it is evident that calcite is the most frequent fissure filling in the Finnsjön area. As calcite does not require extreme pressure or temperature for its formation, but could be formed during present conditions within the Finnsjön test site, is it a highly interesting filling mineral.

Other common fissure fillings are laumontite, prehnite, quartz and chlorite. Less frequent are other clay minerals, pyrite, wairakite-analcime, epidote, and dolomite. In one sample is it also likely that pumpellyite is present.

3.3.1. CALCITE

Calcite is the most common fissure filling mineral in Finnsjön. Some fissures show pure calcite filling, but the calcite is mostly mixed by other minerals like prehnite, laumontite and chlorite.

It is well known that calcite can be crystallized within a large temperature interval including temperatures prevailing at present. Thus, it is possible that the calcite is of recent origin.

As can be shown calcite mostly constitutes the youngest or one of the youngest filling minerals in Finnsjön. Dating of calcite thus makes it possible to get a lower limit for the age of the fissures or for the fissure activation. Absolute dating is a difficult task due to the limited amount of calcite which can be scraped from the fractures and that the closed-system assumption must be fullfilled.

Nevertheless attempts have been made to date some of the calcites by uranium series dating (Chapter 3.3.1.2). Another way to get an idea of the approximate age of the calcite is to get knowledge on the environmental conditions during the crystallization. This makes it possible to distinguish recent calcite from other calcites. Thus oxygen isotopes as well as carbon isotopes were analysed for calcite and at some levels for corresponding water samples. It is also of interest to know if calcite is in chemical equilibrium with the borehole fluid to see whether solution or precipitation is prevailing.

Sampling was carried out from the cores taken from Fi:5, Fi:7 and Fi:8. Some solitary samples were also sampled from Fi:4 and Fi:6. Sampled levels are shown in table 1. Open as well as sealed fissures were chosen. The thickness of the filling material has been 1 mm to 15 mm. Both mixed as well as pure fillings have been considered.

At least two distinct textures of calcite can be distinguished by thin section studies. One, and the most common, is a granular variety. The other variety is a prismatic calcite grown parallel to the fissure wall (Fig. 5). When comparing prismatic and granular calcites it has been found that a granular, undeformed variety of calcite is likely to be youngest. The difference in textures is probabaly due to crystallization during different stress regimes. Kamb (1959) concluded that the preferred orientation for a given mineral is in most cases that in which the weakest axis, i.e. the c-axis of calcite, is aligned parallel to the axis of largest stress. The compressive stress needed to open a fissure is aligned parallel to the propagating fissure. The extreme prismatic texture with crystals grown parallel to the c-axis could thus be explained by a largest compression parallel to the prismatic crystals, i.e. also the fissure. The granularly grown calcites are probably crystallized during a less or insignificant stress gradient compared to that responsible for the prismatically grown calcites.

Surface stress measurements in the region indicate a large stress gradient with the largest stress component orientated

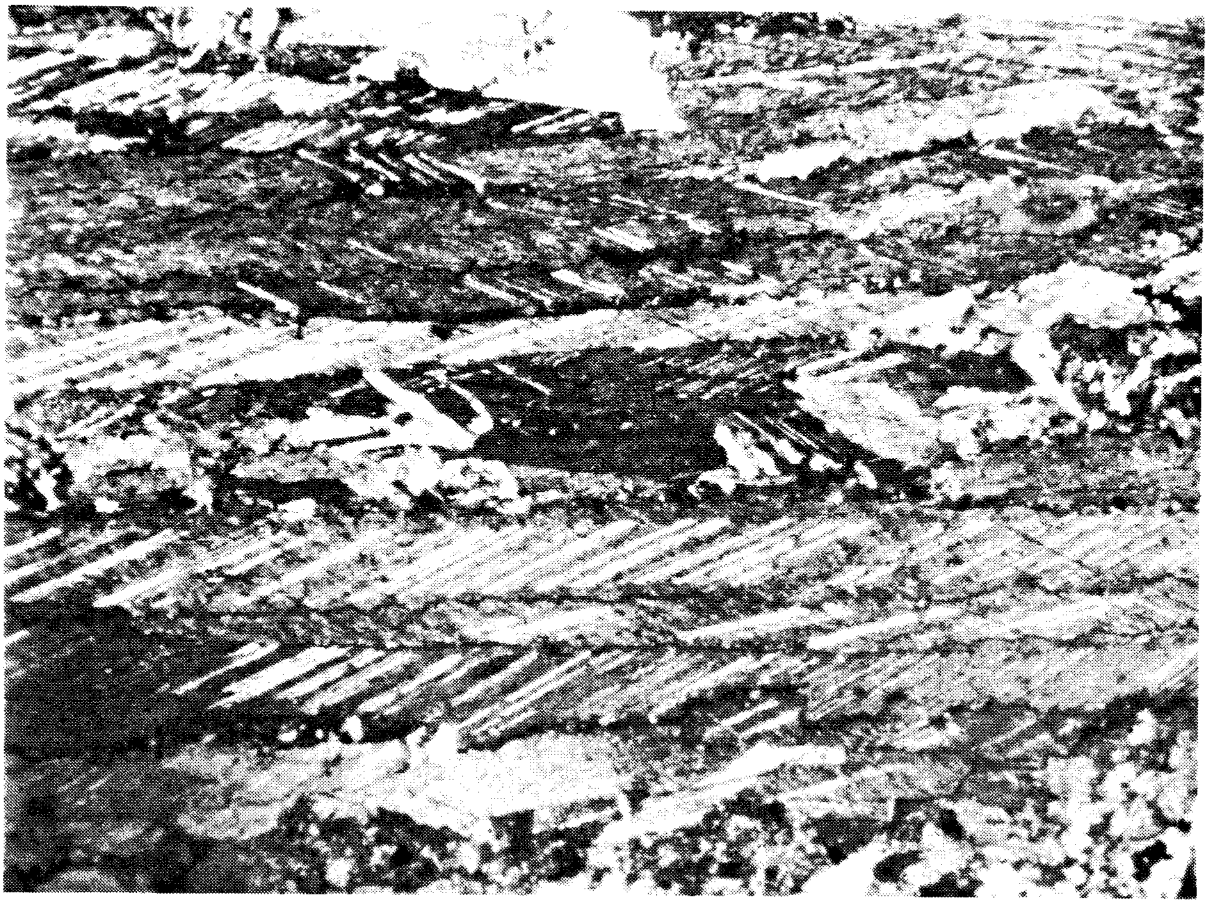


Fig. 3. Micro-photograph showing prismatic crystals of calcite in sample Fi8:52.8.

in an approximately NW direction. A more hydrostatic stress regime will probably prevail at great depth and has probably also prevailed during the last glaciation (cf. The Swedish State Power Board, 1982). The nearly hydrostatic conditions within the bedrock which are likely to have prevailed during the last glaciation are suitable for granular calcite precipitation. However, the melting of the ice cap decreased the vertical stress component, creating a stress gradient forming new near-surface, horisontal fissures (Carlsson and Olsson, 1982). Nevertheless, when considering the dip of fissures mapped from cores in Finnsjön a great dominance of steep or vertical fractures are recorded (Tullborg, in manuscript). As the prismatically grown crystals are considered not to be the youngest type of calcite identified and are even found at great depth (more than 500 metres), they are probably not grown due to the present high stress gradient found within the uppermost hundreds of metres in

Swedish bedrocks. The chemical composition of some calcites was analysed by electron microprobe. This shows that calcites at shallow level (41.1 m) have a lower Ca/Fe+Mn+Mg ratio than calcites at deep level. There is also a difference for prismatic and granular calcites respectively. Thus prismatic calcites show a higher ratio (Ca/Fe+Mn+Mg) than the granular calcites. This shows that fluids have been different for crystallization of prismatic and granular calcites respectively.

Only in one sample calcite has been found together with both prehnite and laumontite. However, in some samples laumontite or prehnite is probably coexisting with the calcites. This defines a temperature-pressure condition which is different from that found at present (c f. Fig. 17).

The chemical composition of some calcites and whole fillings was analysed by electron microprobe, emission spectroscopy and X-ray fluorescens (Tables 7 and 8).

3.3.1.1. Stable isotope and fluid inclusion studies.

The analyses of water from the investigated boreholes at Finnsjön have been published elsewhere (Hultberg et al. 1981 and Laurent, in manuscript 1982). Four levels in each of the investigated boreholes were sampled.

Craig (1961) found a global relationship between δ^2H and δ^{18}O in precipitation, i.e. the meteoric water line ($\delta^2H = 8\delta^{18}O + 10\ ^o/oo$). The intercept with the δ^2H axis defines a particular air mass (the "d-parameter" of Dansgaard, 1964). A decrease in heavy isotopes has been recorded when going from coast to inland, lower to higher latitude and lower to higher altitude, that is the plot of the meteoric water line (MWL) is due to the geographical position (see Fig. 4).

Analysed waters from Finnsjön are plotted in a $\delta^2H/\delta^{18}O$ diagram in figure 5. This plot shows that the sampled waters have not been subjected to any serious exchange with surrounding material except for one sample (c f. Fritz et al., 1979). However, most samples plot beneath the MWL but are aligned parallel to this line. This indicates a local MWL with a intercept with the δ^2H axis of +25 ^{o}/oo. The spread in δ^{18}O for the waters are small and a mean of approximately - 12.0 ^{o}/oo is calculated. Using this figure and the relationship of Dansgaard (1964), $\delta^{18}O = 0.695T\ (^oC) - 13.6$, a mean annual temperature of + 2.6^{o}C is calculated. This can be compared with the mean annual air temperature of + 5.7^{o}C measured during the last 30 years not far from the investigated area. It is well known that in Sweden evaporation mainly occurs during the summer season. Thus it is reasonable to assume that precipitation fallen during the winter season constitutes a major portion of the groundwater. This could explain the differences in calculated temperatures. Analyses of tritium in the waters sampled will indicate if there is any water present of an age of 30 years or younger (Fritz and Fontes, 1981). When analysing the Finnsjön samples most of them showed detectable contents of tritium (mostly between 3 and 14 TU). This means that a young component must be present. Thus, it should be pointed out that all water analyses are results of the chemistry of mixed waters and should be kept in mind when used in the calculations and interpretations.

Calcium and bicarbonate contents were plotted in a diagram (Fig. 6) to see if the waters were saturated or not in respect of calcite, using the equilibrium constant of Garrels and Christ (1965). The diagram shows that most of the samples are connected to and aligned along the saturation line. That is calcite is close to equilibrium with the borehole waters with a few exceptions, and thus calcite can be precipitated from the water or dissolved from the fissure coating, by slight changes in physical conditions.

To see if the calcites were crystallized from the present waters or not oxygen and carbon isotopes of calcite were analysed as well as corresponding waters. The analyses of calcites are listed in table 3.

When plotted in a δ^{13}C/δ^{18}O-diagram (Fig. 7) the sealed fissure fillings are concentrated to a δ^{13}C interval of -2^o/oo

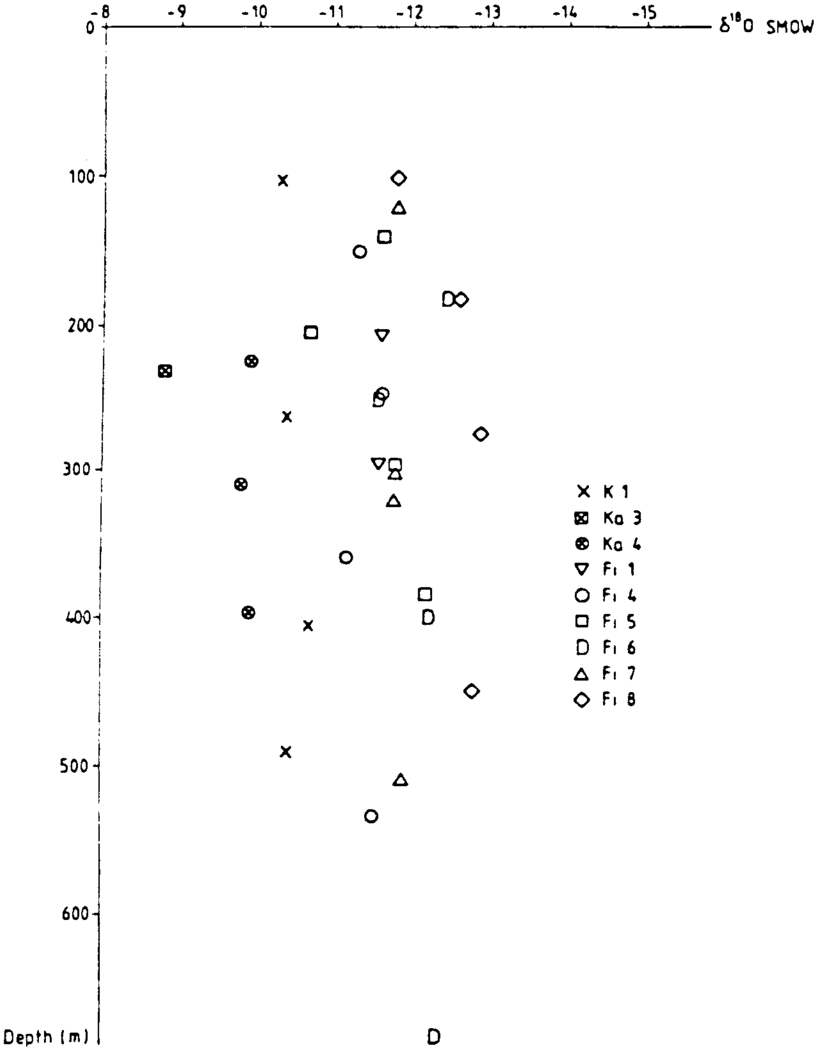


Fig. 4. $\delta^{18}O$ SMOW versus depth for samples from Sternö, Kråkemåla and Finnsjön. The latitudal change of $\delta^{18}O$ is illustrated.

to -6 ^{o}/oo, wheras fissure fillings from open fissures are spread within a much larger interval. It is also quite clear that sealed fissures are concentrated to lower $\delta^{18}O$ than open fissures. If all the calcites are crystallized from one and the same water, plotting in the diagram would give a narrow spread in $\delta^{13}C$-values. These patterns indicate that calcites from sealed and open fissures respectively have got different origin or evolution. The large $\delta^{13}C$ variation for open fissure calcites shown in the figure is

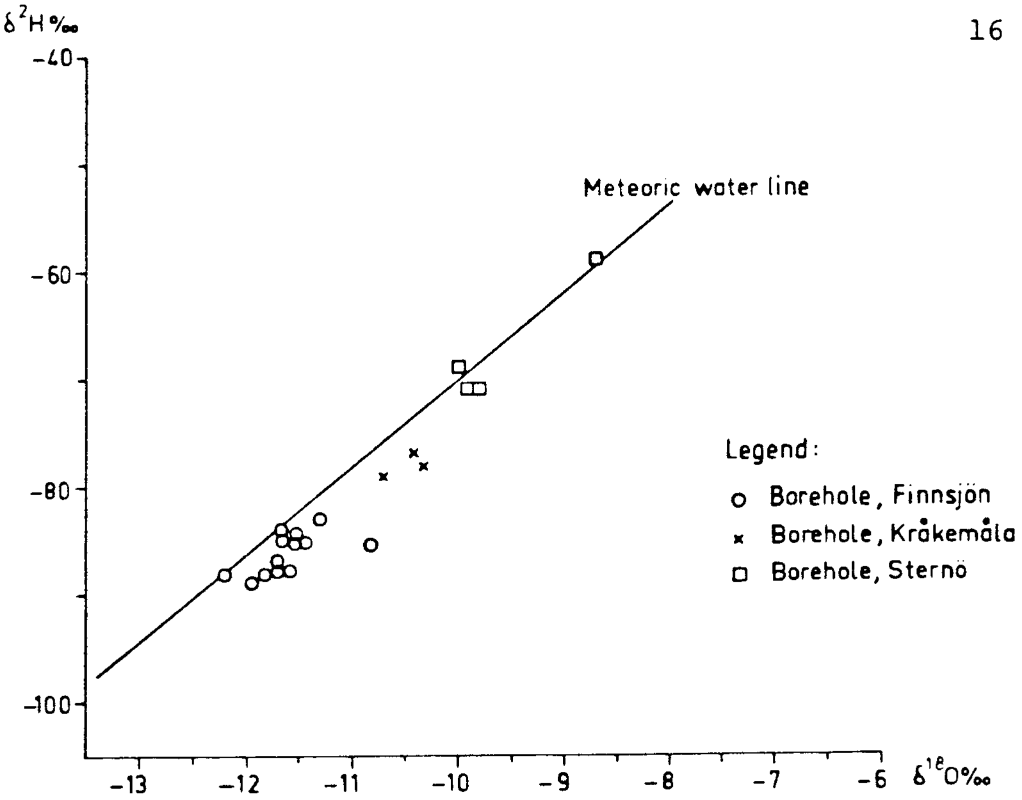


Fig. 5. The relation of sampled waters to the Meteoric Water Line.

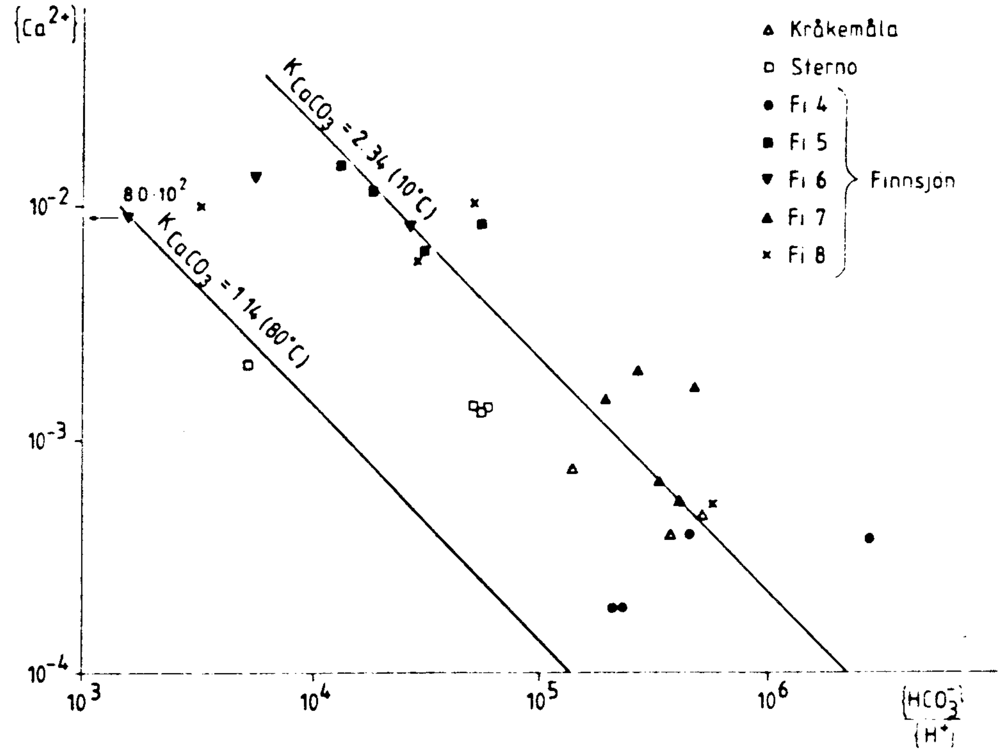


Fig. 6. Stability diagram for calcite. Ks according to Garrels and Christ (1965) at 10^{o}C and 80^{o}C respectively.

