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Fissure fillings from Gideå, central Sweden

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Gothenburg, Sweden August 1983

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A list of other reports published in this series during 1983 is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28) 1980 (TR 80-26), 1981 (TR 81-17) and 1982 (TR 82-28) is available through SKBF/KBS.

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SUMMARY

This report presents results from a fissure filling mineral study from a KBS test site at Gideå, eastern Sweden. Most work has been concentrated on boreholes Gi 2 and Gi 4. The former borehole has been drilled within a discharge area and the latter within a recharge area.

The most frequent fissure filling minerals at Gideå are calcite, chlorite, pyrite, laumontite, stilbite, smectite, quartz and epidote. Potentially "young" minerals, i.e. minerals which can be formed during present conditions, are smectite, calcite and quartz, Equilibrium calculations show that these minerals can be stable in the water analysed from Gideå. In borehole Gi 2, the water exhibits a greater equilibrium with existing minerals in the fissures than water from Gi 4. This is due to the recharge of the water in Gi 4 and discharge of the water in Gi 2. When carbonate saturated water penetrated through the bedrock, calcite precipitated within the more superficial portions of the rock. However, both calcite and zeolite fissure fillings are associated with certain zones in the drill holes.

A large number of fractures can be concluded to be of post-Jotnian age. Stilbite, calcite and smectite are associated with these fractures. Laumontite can also be assumed to belong here. The dolerites in the area exhibit a high fracture frequency but a relatively low hydraulic conductivity. This is due to the fact that smectite is very prevalent in the dolerite fractures, sealing the fractures.

Several generations of fracturefilling minerals (above all calcite) have been found in a single fracture. Both textural and chemical properties distinguish them, which makes it likely that there are large age differences between them.

Stable isotope analyses of fissure filling calcites indicate that there are three different groups of calcite. Most of the calcites could not have been precipitated from water of present-day isotope composition at Gideå, whereas recent calcite may be found in one of the groups. Another group of calcite was precipitated during hydrothermal conditions.