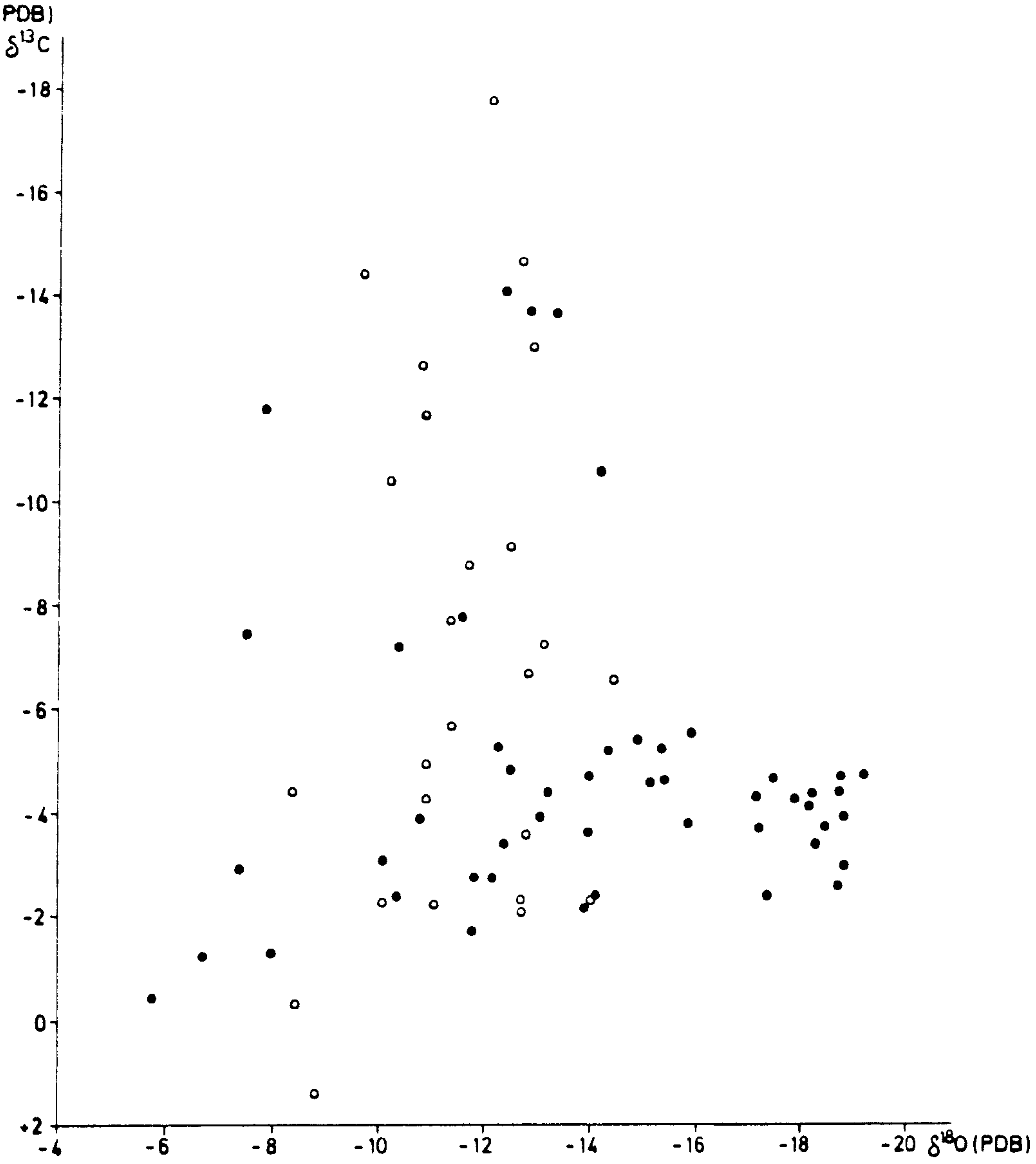


Fig. 7. $\delta^{13}C$ versus $\delta^{18}O$ for calcite infillings.
o = Open fissures ● = Sealed fissures

probably due to later redistribution. This could be caused by influence of ^{13}C-depleted water which has percolated through the vegetation zone, influence of water which has percolated through the marble ($\delta^{13}C = -0.59$) or influence of marine water.

The cluster of $\delta^{18}O$ for sealed fissures in the interval -17 $^{o}/oo$ to -20 $^{o}/oo$ which correspond to a $\delta^{13}C$-interval of -2.5 $^{o}/oo$ to -5 $^{o}/oo$ constitutes a separate group. The calcites contained in this cluster must have been deposited during well defined conditions and have probably not been subjected to redistribution.

Figures 8 and 9 are diagrams showing $\delta^{18}O$ calcite for sealed and open fissures respectively versus borehole depth. The calcite from sealed fissures show lowest $\delta^{18}O$ values at depth (below 300 m). Evidently the degree of redistribution decreases with depth preserving lower $\delta^{18}O$ of calcites at deep levels. The spread in $\delta^{18}O$ for calcites from approximately the same depth as well as for calcites from one and the same fissure also show that sealed fissure fillings contain several calcite generations. $\delta^{18}O$ for calcites from open fissures show a negative correlation with depth which could indicate a temperature increase with depth, possibly a geothermal gradient. If measured temperatures within the boreholes (Fig. 10) are used to calculate calcites in equilibrium with present waters, an interval limited by the two lines shown in figure 11 is received. From this can be seen that only a few samples will appear within the interval. However, concerning calcites from open fissures (Fig. 9) 50% will appear within the interval, which means that some of this coatings have crystallized during present conditions. These coatings are concentrated to the upper 300 metres. Thus the plot of calcites in Fig. 9 could mirror different waters precipitating calcites above and below approximately 300 metres.

In figure 12 is $\delta^{13}C$ for calcite plotted versus $\delta^{18}O$ for waters from which they precipitated. Calculations of $\delta^{18}O$ for the waters have been obtained by using measured $\delta^{18}O$ for the calcites applying fractionation factors given by Friedman and O'Neil (1977) and temperatures given by Duran and Magnusson (1980). The square represents calcite precipitated by present waters and temperatures. As can be seen only a few calcites will fall within the area represented by the square. However, several plots appear in the immediate neighbourhood of the square. Some of these plots could correspond to supersaturated solutions causing isotope disequilibrium during deposition of calcite (cf. Usdowski et al., 1979).

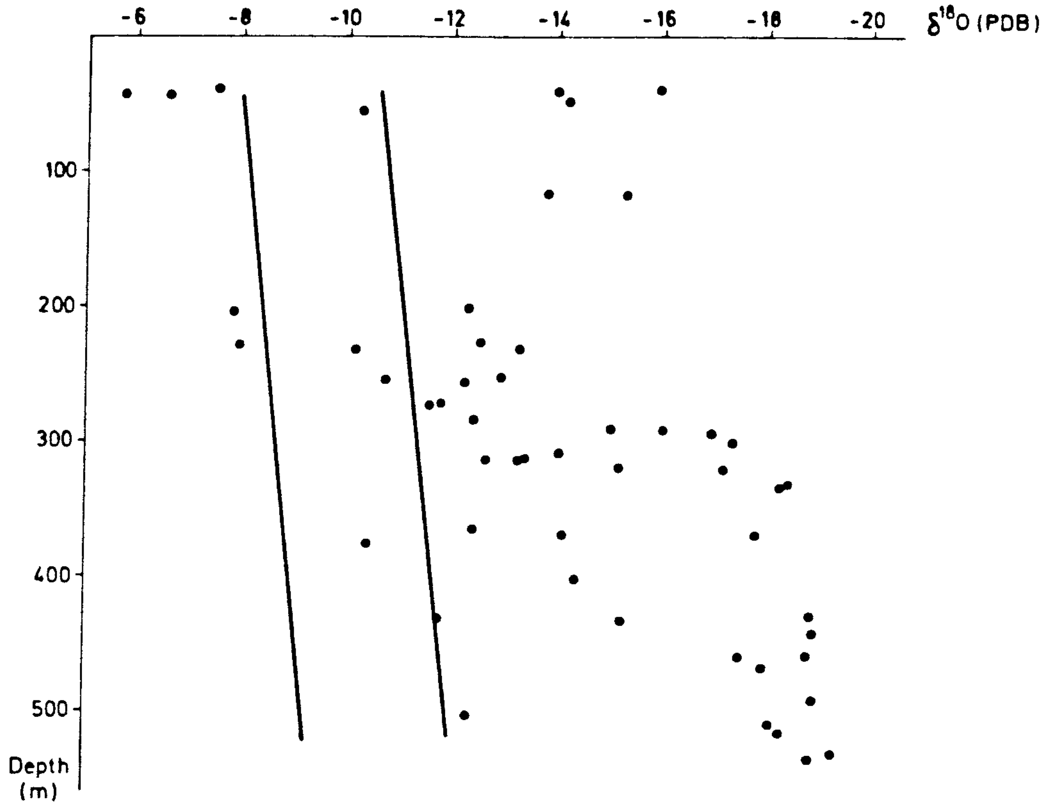


Fig. 8. Variation of $\delta^{18}O$ for calcite infillings versus depth, for sealed fissures.

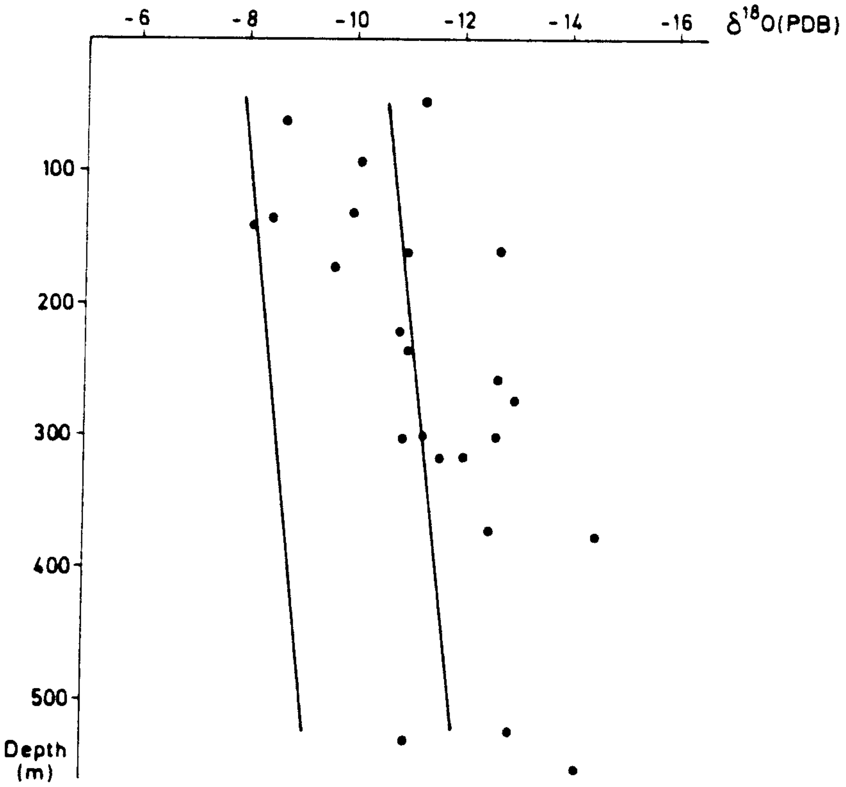


Fig. 9. Variation of $\delta^{18}O$ for calcite infillings versus depth, for open fissures.

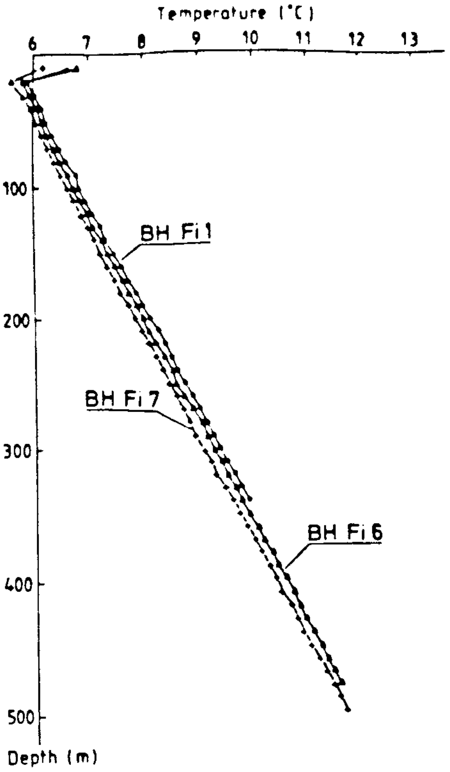


Fig. 10. Temperature gradients for some boreholes in Finnsjön.

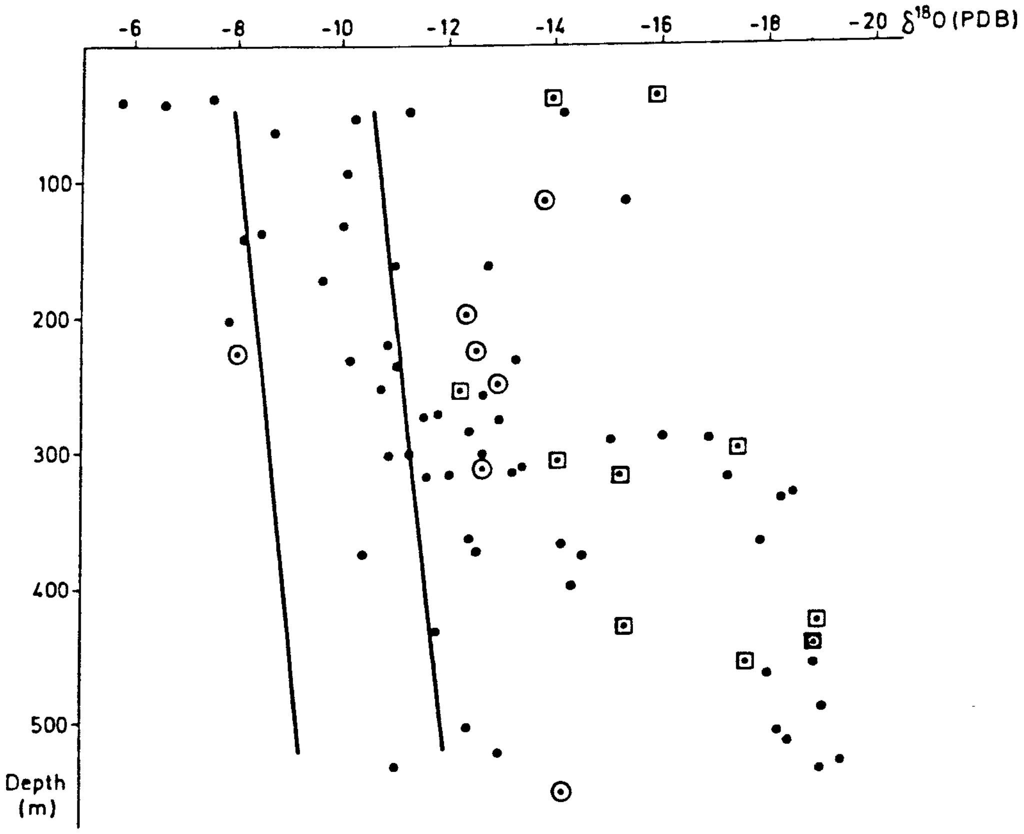


Fig. 11. $\delta^{18}O$ versus depth for all analysed fissure filling calcites. ⊡ = calcite and prehnite probably coexisting. ⊙ = calcite and laumontite probably coexisting.

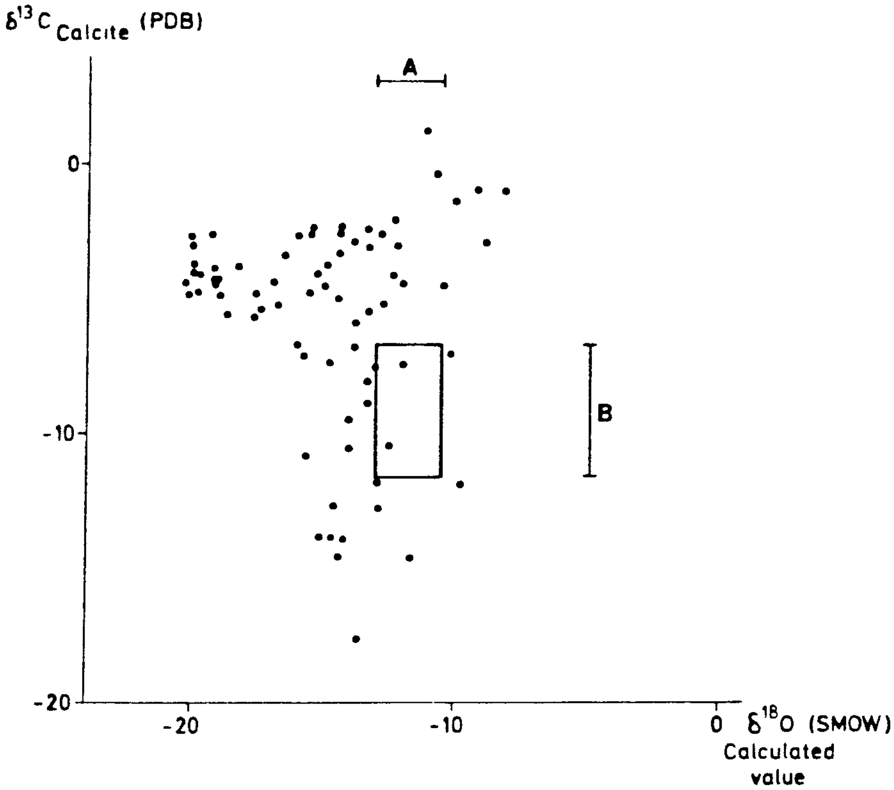


Fig. 12. Measured $\delta^{13}C$ calcite versus calculated $\delta^{18}O_{water}$. Range A represents measured $\delta^{18}O$ in present water; Range B represents calculated $\delta^{13}C$ for calcite precipitated from present waters.

In contradiction to calcite is prehnite a mineral restricted to be crystallized at hydrothermal conditions. A composite mixture of calcite and prehnite is common in sealed fissures. Altogether 30 thin sections were studied. Of these only 10 contained prehnite which could have precipitated during the same event as calcite. In figure 11, where $\delta^{18}O$ calcite is plotted versus depth, are these composite prehnite-calcite fissures distinguished. As can be seen most of these fissures have got calcite fillings depleted concerning ^{18}O. This indicates that the cluster around $\delta^{18}O = -17$ °/oo to -20 °/oo could be calcites crystallized during hydrothermal conditions not seriously influenced by later recrystallization. Laumontite is also a mineral which has been found together with calcite as a filling mineral. Most of the calcites contained in composite laumontite-calcite fissures are less depleted in $\delta^{18}O$ then the calcites associated with prehnite. Laumontite is a mineral mostly crystallizing at lower temperatures than prehnite which can explain their position in figure 11.

Fluid inclusions in fissure filling calcites and prehnite from Finnsjön have been studied by Sten Lindblom. (Internal report, 1982). Three events of fluid activation were documented in the studied fissures.

1. Deposition at 80° C from a solution with 17 eq. wt % NaCl.

2. Deposition at 135° C from a solution with 3.6 eq. wt % NaCl.

3. Deposition or rehealing at 90° C or lower from a meteoric water.

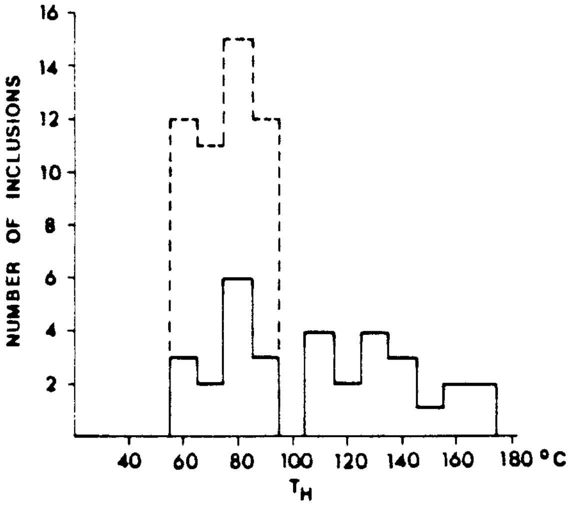


Fig. 13. Homogenization temperatures for calcite fluid inclusions (including populations of metastable inclusions: broken line.) (According to Lindblom, 1982).

There is also indications of a dominating formation at a low temperature connected both with low salt and high salt solutions. Homogenization temperatures for all measured calcites are shown in figure 13. As can be seen temperatures from 175°C down to 55°C (lower detection limit) are recorded.

As some calcite infillings is the youngest mineral observed in the fissures and as low temperature fresh water inclusions have been observed the fissures may have been active quite recently, i.e. during the last glaciation or even later. Low formation temperature and seawater composition indicate possible recent formation in connection with a more saline Baltic Sea. Results from the fluid inclusion studies of prehnite show that the prehnite inclusions may have been refilled with the fluid responsible for late stage calcite crystal growth. The temperature obtained (115°C) is thus less than the temperature required for prehnite formation.

Using temperature data from the fluid inclusion study and $\delta^{18}O$ calcite data it is possible to find out the origin of the water which precipitated the calcites. By using the equation of O'Neil et al. (1969), $1000 \ln\alpha = 2.78\ (10^6 T^{-2}) -3.39$ (valid from 0°C to 500°C), graphs were constructed showing the dependence of temperature of $\delta^{18}O$ of calcite, assuming fixed values of $\delta^{18}O$ water (Fig. 14). Two values are used, 0 °/oo and -12 °/oo respectively. The first value (0 °/oo) corresponds to a marine water, the second value (-12 °/oo) corresponds to present waters at Finnsjön.

In Figure 14 is also shown the distribution of $\delta^{18}O$ of calcites from Finnsjön. The calcites used in the fluid inclusion study showed $\delta^{18}O$ within the interval -8 °/oo to -13 °/oo.

Calcites which belong to group I (Fig. 14) were precipitated from a water richer than the present water in ^{18}O. Group II contains most of the calcites, including calcites in isotopic equilibrium with sampled groundwaters. Using the fluid inclusion data, concerning temperatures it is likely that this group also contains calcites precipitated by hydrothermal solutions. Group III represents calcites from sealed

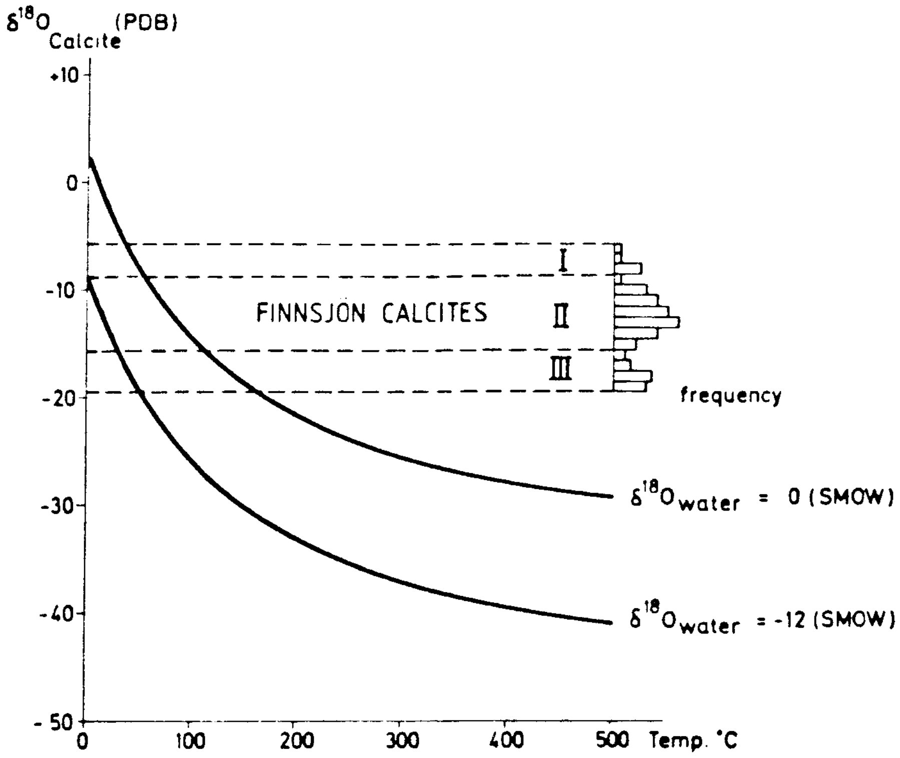


Fig. 14. $\delta^{18}O$ calcite as a function of temperature. Graphs shown represent water composition of 0 ^{o}/oo and -12 ^{o}/oo $\delta^{18}O$ respectively.

fissures sampled below 300 metres depth. These calcites have got a narrow $\delta^{13}C$ (Fig. 7) interval and have probably precipitated at temperature conditions similar to those required for prehnite and laumontite formation (Figs. 12 and 17).

3.3.1.2. Dating of calcites

To get absolute ages of calcite fissure fillings, samples were collected for U-series age dating. The dating as well as the interpretation of ages was carried out by Professor Teh-Lung Ku, University of S.California, Los Angeles. Five fissure filling calcites from Fi:7 and Fi:8 were analysed. These are Fi7:40.9A and C respectively, Fi7:301.8 and Fi8:278.5A and B respectively.

The fissure filling in sample Fi7:40.9 is from a sealed fissure, and can be separated into three zones:

1) An inner close-to-the-wall zone consists of granular calcite mixed with an older prehnite filling.

2) An intermediate zone consisting of prismatically grown calcite mixed with older (or possibly coprecipitated) prehnite. The two minerals occupy approximately 50% each of the space.

3) A central zone of calcite associated with small amounts (approx. 5 vol-%) of clay minerals. This calcite is the youngest material found within the fissure

   Sample 40.9 A, was collected from the inner and intermediate zones while 40.9 C was collected from the central zone.

The fissure filling Fi7:301.8 has been sampled from an open fissure. The filling is thin and consists of almost pure, fine grained calcite. This fissure cuts a prehnite--quartz filled older fissure.

Fi8:278.5B is a filling dominated by rather coarse grained calcite with interstities filled by quartz. Close to one of the fissure walls a younger nearly pure calcite filling appears in sample Fi8:278.5A.

The specific activities of the measured isotopes, expressed in dpm/g of leachate (L), of residue (R), and of whole sample (W), are listed in Table 4 and 5. Data on whole samples are calculated from the leachate and residue activities using the relationship : $W = fL \cdot (L) + (1 - fL) \cdot (R)$. The quoted errors are on standard deviations derived from counting statistics only.

In Table 4 are the activity ratios $^{234}U/^{238}U$ and $^{230}Th/^{234}U$ listed. These two ratios form the basis of calculating the age (t) of a system initially containing some uranium but no ^{230}Th. The age equation is:

$$^{230}\mathrm{Th}/^{234}\mathrm{U} = (^{238}\mathrm{U}/^{234}\mathrm{U})\ 1\text{-}\exp\ (-\lambda_0 t)$$

$$+\ 1-(^{238}\mathrm{U}/^{234}\mathrm{U})\ 1\text{-}\exp\ (\lambda_4 t - \lambda_0 t)_0\ /(\lambda_0 - \lambda_4)$$

where λ_0 and λ_4 are decay constants of ^{230}Th and ^{234}U, respectively.

As shown in Table 6, two kinds of ages are given for each sample:

1. Maximum ages: These ages are calculated from the whole sample (W) data. As any detrital minerals present in the samples are expected to be older than the carbonate, it can be safely assumed that ages thus computed should represent upper-limit estimates for the time of the calcite precipitation. In Fi7:40.9 C and Fi8:278.6 A, are the ^{230}Th/^{234}U ratios beyond the theoretically allowable limits, implying that the closed-system assumption has been violated.

2. Probable ages: These are the averages of one or more of the following age estimates. The errors are standard deviations from the means.
   a. Age calculated directly from the leachate (L) data. The assumption is made that the leaching procedure used releases radioactivities from the calcite while attack minimally the detrital minerals.
   b. Age calculated using the isochron-plot method of Szabo and Sterr (1978). The assumptions involved are: (i) the calcite contains negligible ^{232}Th and initial ^{230}Th, and (ii) the acid leaching does not fractionate U and Th isotopes.

   c. Age calculated using the correction scheme of Ku et al., (1979). The assumption are: (i) the calcite contains negligible ^{232}Th and initial ^{230}Th, or it has ^{230}Th/^{232}Th similar to that in the detrital phase, (ii) secular equilibrium exists in the detrital phase, and (iii) the leaching does not fractionate Th isotopes.

As can be seen from Table 3, except for method a., methods b. and c., when applied to the present data, only succeed partially (i.e., they will sometimes give results that are theoretically impertinent). This seems understandable, since in terms of the number of required constraint (or assumptions) to be fullfilled, method c. > method b. > method a.

As can be seen in table 6 probable ages are estimated from 29 ± 13 x 10^3 years to 79 ± 25 x 10^3 years. The youngest dated calcite in Fi7:40.9 A, is evidently cut by the younger filling in Fi7:40.9 C. Thus a calcite filling younger than 29 ± 13 x 10^3 years is present. This filling consists of calcite crystals of the untwinned type. The thin coating in Fi7:301.8 gives corresponding maximum and probable age (74 000 and 80 000 years respectively). This indicates that the filling is pure calcite. A similar age (79 ± 25 x 10^3 years) is estimated for Fi8:278.5 B. The oldest age estimated is 215 ± 45 x 10^3 years (Table 6), i.e. analysed calcites belongs to the quarternary and must thus have been precipitated during low temperatures. The probable ages are, < 29 000 years to 79 000 years, are also the lower limit for fissure initiation.

Fissures have probably not remained uncoated for a long time after their initiation. This is suggested as conditions for calcite precipitation are at present suitable and probably have been so for a long time. However, original fissure filling calcite could have been recrystallized, i.e. indicated ages of calcite fillings could be much younger than the initiation of the fissures.

Additional dating attempts are at present carried out by the ^{14}C-method and will be published in a separate report.

3.3.2. PREHNITE

Prehnite like calcite, seems to be a general fissure mineral within the Finnsjön area. Prehnite has often been mistaken for epidote during the core mapping but probably also for calcite and chlorite. Thus have not prehnite been mapped at all.

Fig. 15. Micro-photograph showing lath-shaped prehnite crystals from sample Fi8:202.9.

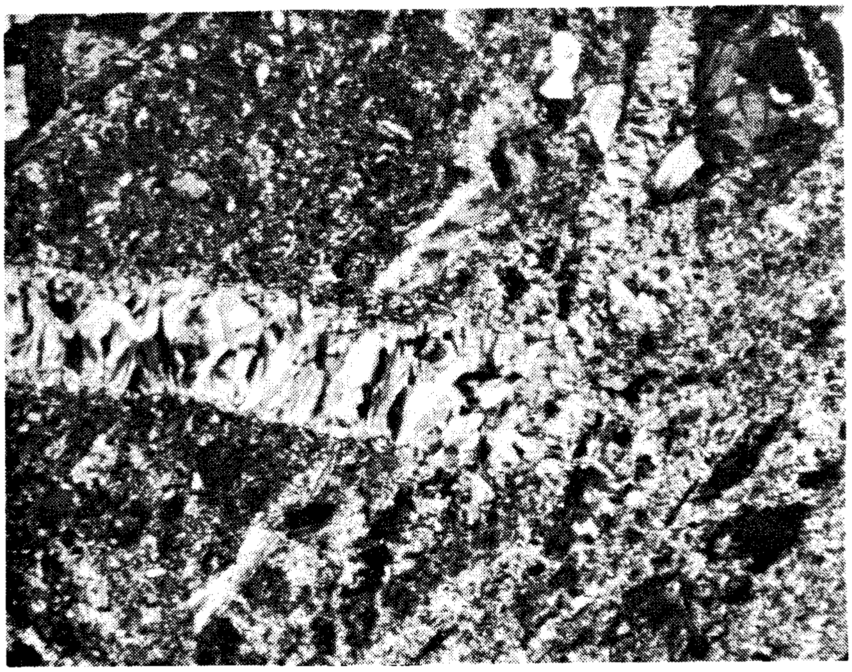


Fig. 16. Micro-photograph showing two generations of prehnite in two crossing fissures from sample Fi7:91.1.

Prehnite has been identified by microscopy as well as XRD. The common habit of prehnite is a fan-like shape (Fig. 15). It is evident (table 2) that prehnite exists as at least two generations (Fig. 16). Prehnite mostly occurs as the oldest fissure filling, sometimes together with calcite. In two samples is prehnite as well as laumontite identified. In one of these is laumontite and prehnite coexisting (cf. Fig. 11). This restricts us to a well defined P-T regime (Liou, 1971) of approximately 2 kb and 250-300° C. (Fig. 17). However, prehnite itself also gives us a hold of the temperature, i.e. approximately 200-400° C.

The chemical composition of the prehnite fillings has been analysed with XRD and microprobe. Results are shown in table 7 and 8 respectively.

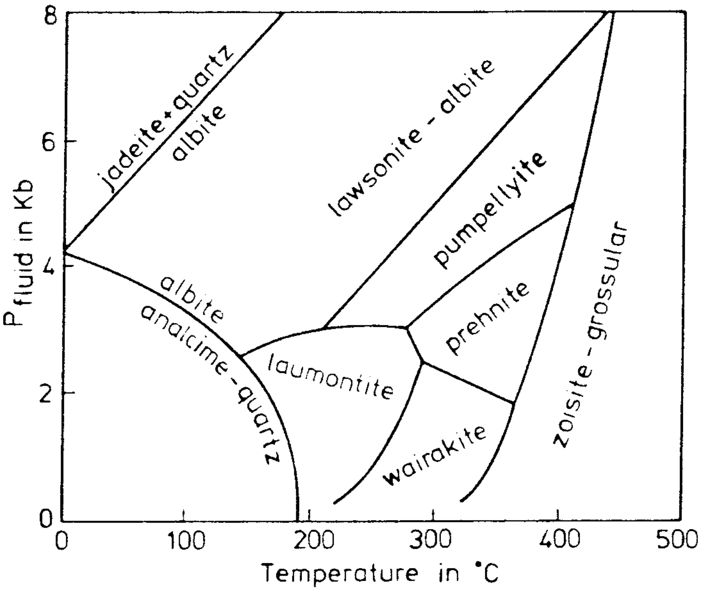


Fig. 17. Stability diagram after Liou (1971).

3.3.3. LAUMONTITE

Laumontite as well as calcite are the most common filling minerals in fissures from borehole Fi8. Laumontite, $Ca(Al_2Si_4O_{12}) \times 4H_2O$, is a zeolite mineral i.e. a mineral with a high ion exchange capacity. It is mostly associated with calcite as a complex mixture but it has been possible to decide the order of crystallization in some samples (table 2). It is evident that a younger generation of calcite postdates the laumontite. Laumontite from Finnsjön exhibits a typical redish colour. The reason for this is not quite clear but x-ray diffractograms from laumontite samples mostly show hematite peaks.

Fig. 18 is from a calcite-laumontite filling in borehole Fi8 (level 342 m). In this fracture, laumontite prisms are grown perpendicular to the wall and are surrounded by calcite which indicates a later crystallization for the calcite. Laumontite crystals show a distinct parting and are stained by very minuite particles (hematite?).

One laumontite filling was separated from a fracture in borehole Fi8 (level 93.3 m) for chemical analysis (table 7). Laumontite in sample Fi5 264.4 have been analysed by electron microprobe. Results are shown in table 8.

Laumontite has also been analysed, by McCulloh et al. (1981), from Sespe hot springs, California. They have found naturally precipitates of laumontite crystallized at a temperature of $89^{\circ}C$ to $43^{\circ}C$ on the surface in a hot spring field. The water from which the laumontite was crystallized originated from a level where the temperature was $125-135^{\circ}C$. According to Liou (1971) (Fig. 17) is the facies boundary for laumontite limited to temperatures between approximately 100° to 300° C. This means that present conditions at Finnsjön can not be responsible for laumontite found in fractures there.

Laumontite seems to be more frequent within the eastern part of the test area than else. One reason for this could be the neighbourhood to the most evident lineament called the Gåvastebo fault within which water could have been circulating for long times. Another reason could be that a younger granite appears to the east, which could have influenced the granodiorite during the intrusion. However, laumontite is also present within fractures found in apophyses from the younger granite into the granodiorite.