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1. INTRODUCTION

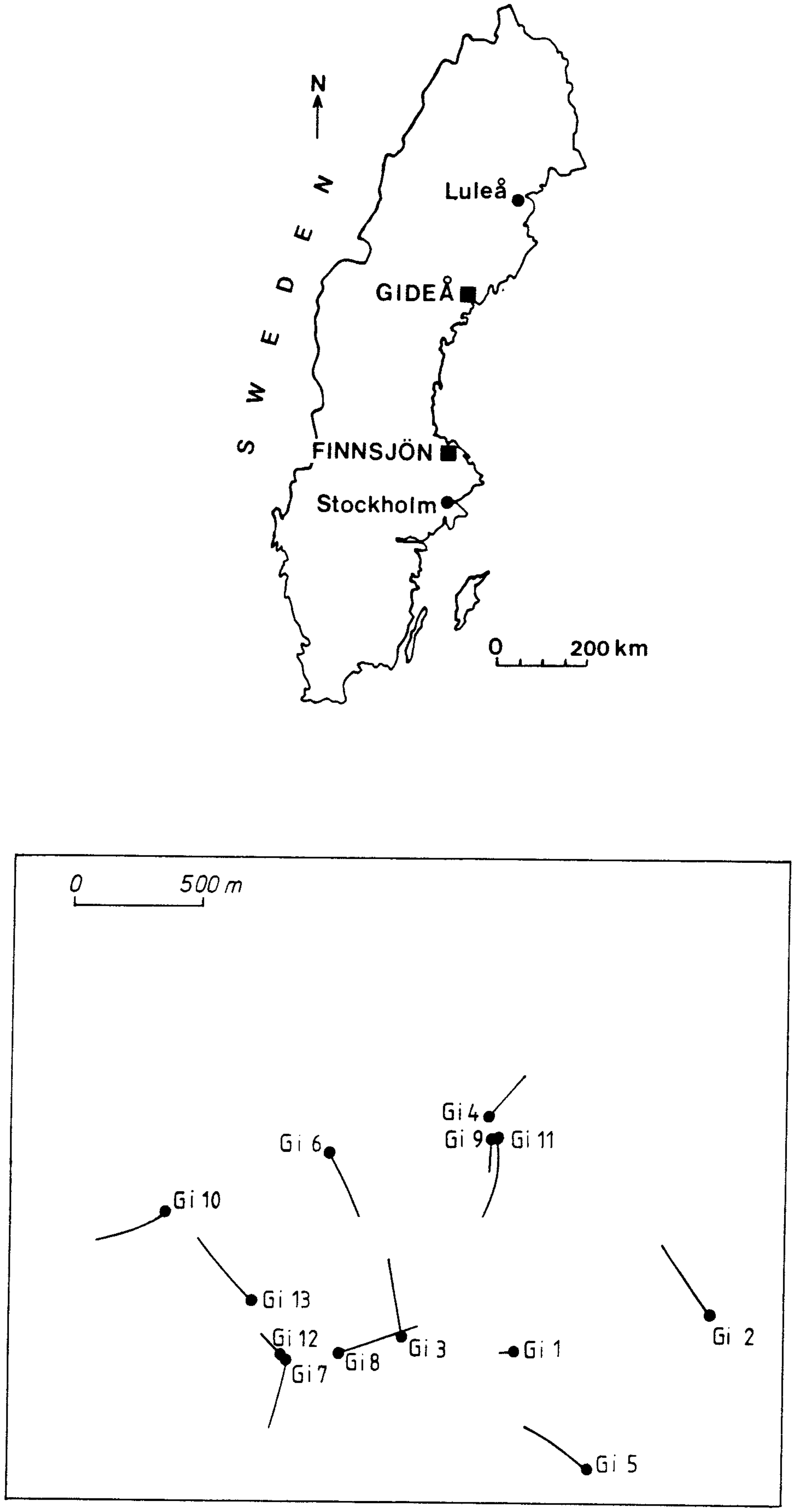
The study site at Gideå is situated approximately 35 km north of Örnsköldsvik in Västernorrland County (Fig. 1) and covers an area of 4 km^2 in flat terrain. Thirteen holes, approximately 700 m long each, have been drilled on the site. The bedrock is dominated by gneisses of sedimentary origin. They were subjected to alteration (migmatitization) more than 1 800 million years ago, whereby the original structures were obliterated and more or less granitic rocks were formed (Th. Lundqvist, 1980).

In addition to migmatites, pegmatites occur on the site (Albino et al, 1982). These are granitic, coarse-grained and massive rock types. They occur both in metre-wide dikes and in massifs.

The third rock type on the site is a dolerite. This rock type was formed by the intrusion of basic magma into the existing bedrock approximately 1 200 million years ago (Welin & Lundqvist, 1975). The dolerites form occasional steeply-dipping dykes that intersect the site in an E-W direction. The dolerite is the youngest rock type on the site and can be assumed to be the one that is contemporary with the last hydrothermal event.

The following papers have been published to date from the investigations at Gideå. A geological/geophysical report on the surface and depth investigations at Gideå has been published by Albino et al (1982). Data from the drill holes within the study site have been compiled by Albino & Nilsson (1982). An evaluation of the investigations at Gideå has been published by Ahlbom et al (1983). An account of the water chemistry at Gideå has been published by Allard et al (1983).

The present report presents a study of which fissure filling minerals are present on the site at Gideå and how these minerals occur in the fissures (chap. 2). Furthermore, mineral-chemical data are presented on both major elements and stable isotopes (for carbonates).



1. Location of the study site and the drill holes at Gideå.

Chapter 3 presents statistics on sealed fissure fillings and fissure directions. Chapter 4 deals with a computer simulation of the equilibrium conditions that prevail between water in the drill holes and fissure filling minerals. The last chapter (5) presents a discussion and a summary.

2. FISSURE FILLING MINERALOGY

The purpose of this study is to identify fissure-filling minerals in detail. A further purpose is to investigate the inter-relationships of the fissure-filling minerals and the equilibrium conditions prevailing between water and certain fissure-filling minerals.

Since fissure-filling minerals can be formed under different physical conditions (pressure and temperature), certain minerals can be characterized as high- or low-pressure/temperature minerals. Through studies of fissure-filling minerals within the study sites, it is therefore possible to obtain not only a charcterization of the chemical environment in which the water finds itself, but also a picture of the geological evolution of the site. The chemical composition of the water and the type of fissure-filling mineral in a water-conducting fissure are parameters that largely control the transport rate of radioactive nuclides. This knowledge constitutes an important factor in the future assessment of the barrier properties the rock will present to a waste repository.

Some 50 samples have been taken from the drill cores on the Gideå site for microscopy, microprobe analyses, X-ray diffraction and isotope analyses. Since water analyses are available from the drill holes Gi2 and Gi4, these drill holes were selected for sampling. Sampling was done to obtain a good idea of the fissure-filling minerals in open versus sealed fissures, at different depths both in the para-gneiss and in the dolerite dykes. The samples were also correlated with the five test-pumped levels in each drill hole. Identification of the fissure-filling mineral phases shows that calcite, chlorite, laumontite and pyrite are the most common. Their relative prevalence varies between the drill holes and between different sections within the drill holes. Other minerals include stilbite, epidote, smectite and quartz. In other words, the fracture-filling minerals include carbonates, sulphides and silicates. The latter comprise mainly zeolites and clay minerals.

2.1 Microscopy

A number of specimens were prepared for microscope studies of the fissure fillings. Identified mineral phases in fissures from the drill holes Gi2 and Gi4 are reported in table 1. The relative age of identified minerals is ranked, where the figure 1 represents the oldest mineral in a fissure filling etc. As is evident, quartz and epidote have always been found to be the oldest fracture-filling minerals. Several generations in one and the same fissure have been found of calcite (3), stilbite (2), (Fig. 2), and chlorite (2).

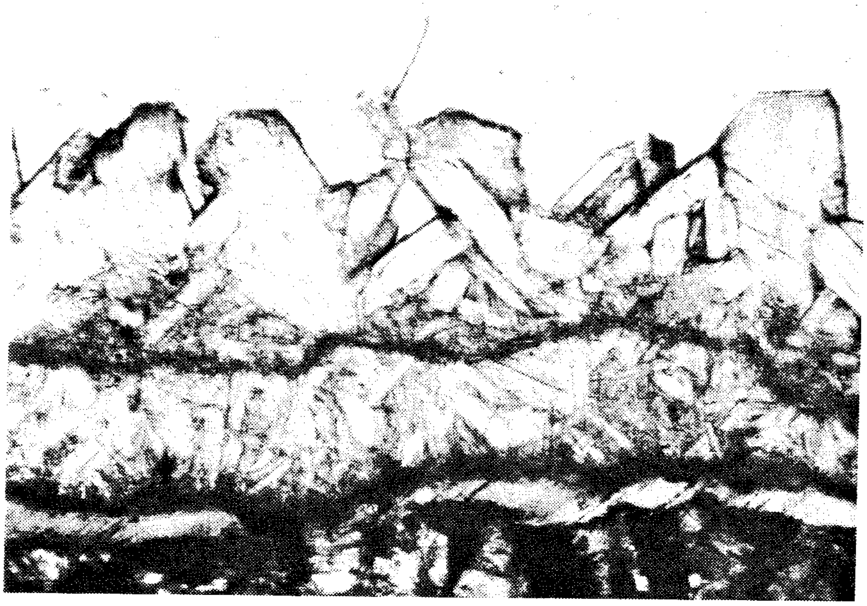
One of the calcite generations is overcut by fissures with hydrothermal fissure mineralizations and is thus considered as a Precambrian sealing. There is also calcite that overcuts the hydrothermal mineralizations, and thus can be potentially young calcite sealings. Table 1 shows that the calcite can be both the oldest and the youngest mineral in the complex fracture mineralizations. The isotope chemistry studies of calcite (chap. 2.3) show that at least three groups of calcites occur as fissure sealings. The calcites that have been judged to constitute hydrothermal sealings or sealings precipitated from a water completely different from the present-day water in the drill holes have been found by microscopy to contain a large quantity of deformation twins. Late or recent calcite in fissure fillings mostly lack twins. Laumontite and stilbite are mostly present together with calcite. Pure laumontite sealings have been found in a few cases, however. Laumontite has been encountered as a fissure-filling mineral in most samples. However, laumontite is missing from the fissures in the dolerite that has been investigated. Stilbite is the zeolite that is only seen as a fissure-filling mineral in the dolerite (Fig. 3). The composition of the plagioclase in the host rock is considered to be able to determine which zeolites are formed (I. Barnes, personal communication 1983) in such a manner that stilbite is favoured by Ca-plagioclase. Since stilbite can be regarded as having been formed from late magmatic solutions at the time of the intrusion of the post-Jotnian dolerite, it is probable that the laumontite was formed at the same time. Small quantities of lawsonite have been detected optically in