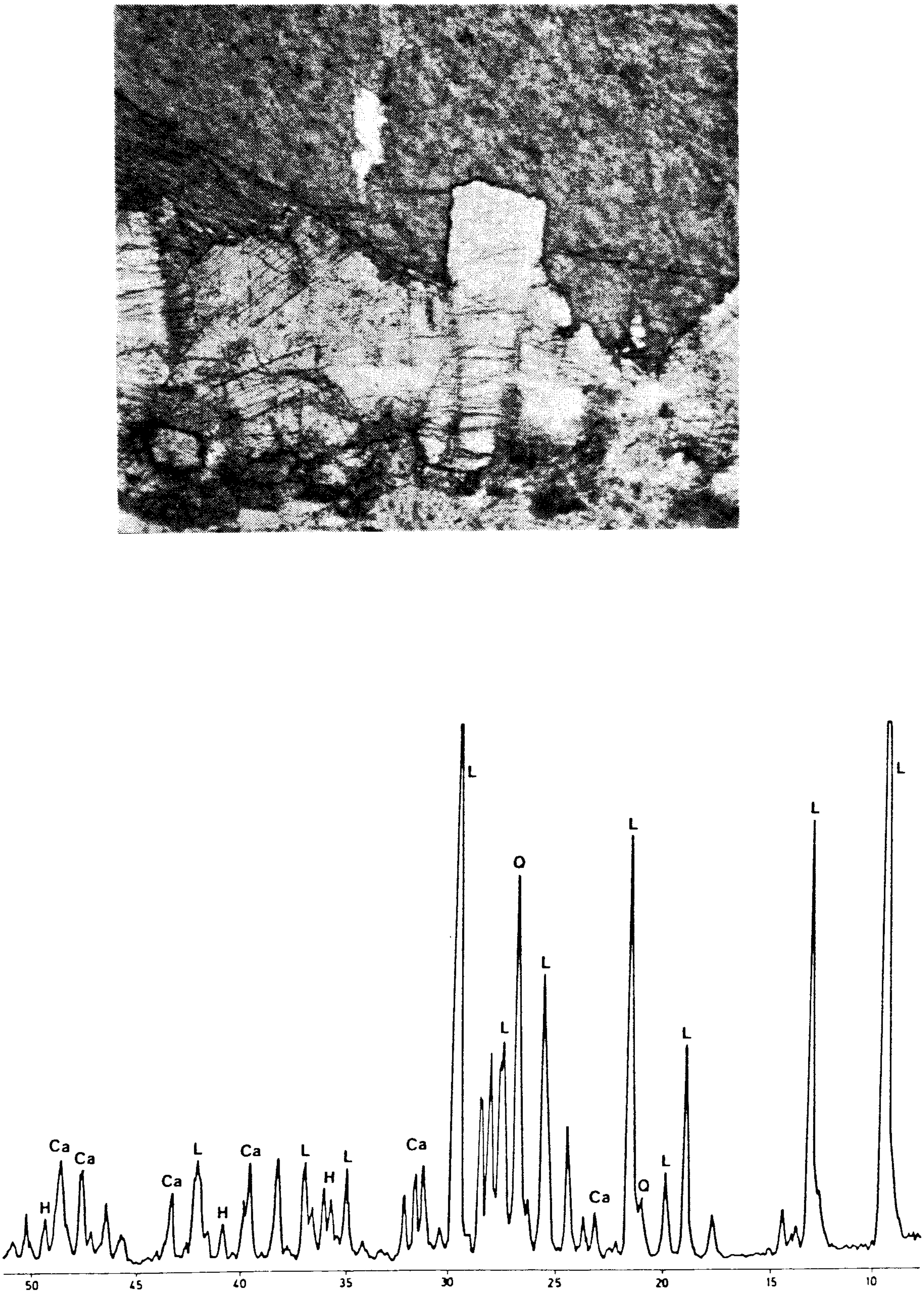


Fig. 18. Micro-photograph and x-ray diffractogram showing laumontite (light gray) and calcite (dark gray) as fissure fillings in sample Fi8:342.9. Ca = calcite; L = laumontite; H = hematite; Q = quartz.

3.3.4. QUARTZ

Quartz has also been identified in most of the thin sections studied. In some of them is quartz coexisting with calcite and prehnite. Some of the samples show two different generations of quartz. Texturally two shapes have been recognized. One of them is a granular texture (Fig. 19) the other is a prismatic texture. The prismatic crystals are grown perpendicular to the fissure wall. The photograph in fig. 20 shows zonary build quartz grown on the fissure wall.

It is however suspected that much of the quartz identified by XRD originates from the fissure wall as the samples have been scraped from the walls by knife.

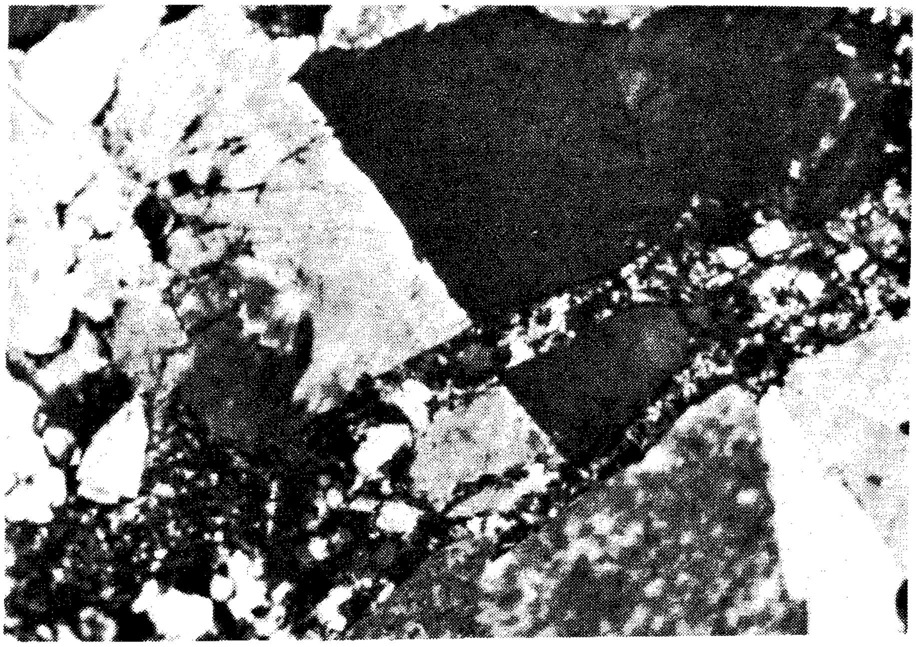


Fig. 19. Micro-photograph showing a thin fissure of granular quartz brecciating a prehnite crystal in two parts. Sample Fi8:72.

3.3.5. WAIRAKITE-ANALCIME

Of all analysed samples only two x-ray diffractograms show peaks which are identified as wairakite. However, wairakite is an endmember of the analcime-wairakite solid solution.

Thus detailed studies of the diffractograms as well as chemical analyses indicate an analcime component within the wairakite. Differential thermal analysis curves show a dominating analcime component of the wairakite-analcime solid solution (Fig. 21).

Wairakite, $CaAl_2Si_4O_{12}$ x $2H_2O$, is the calcium analogue of analcime. Pure wairakite will crystallize in the temperature interval of 250 to 375° C. and at low pressures (less than 3000 bars) (Liou, 1971). Wairakite thus indicates hydrothermal conditions in contrast to analcime which can be formed during "moderate" temperature gradients and temperatures less than approximately 200° C. (Liou, 1971b).

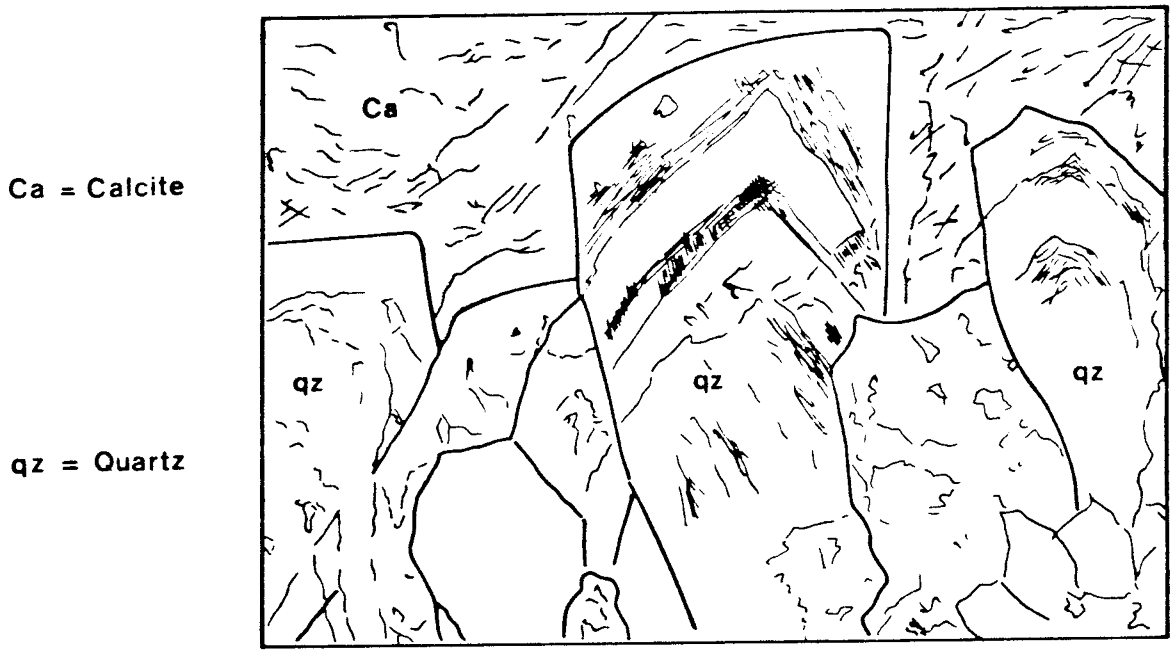


Fig. 20. Sketch from micro photography showing zonary built quartz in sample Fi7:492.4.

3.3.6. EPIDOTE AND CHLORITE

Epidote occurs as a part of the host rock but can also be a filling material in fractures. These fractures mostly have other directions than the calcite-prehnite-laumontite

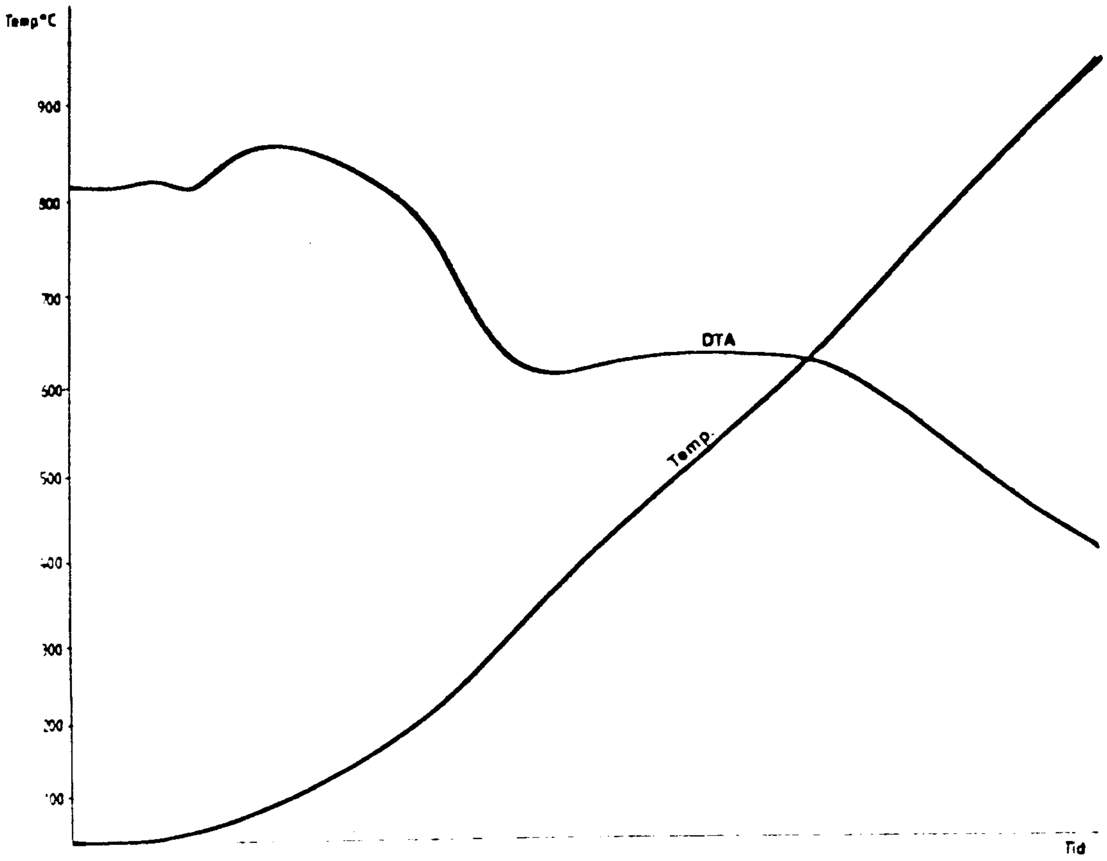


Fig. 21. Differential thermal analysis of sample Fi8:438.7 showing a wairakite-analcime solid solution.

dominated fillings. The general impression is that epidote is a filling mineral which is older than most other minerals but occasionally can be of similar age to one of the calcite and quartz generations respectively.

Chlorite is in reality not so common as indicated by the core mapping. Mostly it appears as an accessory mineral. Only one sampled filling has been shown to contain almost pure chlorite (Fig. 22).

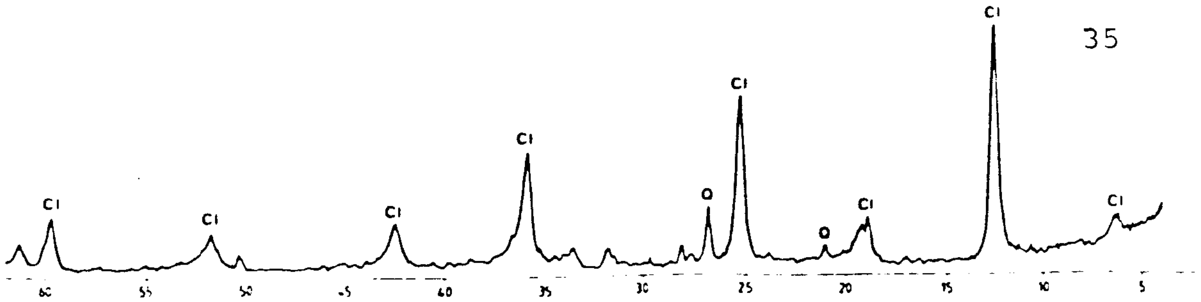


Fig. 22. X-ray diffractogram showing almost pure chlorite in sample Fi8:54.6.

3.4. WATER-ROCK INTERACTION

In this chapter chemical interaction between some common minerals and groundwater is discussed. The chemical data used originate from analyses from the test sites of KBS.

The content of Ca^{2+} and HCO_3^- in groundwater is principally controlled by the calcite-water equilibrium. Ca-plagioclase can also contribute to the Ca^{2+} content of the waters. In figure 23 is $\{Ca^{2+}\}$ plotted versus $\{HCO_3^-\}/\{H^+\}$ for groundwaters from Finnsjön, Kråkemåla and Sternö. One of the lines represents saturation of calcite at constant P_{CO_2} and 10°C. The other line represents saturation of calcite at constant P_{CO_2} and 80°C. (maximum surface temperature of the waste cannister, (KBS II, 1978)). As shown by the figure calcite can be precipitated by most of the analysed waters at present conditions. Raised temperature will decrease the solubility of calcite. Thus at 80°C. only two water samples will be unsaturated concerning calcite.

Also laumontite is a common filling mineral at Finnsjön. As can be seen in figure 24 and 25 analysed waters will plot within the stability field of laumontite (leonhardite) at 0° C. When raising the temperature to 60° C. most of the samples will still plot within the stability field of laumontite (Helgesson, 1971).

Ca^{2+} also participates in other equilibrium reactions, like gypsum ($CaSO_4 \times 2H_2O$)-water and fluorite (CaF_2)-water. These minerals appear as fissure fillings in Sternö and Kråkemåla respectively. Gypsum is a mineral which is easily

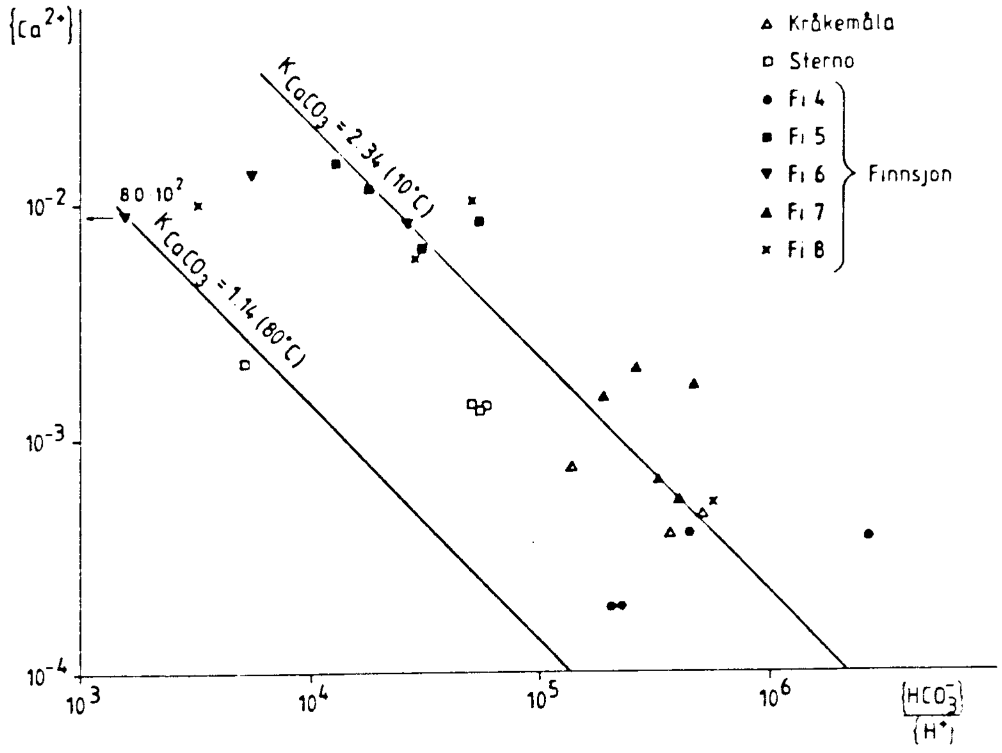


Fig. 23. Stability diagram for calcite. K_s according to Garrels and Christ (1965).

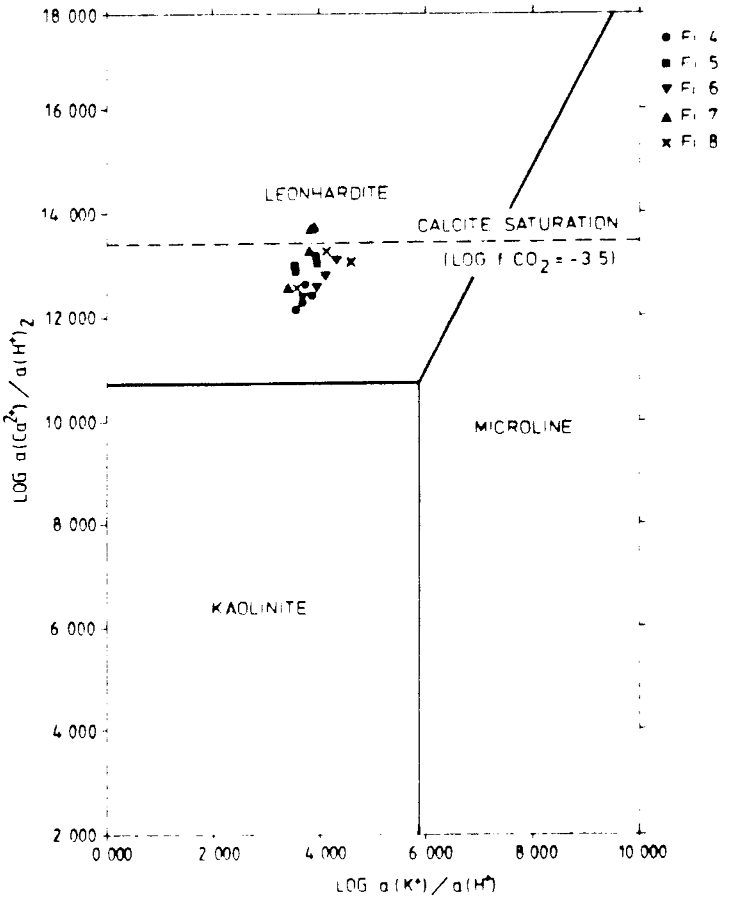


Fig. 24. Analysed waters plotted in the system $HCl-H_2O-Al_2O_3-CaO-CO_2-K_2O-SiO_2$ at 0° C. (Helgesson, 1971).