Table 1. Identified fissure-filling minerals. Relative ages are given by figures where 1 is the oldest etc. The optical microscopy has been supplemented by XRD (X-ray diffraction) in some cases. D = Fracture in dolerite; x = open fracture

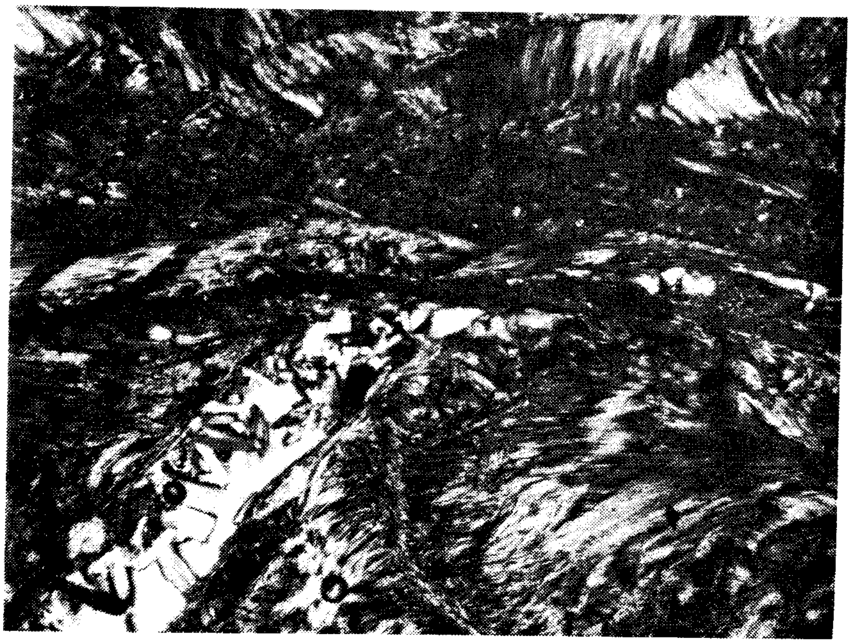
Sample	Calcite	Laumontite/ Stilbite	Pyrite	Chlorite	Quartz	Epidote	Magnetite
Gi 2:31.3	2.3	4				1	
45.2^x		2?		1?			
92.6^x		1					
166.2	1	2	2				
199.oD	1,2	2	1	1			
200.5D				1			
223.0D				1,2			
243.6	1,3,4		1?	2			
280.1a	1	1	1				1
280.1b	2	2	2	2	1		
346.5		1					
399.0	2			3	1		
400.7	2				1		
412.0^x	1				1		
472.7^x	1						
480.9^x	1,2			1			
489.5	1						
544.6D	3	1,2					
556.4^x		1		1,2	1		
559.5		1					
637.6D	2	1		1			
641.0D	1	1		2			
Gi 4:28.8	1	2					
126.6	2				1		
137.7^x	1						
321.6	1						
445.5^x	2	1		1			
525.1	1	2			1		
608.7^x	1	2					
690.4	2				1		