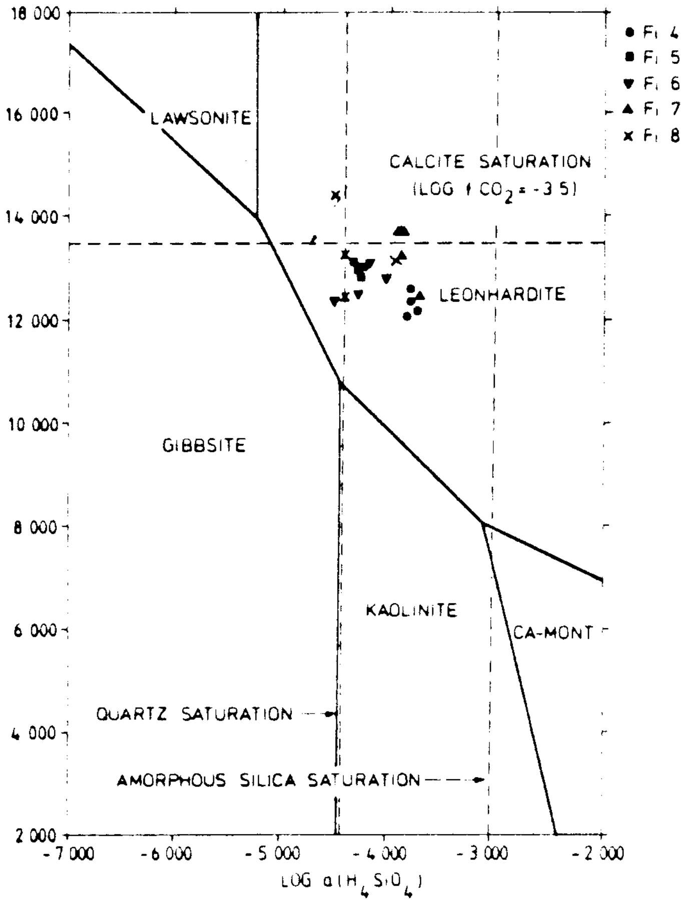


Fig. 25. Analysed waters plotted in the system $HCl-H_2O-Al_2O_3-CaO-CO_2-SiO_2$ at 0° C. (Helgesson, 1971).

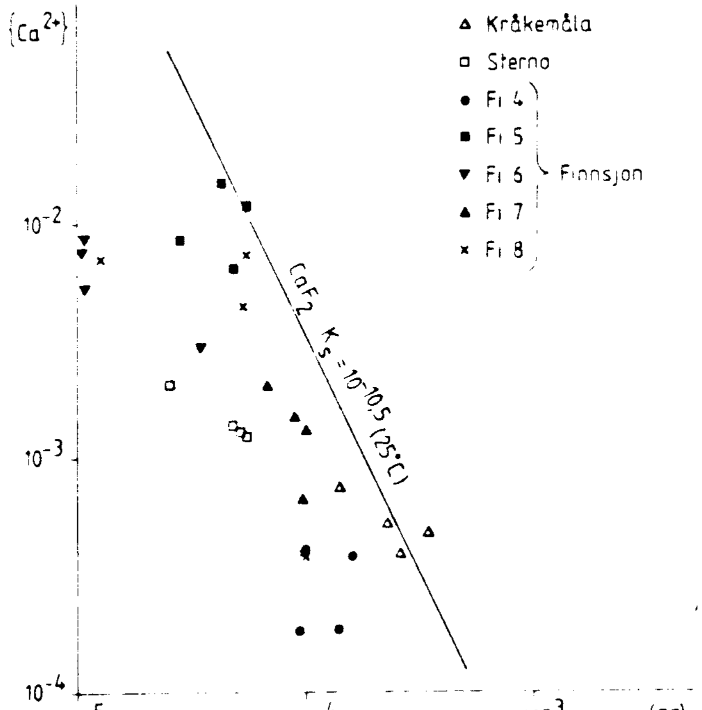


Fig. 26. aCa^{2+} versus aF^- for waters from Finnsjön, Kråkemåla and Sternö. K_s according to Hägg (1963).

dissolvable. Thus high sulphate contents occur in groundwaters from Sternö (110-160 ppm).

The fluorine content of waters is controlled by fluorite. As shown in figure 26 waters from Kråkemåla display the highest fluorine contents and are saturated in respect of fluorite. In contrast most of the waters from Finnsjön are unsaturated in respect of fluorite.

The solubility of silica is controlled by temperature and pH. Thus the solubility will be increased by high temperature as well as high pH. As recorded temperatures and pH of groundwaters are relatively constant will also the silica content be relatively constant. All analysed waters are supersaturated in respect of quartz (Fig. 27). Silica in water can originate from other silicates than quartz. The solubility of silica for different minerals at varying temperatures according to Ronge and Claesson (1982) is shown in figure 28.

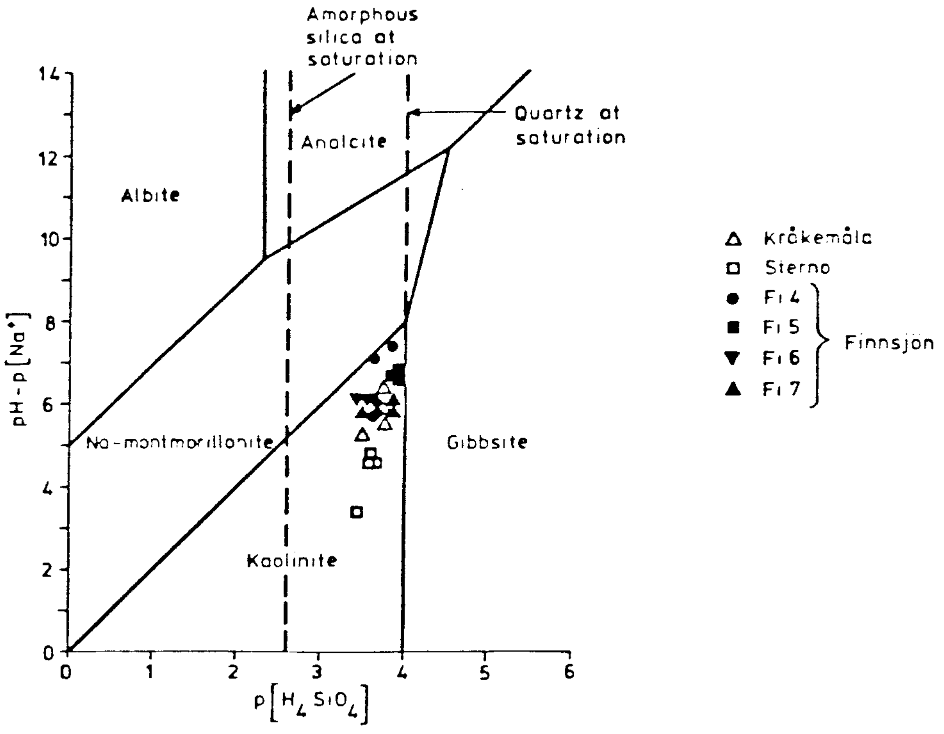


Fig. 27. Stability diagram for the system Na_2O-Al_2O_3-SiO_2 - H_2O-pH. (Eriksson and Khunakasem, 1970).

Weathering of feldspars as well as ion exchange of clay minerals contributes to the sodium and potassium content of waters. As can be seen in figure 27 groundwaters are plotted within the stability field of kaolinite which means that Na-montmorillonite as well as albite (Na-feldspar) are unstable. From figure 24 it can be seen that also K-feldspar is unstable. A raised salinity in the water will increase leaching of sodium and calcium from the minerals (Ronge and Claesson, 1982). Iron and magnesium is preferably leached from ferromagnesium silicates like chlorite, a typical fissure filling within the test sites. Magnesium is easily exchanged by calcium in ion exchange reactions. This means that the magnesium content in the water will be relatively low. The solubility of iron in the pH interval recorded is low. Thus iron will be precipitated as hydroxide and the iron content of the water will be low. Most of the iron content of the water is divalent. Other fissure filling minerals containing iron besides chlorite are prehnite (less than 7% Fe_2O_3) and pyrite. Iron also exists in hematite microlites within laumontite crystals (red staining of the latter). Prehnite as well as hematite contain ferric iron in contrast to the ferrous iron in pyrite.

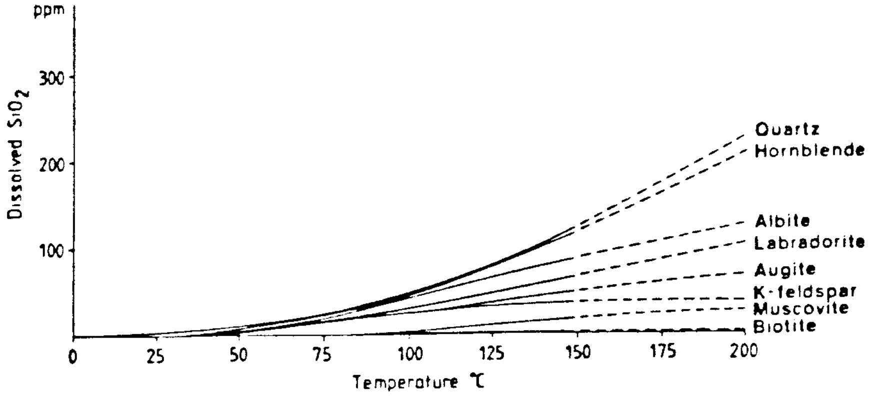


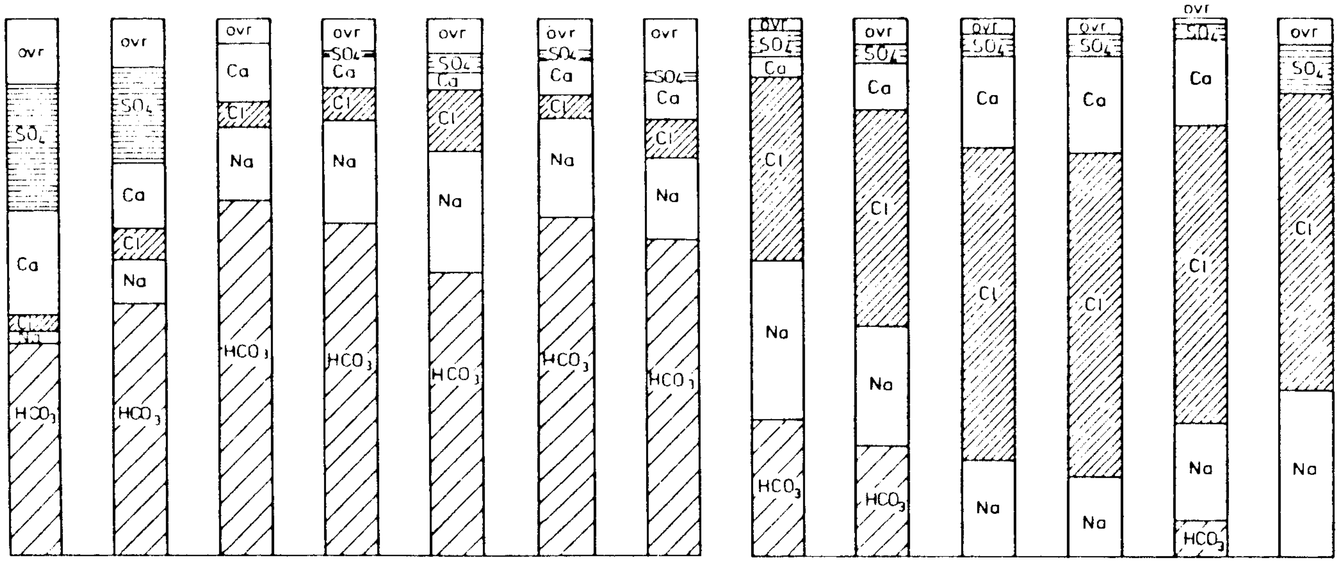
Fig. 28. The relation between dissolved SiO_2 and temperature for rock-forming silicates. (Ronge and Claesson, 1982).

The chlorine content of groundwaters in crystalline rocks usually do not originate from mineral leaching. Two possible sources of the chlorine content are the precipitation and relict salt water. Fluid inclusions within minerals could also contribute to the chlorine content. The analysed water samples from Finnsjön show a large spread in chlorine content. Figure 29 shows the distribution of the dominating ions in the analysed waters.

To see how the chemistry of whole rock samples from Finnsjön will change when weathered, altogether six samples were taken from fresh and weathered parts of a drill core containing one and the same rock type. These were analysed for principal elements as well as some trace elements (table 9). An increasing content of CaO was obtained for all weathered samples in relation to corresponding fresh samples. In the two granodiorite samples the content of Fe_2O_3 was increased and FeO as well as MgO was decreased for weathered samples. A significant decrease was found for two of the weathered samples concerning Si, Na and K. Some general conclusions concerning leaching of minerals can be considered:

If temperature and pressure are increased the solubility of rock forming minerals will increase except for carbonates. Weathering of K-feldspar, quartz but also Na-feldspar (main minerals in granitic rocks) will contribute SiO_2, Na_2O, CaO, K_2O and Al_2O_3 to the water. Weathering of Ca-feldspar, pyroxene but also amphibole (main minerals in gabbroid rocks) will contribute SiO_2, Na_2O, CaO and Al_2O_3 to the water, (Ronge and Claesson 1982).

Cation exchange capacities (CEC) vary within a large interval for fissure filling minerals as well as rock forming minerals (Fig. 30). The most common fissure fillings in Finnsjön are calcite, prehnite, laumontite, chlorite and quartz. Of these minerals quartz, calcite and prehnite have a CEC lower than that for a granite sample from Finnsjön. Laumontite and chlorite show higher CEC than the granite sample (Allard et al., 1981). Thus if relatively



Borehole	KA3	KA4	Fi1	Fi2	Fi4	Fi7	K1	K1	Fi7	Fi8	Fi5	Fi6	Ocean water
Sampled level(s) (m)	232	226 312 397	206 293	385	152 247 368 534	123	103 264 491	406	301 322 511	100 186 275 383	141 205 297 384	184 250 398 688	
Mean total salt-content (mg/l)	672	630	543	515	751	528	384	846	1312	6210	6989	6786	

Fig. 29. Distribution of total dissolved species in analysed waters and ocean water (in weight%). Mean of total salt content from sampled levels. The seven piles to the left correspond to levels dominated by a bicarbonate water. The six piles to the right correspond to levels dominated by a chlorine water.

high CEC is desirable for minerals in the surroundings of a waste disposal, quartz, prehnite and calcite are undesirable fissure fillings. As the temperature will be raised around the waste disposal the solubility of calcite will decrease. This means that if the water is saturated in respect of calcite new calcite will be precipitated on the fissure walls. Dandurand et al. (1982) carried out a study on calcite precipitation from a spring in the Pyrenees of France. They found that in order to start the precipitation, a supersaturation (x 10) is required and the activity of CO_2 appears to be the most critical factor.

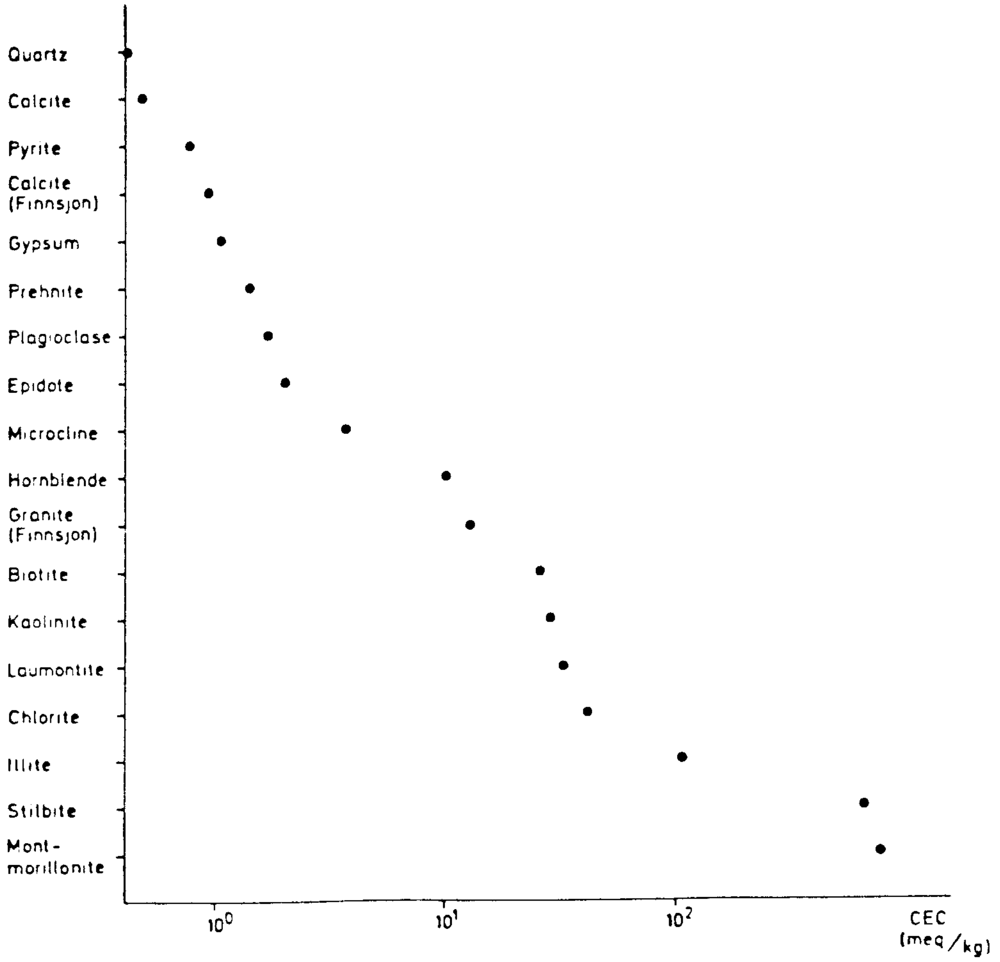


Fig. 30. Cation exchange capacities (CEC), at pH 8 for different minerals and the granite at Finnsjön, according to Allard et al. (1981).

Diffusion through a geological medium is likely to be a function of grain size (number of grain boundaries). A general observation for fissure filling calcite in Finnsjön is that the last crystallized calcite in complex fissure fillings mostly are pure and has a larger grain size than else. Diffusion tests on natural fissures from Finnsjön are in progress (Christina Skagius, Stockholm).

3.5. CONCLUSION

It is evident that calcite is one of the most important fissure minerals at the Finnsjön test site. The reason for this is the general and frequent appearance of this mineral in combination with the water chemistry of present waters. The low sorption capacity of calcite as well as its textural appearance as the youngest fissure infilling in many of the fissures are some other reasons.

The results accounted for elsewhere in this paper show that calcite will precipitate or solute at slight changes in temperature. This means that unfilled fresh fissures could be coated by calcite at temperature increase due to heating in the vicinity of a radioactive waste disposal.

Analysed calcite fissure infillings indicate a complex fissure history. At least three different generations of calcite can be distinguished by textural evidence. This is also confirmed by the fluid inclusion studies. The infillings in the fissures have been precipitated during high temperature as well as low temperature conditions. Calcites from open and sealed fissures respectively can mostly be distinguished by stable isotope data, indicating different evolutions. Open fissures generally show lower $\delta^{13}C$ and higher $\delta^{18}O$ for calcites than in sealed fissures. Some of the calcite infillings in open fissures have been precipitated by present waters and are most frequent within the upper 300 metres of the crust. However, several of the calcites have equilibrated with waters similar to an ocean water or a water concentrated in ^{18}O (hydrothermal conditions) ($\delta^{18}O > 0$). Most of the fissures show fluid reactivation, i.e. high as well as low temperature calcite would be found within one and the same fissure.

U-series dating indicate fluid activation in fissures within approximately 80 000 to 29 000 years ago. These ages probably are average ages of older and younger components. It is however quite clear that most of the dated fissure fillings are of a quaternary age and that some of the fissure infillings precipitated during the last glaciation or even later.

Common fissure infillings, other than calcite, are prehnite, laumontite, chlorite and quartz. These minerals generally need formation conditions which are quite different from those prevailing. Temperature and pressure needed could be obtained during hydrothermal activity. Such conditions have not been prevailing in Sweden within approximately 100 million years (Klingspor, 1976).

Also pyrite, epidote, dolomite, wairakite-analcime and illite have been observed. Of these illite and chlorite together with laumontite exhibit high cation exchange capacities, as they belong to the clay mineral and zeolite group respectively. Present water in Finnsjön are likely to be in chemical equilibrium with kaolinite, laumontite and calcite but not with the rock forming minerals like albite and K-feldspar. Most of the waters are supersaturated in respect of quartz. A mixed water origin with a young component is evident in waters from Finnsjön.

Analysed fracture filling minerals from Finnsjön

Table 1.

Borehole (dip)	Level x)	Open/sealed	Dip xx)	Identified	Chemical analysis xxx)	Microscopy xxxx)	XRD
Fi4 (80°)	162.0	open	35°	Cl,Ca,Hbl,Py	S	T	
"	260.0	sealed	25°	Ca,Pr	OC	T	
"	449.0	open	40°	Ca,La	OC	T	X
"	562.0	open	-	Ca,La	XRF	T	X
Fi5 (50°)	264.4	sealed	40°	Ca,(Py),Pr,La	OC,EM,I	T	
"	264.5	sealed	50°	Ca,A	OC,I		
"	295.0	open	60°	Ca	OC	T,F	
"	383.0	crushed	-	Ca,Cl,Hbl			X
"	416.0	open	50°	Ca	OC,XRF		
"	483.4	open	55°	Ca,Cl	OC,XRF		
"	489.9	open	50°	Py,Ca,Cl	S,OC,I	T	
"	601.3	sealed	45°	Ca	OC,XRF	T	
"	602.2	sealed	50°	Ca	OC,XRF		
Fi6 (90°)	309.0	sealed	10°	Ca	OC,I	T	X
Fi7 (85°)	40.0	open	30°	Ca,Cl,Qz,W	OC,XRF		X
"	41.1	sealed	15°	Ca,Pr,Qz,W	OC,EM,I,XRF,DTA,DA	T	X
"	41.7	open	60°	Ca,Qz	OC	T	
"	61.7	sealed	35°	Pr,Ca,Qz	CO	T	
"	94.1	sealed	40°	Ca,Pr,Qz	CO	T	
"	94.3	open	10°	Pr,Ca,Do,Cm	XRF,CO		X
"	130.2	open	5-15°	Ca,Pr	CO,I	T	
"	135.8	open	20°	Ca	CO		
"	147.0	sealed	80°	Pr		F	
"	160.6	open	15°	Ca	CO		
"	231.7	sealed	80-90°	Ca,Qz,Cl,Pr	XRF,CO	T	X
"	232.1	sealed	10°	Ca	CO,XRF		

Analysed fracture filling minerals from Finnsjön

Table 1. (cont.)

Borehole (dip)	Level$^{x)}$	Open/sealed	Dip$^{xx)}$	Identified	Chemical analysis$^{xxx)}$	Microscopy$^{xxxx)}$	XRD
Fi7 (85°)	285.8	open	20°	Ca	CO,XRF		
"	293.8	open	10-25°	Ca	XRF		
"	302.7	open	0-10°	Ca,Py,Cl	CO,Da ,S	T	
"	303.0	sealed	80°	Qz,Pr		T	
"	303.9	sealed	60°	Ca,Pr,Qz	CO	T	
"	318.8	open	0-10°	Ca	CO	F	
"	319.3	open	0-15°	Ca,Py,Qz,La	CO,S	T	
"	321.2	sealed	5-10°	Pr,Ca,Qz	CO,I	T	X
"	335.1	open	70°	Pr,Do,Ca,Cl,Qz		T	X
"	362.6	sealed	15°		S		
"	362.9	sealed	30°	Ca,Pr,Qz		T ,F	X
"	363.3	open	5-20°	Ca	CO,I		
"	379.5		60°	Pr,Ca,Qz,Do Cl,Ep	EM,I		X
"	438.7	open	50°	Ca,Pr,Qz,Ep	CO,EM,XRF	T	X
"	467.0	sealed	70°	Ca,Qz,Cm, Pr, Pu,Cl	CO	T	X
"	494.2	sealed	25°	Ca,Qz	EM,XRF,CO	T,	X
"	517.9	sealed	40°	Pr,Ca,Qz			X
"	519.1	sealed	35°	Ca,Pr,Qz	EM,CO,I	T	X
"	506.3	sealed	20°	Ca	CO		
"	513.1	open	60°	Ca	CO		
"	526.5	open	10°	Ca,La,Cl	CO		X
"	535.5	sealed	30°	Ca	CO		
"	535.5	open	30°	Ca	CO		
"	535.7	sealed	55°	Ca	CO		

Analysed fracture filling minerals from Finnsjön

Table 1. (cont.)

Borehol (dip)	Level$^{x)}$	Open/sealed	Dip$^{xx)}$	Identified minerals	Chemical analysis$^{xxx)}$	Microscopy$^{xxxx)}$	XRD
Fi8 (60°)	52.8	open	50°	Ca,Qz,Cl	CO	T	X
"	52.8	sealed	30°	Ca	CO		
"	54.6	open	30°	Cl		T	X
"	59.6	sealed	10°	Ca	CO		
"	72.0	open	0-10°	Ca,Qz,La,Pr	CO,EM	T	X
"	93.3	sealed	0-10°	La,Qz,Cl	XRF		X
"	93.8	sealed	0-10°	La,Qz			X
"	134.1	open	20°	Ca,La,Qz	CO		X
"	134.8	open	15°	Ca,La,Cl(Cp)	CO	T	X
"	138.9	open	15°	La,Ca,Qz			X
"	190.7	sealed	20°	Ca,Qz			X
"	191.4	open	10°	Q,La,Cl			X
"	201.5	open	-	Ca	CO		
"	202.9	open	80°	Qz,Pr,Cl		T	X
"	254.0	open	80°	Ca,Qz,Pr	CO		X
"	317.1	open	0-10°	Ca,Q	CO		X
"	321.6	sealed	0-10°	Ca,Q	I,CO,Da	T	X
"	342.9	sealed	40°	Ca,L,Q	I,CO	T	X
"	358.1	sealed	-	Ca	CO		
"	388.4	sealed	40°	Ca,Q	CO	T	X
"	438.7	sealed	50°	Ca,Q,W	CO,XRF,DTA		X
"	440.2	sealed	10-20°	Ca,Q,Cl	CO		X

x) Core length in metres

xx) Deviation from core axis in degrees

xxx) XRF = X-ray fluorescens. I = Emission spectroscopy; EM = Electrone Microprobe analysis;

OCS = Stable isotope analysis of oxygen, carbon and sulphur respectively.

Da = U - Th isotopes for dating. DTA = Differential Thermal Analysis.

xxxx) T = Identification and textural study on transmission microscope. F = Fluid inclusion study.

Ca = Calcite, $CaCO_3$; DO = dolomite, $MgCa(CO_3)_2$; Pr = Prehnite, $Ca_2Al_2Si_3O_{10}(OH)_2$; Q = Quartz, SiO_2;
Cl = Chlorite, $(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2(Mg,Fe)_3(OH)_6$; W = Wairakite - analcime, $CaAl_2Si_4O_{12}x2H_2O$-$NaAl_2Si_4O_{12}x6H_2O$;
La = laumontite $(Ca,Na)Al_2Si_4O_{10}x4H_2O$; Ep = Epidote $(Ca,Fe)Al_2OxOH(Si_2O_7)(SiO_4)$;Cm = unspecified clay mineral;
Hbl = hornblende $(Ca,Na)_{2-3}(Ms,Fe,Al)_5xSi_6(SiAl)_2O_{22}(OH)_5$; A = Asphaltite; Py = pyrite, FeS_2.

Table 2

Identified mineral phases (microscopy)

Relative age is indicated by the figures (1 = oldest)

Borehole/ Level	Calcite	Quartz	Prehnite	Laumonite	Chlorite	Epidote	Accessory minerals
Fi4: 260.0	1		1				
449.1	1		1	1			
Fi5: 264.4	2^{x},3		1,2	3,4		1	
295.5	2	2	1,3				
489.9	1						
601.3	1,2		1				
Fi6: 309.0	1^{x},2	1,2	1,2		+		
Fi7: 41.1	2,3^{x},4		1,2				Pumpellyite
41.7	2	1					
61.2	2		1				
91.1	1	1	1				
130.1	1		1				
231.8			2,3			1	
303.0	1		1				
303.9	1	1	1				
319.3	1,2	1		1			
321.5	1	1	1				
335.1	2		1				
379.0	2	1,3	1			3	
438.8	2^{x}	1	+			1	
467.0	3	1,2	1,2				
494.2	2^{x}	1					
519.0	3^{x},4	4	1,2				
Fi8: 52.8	1	+			+		
54.6					+		
72.2	2		1				
134.8	+			1	1	+	
202.9	1	1	1				
321.6	1,2	3					
342.9	2			1			
294.2	1	+		1		1	
295.6	1			2			
388.4	1^{x},2	1		1			

Table 3. Analyses of $\delta^{18}O$ and $\delta^{13}C$ in calcites from Finnsjön. Values related to PDB.

Borehole: Depth (m)	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	Open/Sealed fissure
Fi4: 256.0	- 2.80	-12.20	sealed
Fi4: 442.7	- 2.65	-18.89	sealed
Fi4: 553.5	- 2.43	-14.14	open?
Fi5: 202.5	-14.04	-12.32	sealed
Fi5: 202.6	-11.85	- 7.86	sealed
Fi5: 226.0 A	- 4.95	-12.50	sealed central part of fissure
Fi5: 226.0 B	- 1.35	- 8.00	sealed marginal part of fissure
Fi5: 318.7 A	- 2.09	-12.63	sealed marginal part of fissure
Fi5: 318.7 B	- 4.48	-13.21	sealed central part of fissure
Fi5: 367.1	- 2.90	- 7.40	sealed
Fi5: 370.3 A	- 2.51	-14.03	sealed marginal part of fissure
Fi5: 370:3 B	- 2.52	-17.80	sealed central part of fissure
Fi5: 375.3	- 9.14	-12.49	open
Fi5: 460.6 A	- 4.74	-17.48	sealed
Fi5: 460.6 B	- 4.07	-18.74	sealed
Fi6: 309	- 4.90	-13.95	sealed
Fi7: 39.8	- 7.55	- 7.50	sealed
Fi7: 40.9 A	- 3.94	-15.86	sealed marginal part of fissure
Fi7: 40.9 B	- 3.68	-13.99	sealed marginal part of fissure
Fi7: 40.9 C	- 1.20	- 6.62	sealed central part of fissure
Fi7: 41.5	- 0.51	- 5.75	sealed
Fi7: 93.9	-10.48	-10.14	open
Fi7: 129.5	- 2.12	-10.02	open?
Fi7: 135.3	- 0.32	- 8.49	open?
Fi7: 160.0	- 2.38	-11.03	open
Fi7: 160.1	- 3.65	-12.72	open
Fi7: 230.8	- 3.08	-10.14	sealed
Fi7: 231.2	- 4.03	-13.15	sealed
Fi7: 284.7	- 3.50	-12.40	sealed

Table 3. (cont.)

Borehole: Depth (m)	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	Open/Sealed fissure
Fi7: 301.5	- 5.18	-10.90	open
Fi7: 301.5	- 7.74	-11.34	open
Fi7: 302.7	-14.61	-12.63	open
Fi7: 302.7	- 3.79	-17.35	sealed
Fi7: 317.6	- 8.81	-11.65	open
Fi7: 317.6	-10.62	-12.24	open (reanalysed)
Fi7: 318.4	-17.71	-12.03	open?
Fi7: 320.0	- 4.62	-15.16	sealed
Fi7: 320.3	- 4.39	-17.17	sealed
Fi7: 361.9	-13.05	-12.99	open?
Fi7: 437.0 A	- 5.34	-15.36	marginal part of fissure
Fi7: 437.0 B	- 4.53	-18.83	central part of fissure
Fi7: 437.0	- 1.80	-11.71	sealed
Fi7: 465.2	- 4.31	-17.97	sealed
Fi7: 492.3	- 3.02	-18.91	sealed
Fi7: 504.4	- 5.43	-12.27	sealed
Fi7: 511.1	- 4.20	-18.05	sealed?
Fi7: 517.1	- 4.54	-18.22	sealed
Fi7: 524.5	- 6.63	-12.90	open?
Fi7: 533.5	- 4.78	-19.14	sealed
Fi7: 533.5	- 4.36	-10.95	open
Fi7: 533.7	- 4.71	-18.81	sealed
Fi8: 45.7	- 5.80	-11.39	open?
Fi8: 45.7	- 5.39	-14.29	sealed
Fi8: 51.6	- 2.47	-10.38	sealed
Fi8: 62.5	+ 1.34	- 8.81	open?
Fi8: 116.1	- 4.68	-15.38	sealed
Fi8: 116.7	- 2.35	-13.83	sealed
Fi8: 142.5	- 4.52	- 8.29	open?

Table 3. (cont.)

Borehole: Depth (m)	$\delta^{13}C_{PDB}$	$\delta^{18}O_{PDB}$	Open/Sealed fissure
Fi8: 174.5	-14.59	- 9.62	open?
Fi8: 220.0	-12.68	-10.91	open
Fi8: 237.8	-11.72	-10.98	open
Fi8: 256.0 A	- 3.99	-10.74	sealed
Fi8: 256.0 B	-13.83	-12.88	sealed. older than A
Fi8: 259.4	- 2.45	-12.65	open
Fi8: 274.6	- 7.40	-13.05	open?
Fi8: 278.5 A	- 2.89	-11.78	sealed, marginal
Fi8: 278.5 B	- 7.96	-11.54	sealed, central
Fi8: 297.0	- 5.51	-16.99	sealed
Fi8: 297.0	- 5.63	-15.99	sealed
Fi8: 310.1	-13.86	-13.33	sealed?
Fi8: 336.4	- 3.59	-18.22	sealed?
Fi8: 336.4	- 3.98	-18.26	sealed?
Fi8: 379.9	- 7.37	-10.45	sealed?
Fi8: 381.2	- 6.63	-14.45	open?
Fi8: 381.2	- 6.79	-14.33	open?
Fi8: 400.5	-10.74	-14.22	sealed?

Table 4. Activity Ratios

Sample No.		$\frac{^{234}U}{^{238}U}$	$\frac{^{230}Th}{^{234}U}$
Fi7: 41.10A	(L)	1.141 ± 0.062	0.414 ± 0.027
	(R)	1.015 ± 0.048	1.109 ± 0.069
	(W)	1.053 ± 0.052	0.873 ± 0.043
Fi7: 41.10C	(L)	0.992 ± 0.028	0.587 ± 0.030
	(R)	1.179 ± 0.100	4.989 ± 0.357
	(W)	1.015 ± 0.041	1.165 ± 0.046
Fi7: 303.0	(L)	2.575 ± 0.089	0.343 ± 0.014
	(R)	1.280 ± 0.047	1.101 ± 0.055
	(W)	2.020 ± 0.067	0.549 ± 0.018
Fi8: 321.6A	(L)	1.310 ± 0.058	1.070 ± 0.047
	(R)	0.895 ± 0.122	2.823 ± 0.306
	(W)	1.255 ± 0.056	1.240 ± 0.049
Fi8: 321.6B	(L)	1.525 ± 0.145	0.619 ± 0.051
	(R)	1.351 ± 0.203	0.867 ± 0.120
	(W)	1.448 ± 0.132	0.714 ± 0.056

Table 5. Radiochemical Data on Leachate (L), Residue (R) and Whole Sample (W)

Sample No.	f_L		^{238}U (dpm/g)	^{234}U (dpm/g)	^{232}Th (dpm/g)	^{230}Th (dpm/g)
Fi7: 41.10A	0.802	(L)	0.331±0.014	0.377±0.015	0.020±0.003	0.156±0.008
		(R)	2.932±0.140	2.975±0.142	0.246±0.025	3.298±0.130
		(W)	0.846±0.030	0.891±0.031	0.065±0.006	0.778±0.027
Fi7: 41.10C	0.884	(L)	1.450±0.046	1.440±0.045	0.019±0.004	0.845±0.036
		(R)	1.409±0.095	1.661±0.104	0.650±0.059	8.287±0.287
		(W)	1.445±0.042	1.466±0.042	0.092±0.008	1.708±0.046
Fi7: 303.0	0.901	(L)	0.542±0.019	1.396±0.036	0.067±0.005	0.479±0.016
		(R)	3.718±0.135	4.758±0.162	1.295±0.075	5.239±0.194
		(W)	0.856±0.022	1.729±0.036	0.189±0.009	0.950±0.024
Fi8: 321.6A	0.937	(L)	0.260±0.009	0.341±0.011	0.010±0.002	0.365±0.011
		(R)	0.612±0.060	0.548±0.056	0.259±0.021	1.547±0.056
		(W)	0.282±0.009	0.354±0.011	0.026±0.002	0.439±0.011
Fi8: 321.6B	0.840	(L)	0.041±0.003	0.063±0.004	0.013±0.001	0.039±0.002
		(R)	0.145±0.017	0.196±0.020	0.127±0.014	0.170±0.016
		(W)	0.058±0.004	0.084±0.005	0.031±0.002	0.060±0.003

Table 6. Age Estimates

Sample No.	Age (10^3 years)	
	Maximum[0]	Probable
Fi7: 41.10A	215 ± 45	29 ± 13[1,2,3]
Fi7: 41.10C	-	No relevant ages was calculated
Fi7: 303.0	80 ± 4	74 ± 21[1,2,3]
Fi8: 321.6A	-	No relevant ages was calculated
Fi8: 321.6B	124 ± 20	79 ± 25[1,2]

[0] Based on $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ ratios of the whole sample.

[1] Based on $^{230}Th/^{234}U$ and $^{234}U/^{238}U$ ratios of the leachate fraction.

[2] Based on the pseudo-isochron-plot method of Szabo and Sterr (1978).

[3] Based on the correction scheme of Ku, *et al*. (1979).

Table 7. Chemical analyses of fissure filling minerals from Finnsjön.

XRF

Fissure fillings of calcite types

Sample no.	SiO_2 %	TiO_2 %	Al_2O_3 %	Fe_2O_{3tot} %	MnO %	CaO %	MgO %	Na_2O %	K_2O %
Fi7:39.95	6.4	0.01	2.4	0.9	0.11	49.6	0.48	0.2	1.1
Fi7:94.3	6.9	0.10	2.0	1.5	0.02	50.0	0.77	0.1	0.5
Fi7:160.6	24.3	0.05	7.5	2.7	0.03	33.1	2.5	1.2	1.7
Fi7:231.7	2.1	<0.01	1.0	0.1	0.05	55.2	0.10	<0.1	<0.1
Fi7:232.1	19.1	0.02	5.2	1.7	0.03	42.6	1.0	<0.1	1.0
Fi7:285.75	3.5	<0.01	1.7	0.3	0.04	54.8	0.14	<0.1	<0.1
Fi7:293.65	9.2	0.04	3.5	1.5	0.03	48.8	0.69	<0.1	0.3
Fi7:319.6	7.9	0.03	2.1	0.7	0.05	49.2	0.38	<0.1	1.4
Fi7:438.7b	19.8	0.01	8.1	1.5	0.03	42.9	0.09	<0.1	0.2
Fi7:494.2	25.0	<0.01	0.2	0.1	0.03	42.0	0.05	<0.1	0.1
Fi5:416.0b	0.1	<0.01	0.2	<0.1	0.34	56.8	0.09	<0.1	<0.1
Fi5:483.4	1.7	0.03	0.6	0.4	0.06	55.0	0.16	0.1	0.2
Fi5:601.3b	0.8	<0.01	0.3	0.1	0.11	55.6	0.14	<0.1	0.1
Fi5:602.15	1.7	<0.01	0.2	0.1	0.03	55.9	0.11	<0.1	0.1
Fi4:562.0	5.0	<0.01	0.6	<0.1	<0.01	53.5	0.07	<0.1	<0.1
Fi8:93.3	53.2	0.01	21.0	0.3	0.01	10.4	0.07	0.8	0.7

Table 7. (cont.)

Emission spectroscopy

Calcite

Sample no.	Ca %	Mg %	Na %	Mn %	Fe %	Si %	Sr ppm	Zn ppm	Ba ppm	Pb ppm	Co ppm	Cu ppm
Fi4 162.0	34.7	0.59	0.1	0.13			57	10				
Fi5 264.4	39.4	<0.01	< 0.1	0.48	< 0.1		61	<10				
Fi5 264.5	32.1	<0.01	< 0.1	0.24	0.4		61	24				
Fi5 489.9	37.6	<0.01	< 0.1	0.11	< 0.1		< 10	<10				
Fi6 309.0 Ca+Pr	21.0	0.09	1.3	0.12	0.20	10.4	146	12	98	< 0.2	0.1	8
Fi7 41.1a	38.2	<0.01	< 0.1	0.30	< 0.1		68					
Fi7 41.1c	35.3	0.20	0.2	0.52	0.6		169					
Fi7 130.0	37.9	0.08	< 0.1	0.52	0.6		176					
Fi7 302.7	35.2	0.20	0.22	0.20	1.0		72					
Fi7 321.2	39.1	0.09	< 0.1	0.18	0.2		288					
Fi7 363.3	36.6	<0.01	< 0.1	0.15	0.3		< 10					
Fi7 517.9	37.8	0.28	< 0.1	0.07	0.6		66					
Fi7 519.1	37.0	<0.01	< 0.1	0.10	0.2		220					
Fi8 312.6 Ca+Q	18.1	0.01	0.60	0.04	0.20		16	7	8	< 0.2	< 0.1	10
Fi8 342.9 Ca+La	20.8	0.06	0.72	0.04	0.70	6.6	112	5	10	13	< 0.1	5

Prehnite

Sample no.	Ca %	Mg %	Na %	Mn %	Fe %	Al %	Ba %	Sr ppm
Fi7 41.1	21.0	<0.01	< 0.1	0.10	1.5	12.1	< 0.01	<10
Fi7 379.5	20.1	<0.01	< 0.1	0.11	3.9	10.7	< 0.01	<10
Fi7 519.1	20.2	<0.01	< 0.1	0.07	1.4	10.6	< 0.01	<10

Table 7. (cont.)

Trace elements XRF	Fi7:41.1 Prehnite	Fi7:438.7 Prehnite + Quartz	Fi8:93.3 Laumontite
Na_2O %	0.14	0.23	0.66
K_2O %	0.63	0.33	0.65
MgO %	0.70	0.42	0.15
CaO %	19.1	19.2	20.6
Al_2O_3 %	16.1	13.7	19.4
SiO_2 %	39.4	50.6	54.4
P_2O_5 %	0.01	0.02	0.01
S ppm	< 50	75	< 50
Cl ppm	990	250	85
Co ppm	< 10	<10	< 10
Ni ppm	10	10	< 10
Cu ppm	13	27	10
Pb ppm	< 20	<20	< 20
Zu ppm	< 10	<10	< 10
AS ppm	< 20	<20	< 20
Mo ppm	< 10	<10	< 10
W ppm	< 10	<10	< 10
BaO %	< 0.01	< 0.01	0.01
TiO_2 %	0.03	0.06	< 0.01
V ppm	200	200	30
Cr ppm	< 10	<10	10
MnO %	0.04	0.04	0.01
Fe_2O_3 %	2.0	3.4	0.26
Sr ppm	20	140	140
Y ppm	< 10	<10	21
Zr ppm	< 10	11	21

Table 8. Microprobe analyses of minerals. (Contents are given in weight-%).

Laumontite	K_2O	Na_2O	CaO	MgO	Al_2O_3	SiO_2
Fi5:264.4 m	0.53	0.23	11.1	0.1	21.8	52.1
"	0.51	0.34	11.3	0.1	22.2	50.4

Prehnite	TiO_2	CaO	MgO	MnO	Al_2O_3	FeO	SiO_2
Fi5:264.4 m	-	27.3	0.2	-	23.3	1.9	43.6
"	-	27.3	0.1	-	22.6	2.7	43.8
Fi7:335.1 m	-	26.5	0.2	0.1	23.1	1.7	44.8
"	0.1	26.4	0.2	-	22.9	1.8	44.4
Fi7:379.5 m	0.1	27.7	0.1	-	21.2	3.7	41.8
"	-	27.8	0.2	-	21.9	3.1	41.4

Calcite		BaO	CaO	CO_2	MnO	SrO	MgO	FeO
Fi7:41.1 m		-	54.5	43.2	0.2	0.1	0.8	0.4
"		-	54.7	44.2	0.5	-	1.0	0.4
"	(Prismatic)	0.1	55.5	42.9	0.3	-	0.6	-
"	"	-	56.0	42.8	0.1	-	0.7	-
"	"	-	55.8	44.5	0.1	0.1	0.6	-
Fi7:335.1		0.2	55.8	43.8	0.2	0.1	0.6	-
"		-	55.6	44.2	0.3	-	0.7	-
Fi7:494.2		-	55.9	43.3	-	-	0.4	-
"		0.2	55.8	43.3	0.1	0.1	0.4	-
Fi7:519.1		-	56.1	44.4	0.1	0.1	0.6	-
"		-	56.4	43.0	-	-	0.6	-
"	(Prismatic)	-	56.2	43.0	0.1	-	0.4	-
"	"	-	56.2	42.7	-	0.1	0.4	-

Table 9. Chemical analyses of fresh and weathered whole rock samples from Finnsjön. (XRF)

	Granodiorite		Granodiorite		Granite	
Trace elements	Fi8 294.2 fresh	Fi8 295.6W weathered	Fi8 300.1 fresh	Fi8 299.4W weathered	Fi8 396.1 fresh	Fi8 396.8 weathered
Na_2O%	2.5	1.0	2.3	2.5	3.7	1.6
K_2O%	3.9	4.2	3.8	3.1	5.0	4.1
MgO%	2.3	1.94	2.9	1.7	0.03	0.26
CaO%	2.3	4.1	2.5	3.9	0.7	4.4
Al_2O_3%	14.0	14.0	14.7	13.2	12.7	14.2
SiO_2%	66.2	61.5	64.1	64.9	75.5	65.8
P_2O_5%	0.12	0.13	0.13	0.12	0.025	0.034
S ppm	<50	55	<50	<50	<50	<50
Cl ppm	150	130	140	190	160	150
Co ppm	84	48	120	93	45	61
Ni ppm	<10	10	<10	13	<10	<10
Cu ppm	14	11	18	27	<10	10
Pb ppm	<20	22	26	27	<20	<20
Zn ppm	45	49	63	44	<10	26
As ppm	<20	<20	<20	<20	<20	<20
Mo ppm	11	13	21	19	<10	<10
W ppm	980	370	1540	760	400	770
BaO%	0.09	0.09	0.09	0.09	0.05	0.06
TiO_2	0.42	0.52	0.50	0.44	0.08	0.13
V ppm	59	85	64	70	19	26
Cr ppm	27	28	32	25	<10	10
MnO%	0.12	0.1	0.15	0.10	0.02	0.06
Fe_2O_3%	5.2	5.2	6.0	5.2	1.1	1.6
Sr ppm	240	200	300	200	64	160
Y ppm	<10	13	10	11	<10	<10
Zr ppm	120	150	160	140	76	100

4. STUDSVIK

4.1. INTRODUCTION

The bedrock in the region belongs to the Svecokarelian belt of Sweden (1800-2000 Ma). The rock type present at the test site is a gneiss of sedimentary origin, which in parts is strongly migmatized and veined. Also thin sheets and layers of metabasite occur. Just to the west of the test site is a synorogenic, migmatized granodiorite outcropping (Lundström, 1976).

The main interest in the Studsvik studies on fissure filling materials has been to clarify the chemical environment within the fissures. This was especially important around the 100 metres level where sorption studies have been carried out by injection of tracers into one borehole followed up by detection in a second borehole (Landström, 1978). None of these boreholes were core drilled so fissure fillings from a core drilled hole situated in the immediate neigbourhood were investigated (Fig. 31). This core was 200 metres long and was mapped considering fractures, fracture fillings and rock types (Klockars et al., 1980). Fracture and crushed zones as well as rock types within the core are shown in Fig. 32.

Three types of rocks have been distinguished. The most common type is a veined gneiss which by Lundström (1976) is characterized as a very heterogeneous rock with biotite--foliated paleosomes. Typical minerals in the paleosomes are quartz (40-70%), feldspars (10-40%) and biotite as well as chlorite. Andalusite, sillimanite, garnet and cordierite are minerals which usually constitute up to 20% of the paleosome. Garnet as well as cordierite is also present in neosomes.

Another rock type distinguished is a granite-pegmatite. This rock type mostly represents the leucocratic material of migmatites with a granitic composition and with aplitic to pegmatitic textures. The third type is a fine grained, homogeneous metabasite.

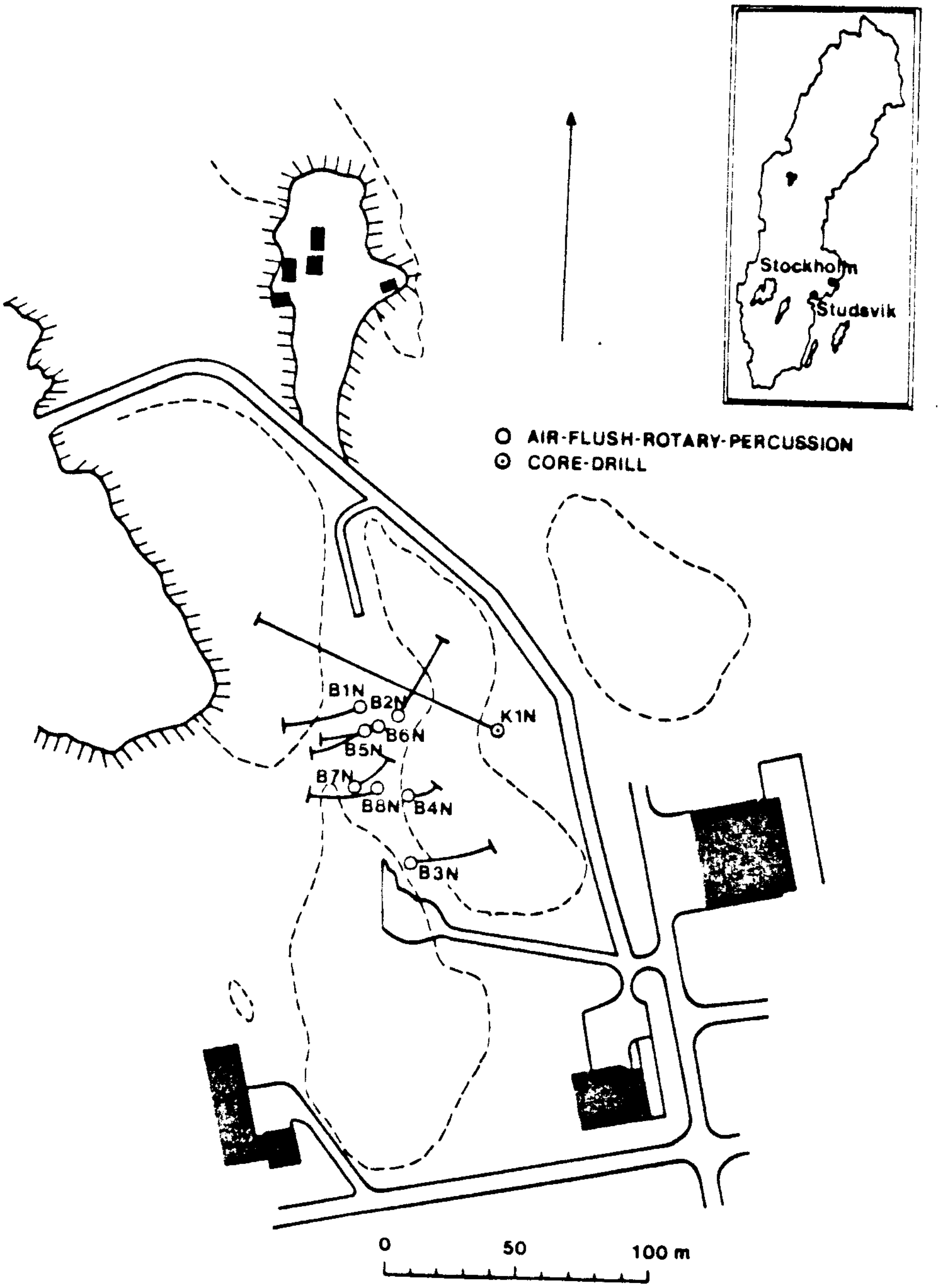


Fig. 31. The Studsvik test site.

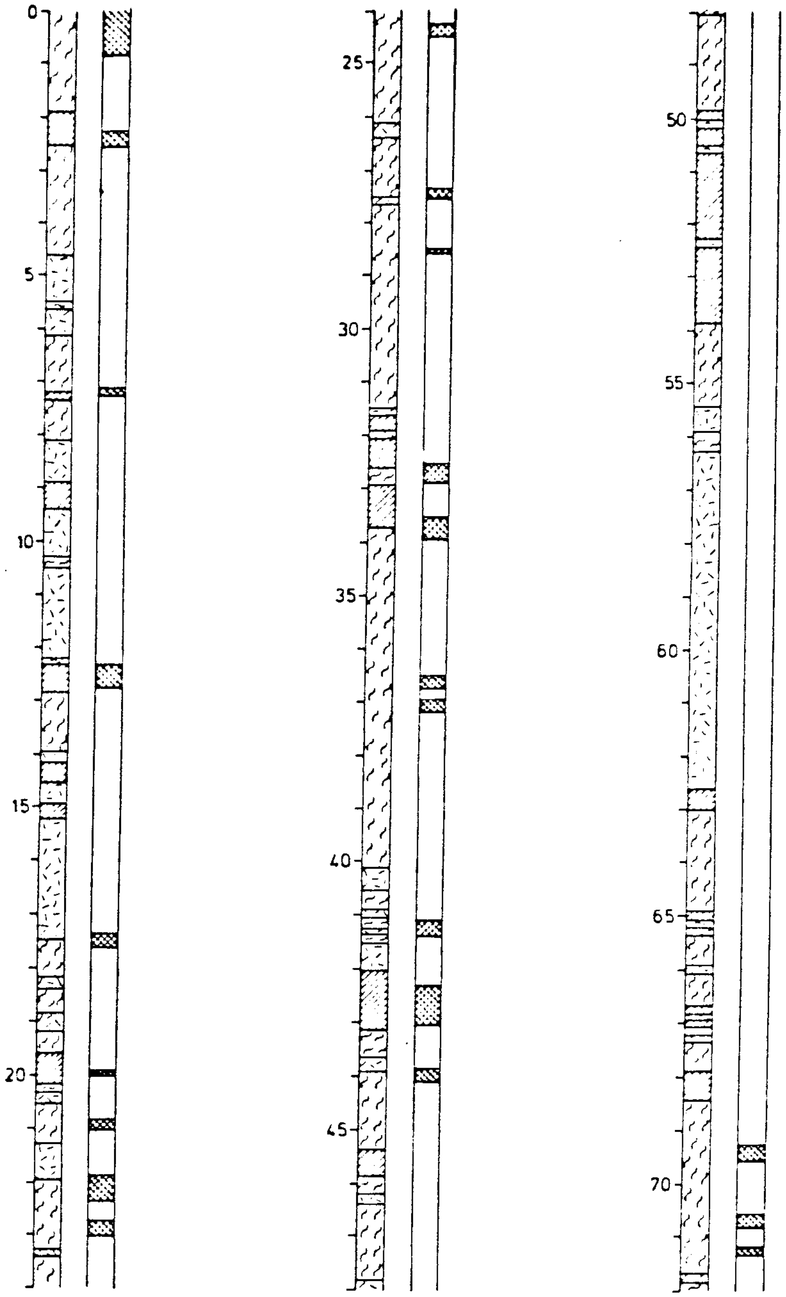


Fig. 32. Core mapping of borehole K1 at Studsvik. Rocktypes and crushed zones are distinguished. (Legend see page 65).

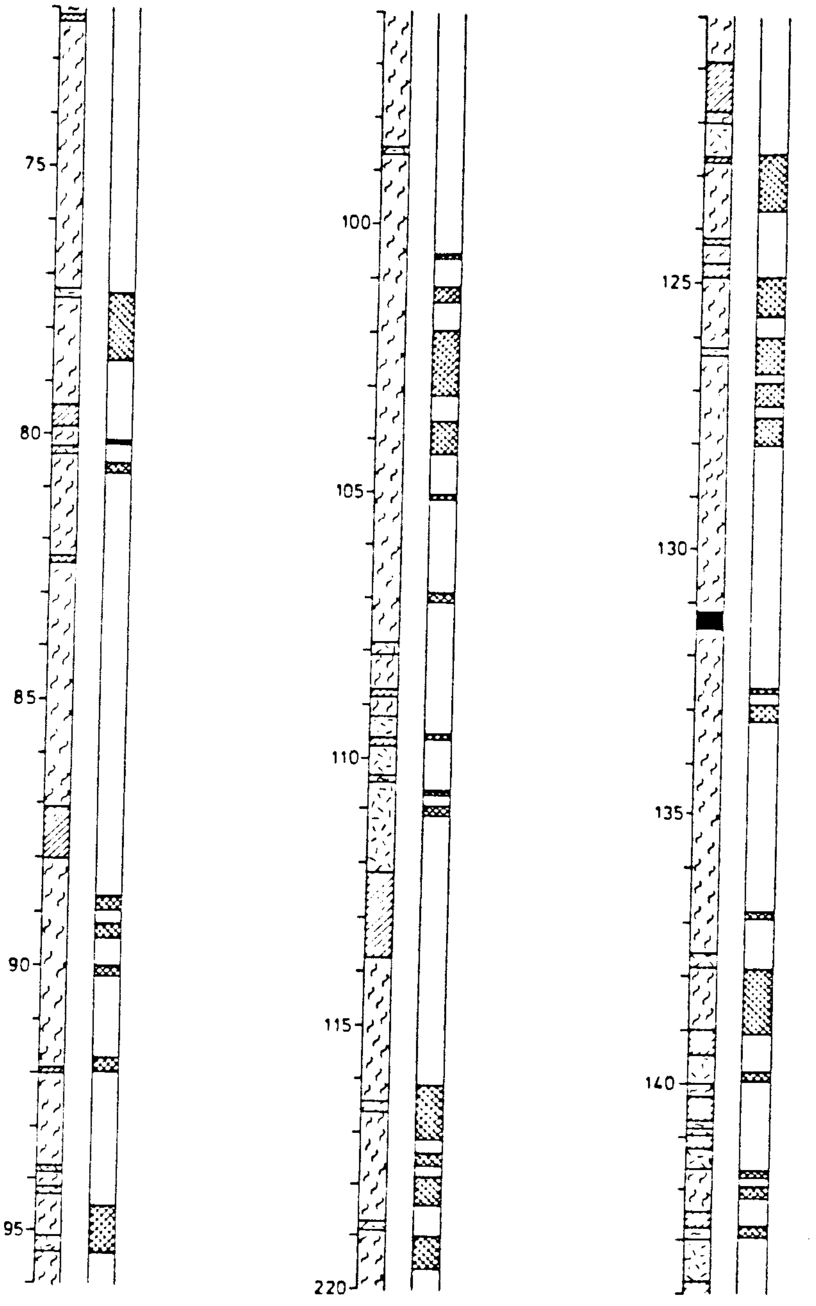


Fig. 32. Core mapping of borehole K1 at Studsvik. Rocktypes (cont.) and crushed zones are distinguished. (Legend see page 65).

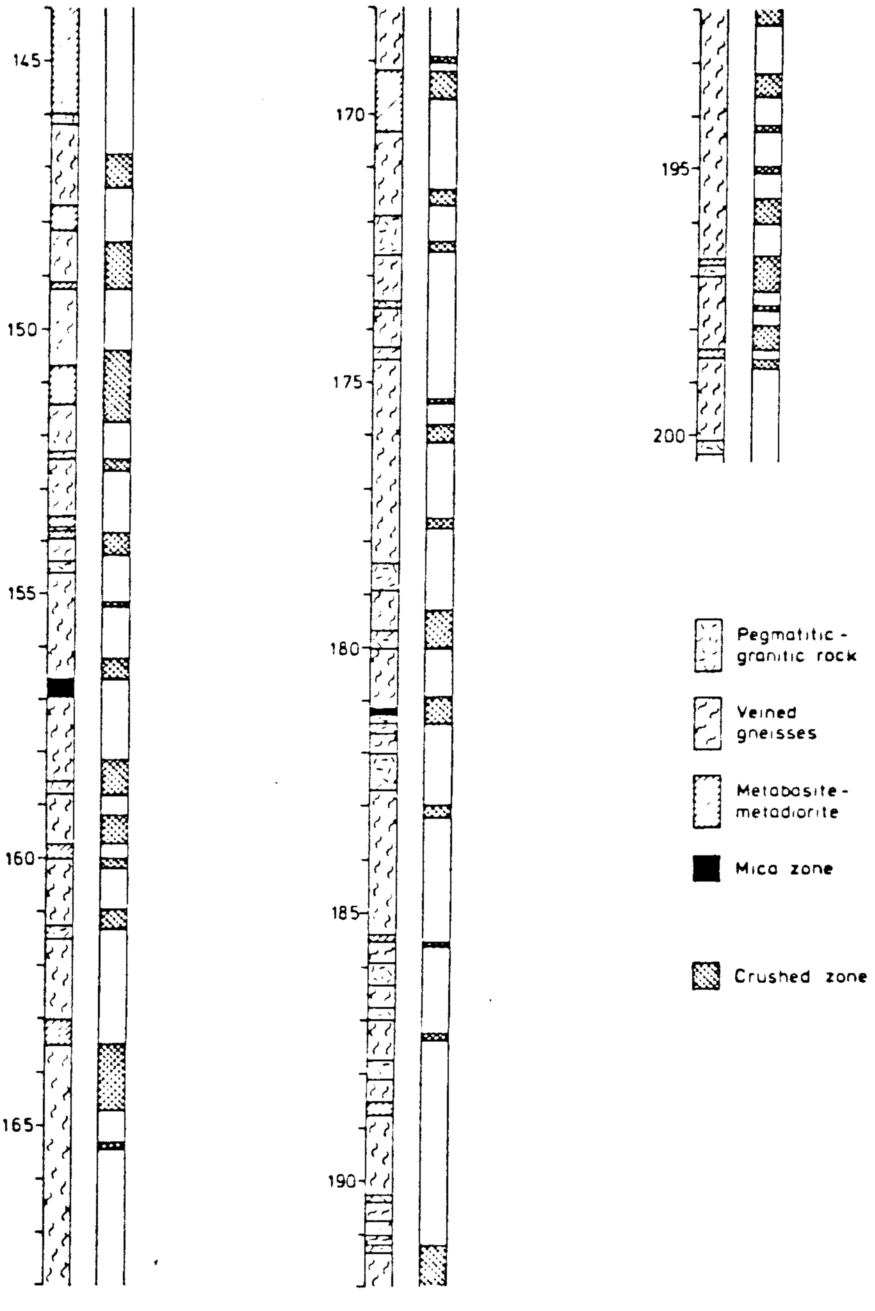


Fig. 32. Core mapping of borehole K1 at Studsvik. Rocktypes (cont.) and crushed zones are distinguished.

4.2. EXTENT OF THE INVESTIGATION

Fissure fillings were scraped from the fissure walls at levels along the core length. Investigated levels are shown in table 9. The filling material was studied by microscope and/or by XRD. Some material was also sampled for sorption studies. These are at present carried out at the Dept. of Nuclear Chemistry, Univ. of Technology, Chalmers, Göteborg.

Open as well as sealed fissures were considered. Most of the fractures seen in the core are coated and open. It is suspected that many fissures have been opened during the drilling operation. This suspicion is strengthened by the fact that also many rough and fresh uncoated fractures are present in the drill core.

4.3. FILLING MINERALS

Core mapping of fissures has been carried out for the 200 metres deep hole. This mapping shows that most coated fissures are thin (usually less than 1 mm) and mostly with a coating of chlorite and calcite. Some of what has been mapped as "chlorite" and "talc" has been checked by XRD. It has then been found that also clay minerals appear in coatings named "chlorite" as well as "talc". Further XRD studies (samples treated by ethylenglycol) made clear that most of the clay minerals were of a swelling type (smectite). The look of this smectite is nearly black and valvet like. The black colour could be due to a mixing with organic material.

It is also evident that smectite is a main fissure filling mineral together with calcite and chlorite. Other filling materials observed are feldspar, pyrite, palygorskite and some mica. To find out the frequency of smectite and other minerals mapping of a core interval (50-125 m) was carried out, the result which is shown in fig. 33. A comparison between open and sealed fractures has been omitted due to the difficulties in deciding whether a fracture originally was open or sealed in situ. This is

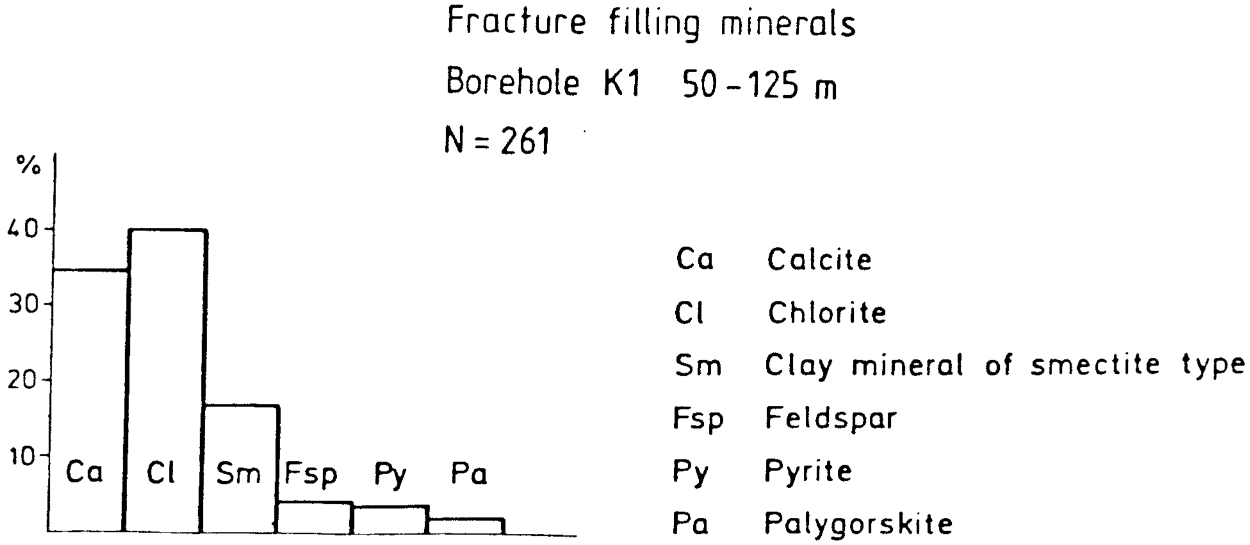


Fig. 33. Frequency diagram for fissure filling minerals at Studsvik.

especially difficult as clay mineral coating is common which makes the fracturing very easy during the drilling operations. However, it is quite evident that the feldspar is most frequent in the sealed fractures. In contrast to this has palygorskite only been observed within open fractures.

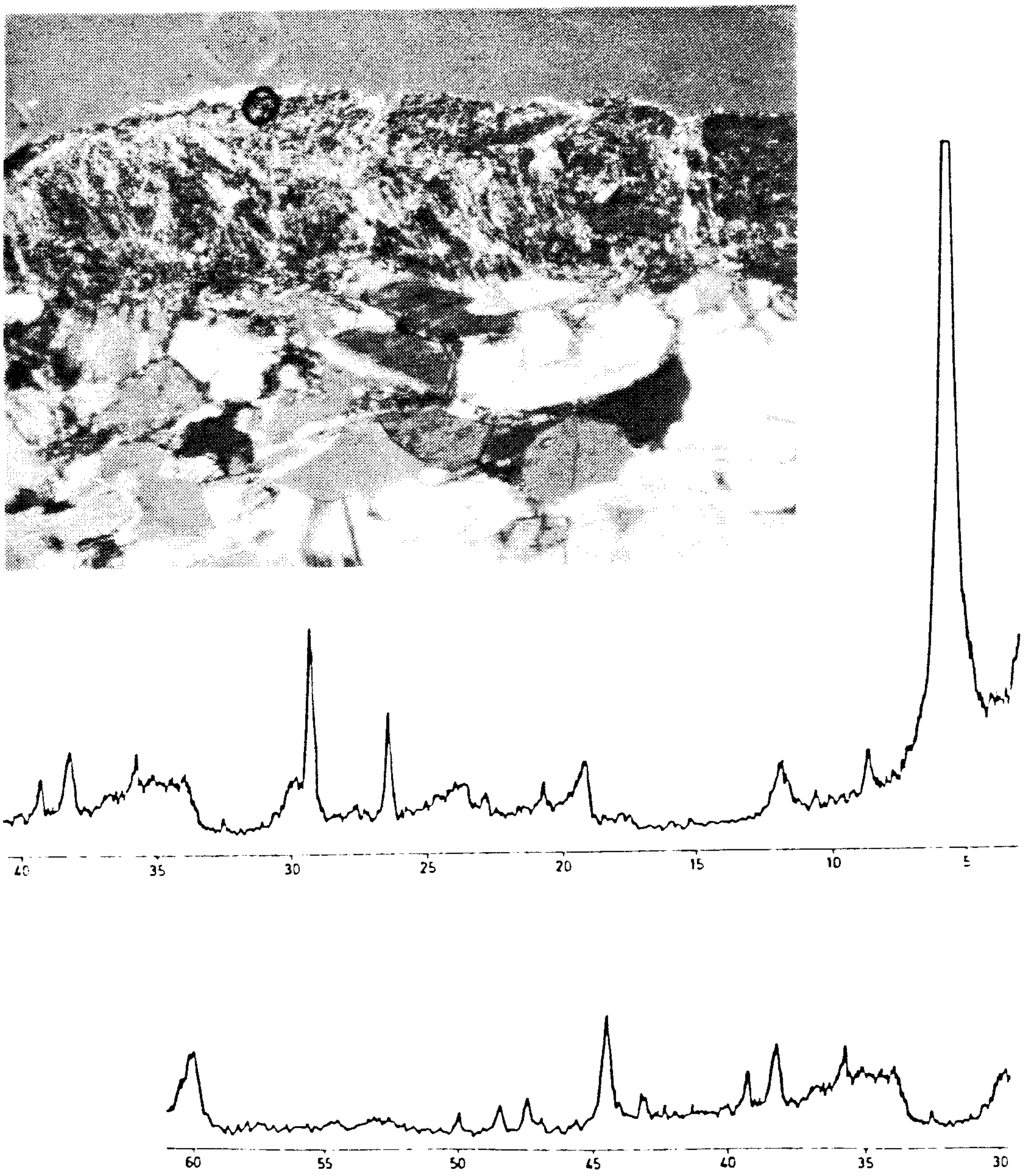


Fig. 34. Microphotograph and X-ray diffractogram showing smectite as fissure filling in sample 104.2 (the fibrous, dark grey material seen in the upper part of the photo).

It has not been possible to distinguish different mineral generations of filling material. At level 104.2 m, which is suggested to be the fracture which is used during the in situ experiments (Landström, in progress), the filling material is smectite, calcite and quartz (Fig. 34). However, quartz has only been registrated on the XRD and has probably been scraped from the fissure wall during the sampling. The filling is dominated by smectite (Fig. 34). When treated by ethylenglycol a small content of chlorite was identified together with smectite and calcite.

4.4. CONCLUSION

As smectite as well as calcite can be deposited at low temperatures and pressures a recent age for these minerals can not be ruled out. Some of the present waters are saturated in respect of calcite. Only one generation smectite and calcite is verified.

To find out if smectite is a stable mineral phase within the present water environment, sampled waters have been plotted in a Helgesson(1971) stability diagram. This shows that most of the water samples allow kaolinite as a stable mineral phase. However, the montmorillonite (smectite) field is very close to the plots representing the water analyses (Fig. 35). The water also plots within the quartz saturation field.

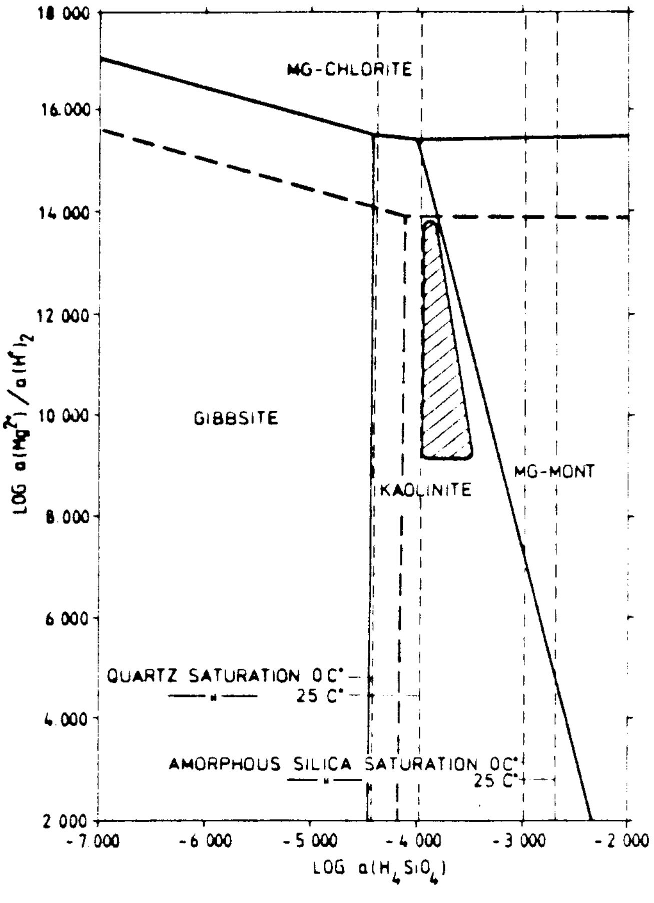


Fig. 35. Stability diagram of the system HCl-H_2O-Al_2O_3--CO_2-MgO-SiO_2 at 0°C (full core) and 25°C (broken line). According to Helegsson (1971). Ruled area includes analysed waters (Landström, 1980).

Table 10. Analysed fissure fillings from Studsvik.

Borehole	level[x)]	open/sealed	Dip[xx)]	Identified minerals	Microscopy	XRD	sorption test
K1 60°	5.4	open	20	Ca,Q,Pa		x	x
"	11.9	sealed	30	Ca,Q,Cl,Pa		x	x
"	12.6	open	0	Sm,Ca,Q			
"	17.7	sealed		Ca,Q,Cl,Il		x	
"	17.9	open		Cl			
"	29.3	open	70,30	Ca,Q,Cl	x	x	
"	42.5	sealed	50	Ca,Q,Cl	x		
"	74.9	open	40	Ca,Q,Py		x	x
"	79.9	open	30	Sm,Ca,Q		x	x
"	94.9	open	40	Ca,Q		x	
"	102.3	open	CZ[xxx]	Ca,Q,Cl		x	
"	104.2	open	0,30	Sm,Ca,Cl	x	x	x
"	116.7	open	CZ[xxx]	Cl,Ca,Q		x	x
"	123.3	open	10	Ca,Q,Cm		x	
"	139.8		20	Ca,Cl,Cm,Py		x	x
"	146.2	sealed	60	Ca,Cl,Q		x	x
"	148.5	open	30	Ca,Q,Sm		x	
"	160.2	open	15	Sm,Q,Cl	x	x	

Table 10. (cont.)

Borehole	level$^{x)}$	open/sealed	Dip$^{xx)}$	Identified minerals	Microscopy	XRD	sorption test
Kl 60°	165.5	open	10,30	Ca,Q, Cl		x	
"	169.25	open	30	Q,Sm,Ca,Cl		x	
"	169.4	open	40-50	Ca,Q,Cl,Sm	x		
"	172.8	open	40	Ca,Q,Cl,Sm		x	
"	179.3	open		Cl,Ca,Q		x	
"	183.1	sealed	10	Ca,Q,	x	x	x
"	185.3	sealed	70	Cl,Q,Py			
"	189.45		20	Ca,Q		x	
"	193.6	open	70	Ca,Cl	x	x	
"	198.0	sealed	30	Ca,Q,Cl		x	
"	198.25	open	?	Bi,Q	x	x	

x) core length in metres

xx) deviation from core axis in degrees

xxx) crushed zone

xxxx) sample for sorption studies (Allard, in progress)

Ca = Calcite, Q = Quartz, Sm = Smectite, Cl = Chlorite, Py = Pyrite, Pa = Palygorskite

Bi = Biotite, Il = Illite, Cm = Unidentified clayminerals

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Identification, chemistry and dating
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Sven Åke Larson
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