<u>XRD</u>:

Gi 2:	182.8	Laumontite, calcite
	199.5	Stilbite
	200.5	Analcime, chlorite, smectite
	207.7	Apophyllite, muscovite, (laumontite, quartz)
	223.0	Smectite, chlorite, (kaolinite?)
	280.1a	Laumontite, quartz, K-feldspar, illite
	489.5	Quartz, plagioclase, K-feldspar, mica
	544.b	Stilbite, (smectite)
	559.5	Laumontite
	586.3	Mixed clay, (smectite, laumontite, quartz)
	627.2	Laumontite
	641.0	Stilbite, smectite
Gi 4:	226.0	Laumontite, (quartz, kaolinite?)
	302.2	Muscovite, quartz, plagioclase
	525.1	Laumontite
Gi 3:	226.0	Stilbite, (clay mineral)
Gi 6:	17.8	Stilbite, (clay mineral)
Gi 7:	527.9	Stilbite, (illite)
	585.0	Laumontite
	597.2	Stilbite, (clay mineral).



2. Two generations of stilbite (lower part of the photograph) in fissure Gi 2: 544.b. The upper part of the photograph shows a younger calcite filling.



3. Fissure-filling stilbite (light) cut by a later fissure sealed by chlorite and smectite in dolerite sample Gi 2: 199.5.

the sample Gi4:690.4. In contrast to Finnsjön (Tullborg & Larson, 1982), prehnite and pumpellyite are lacking. The different parageneses may indicate a slightly lower temperature and possibly higher pressure during formation of these minerals than was the case at Finnsjön.

Chlorite appears as two texturally different generations. It is also possible to reveal two generations by means of mineral chemistry analyses (see chap. 2.2). Chlorite is sometimes the youngest, sometimes the oldest mineral in the complex fracture fillings. Pyrite occurs as idiomorphic crystals and is, for the most part, contemporary with or older than the laumontite fillings (Fig. 4).

2.2 Mineral chemistry

Mineral-chemical analyses have been carried out with a microprobe on mineralizations of calcite, chlorite, smectite, laumontite and stilbite. Analyses of calcite, laumontite and stilbite were carried out by C. Ålinder at SGU´s (the Geological Survey of Sweden) mineral chemistry laboratory in Uppsala, while the chlorite and smectite analyses were carried out by J. Duplay at Universite´Louis Pasteur, Strassbourg.

The analyses of calcite and laumontite are presented in tables 2 and 3. A total of twelve calcite crystals from different depths in drill holes Gi2 and Gi4 were analyzed. Two points in each crystal were examined. Table 2 shows that the calcite is very pure with respect to interchangeable elements.

The calcites that can be considered as hydrothermal precipitation (on the basis of textural and stable isotope considerations) have been plotted in a graph (Fig. 5) where $CaO/(MgO+FeO+MnO)$ for the calcites is plotted versus depth. Samples from Finnsjön (Tullborg & Larson, 1982) have also been included in the figure. The graph shows a correlation between the purity of the calcites and depth, purity increasing with depth. This can probably be explained by the competition that occurs between different mineral phases for, especially, available MgO under hydrothermal conditions, whereby the water is

Table 2. Microprobe analyses of calcite from different depths in Gi 2 and Gi 4. Contents are given in weight-%.

Sample	BaO	CaO	MgO	MnO	SrO	FeO
Gi 2: 31.1	-	55.0	0.2	0.1	0.1	< 0.1
"	-	55.6	0.3	0.1	0.1	< 0.1
:199.5	-	56.0	0.2	<0.1	< 0.1	-
"	-	56.2	0.2	-	< 0.1	< 0.1
:243.6	0.1	55.1	0.4	0.7	-	-
"	0.1	54.5	0.4	0.5	< 0.1	0.2
:399.0	-	55.6	0.4	-	0.1	< 0.1
"	-	55.4	0.3	<0.1	-	0.1
:400.7	-	54.8	0.2	-	-	< 0.1
"	0.1	54.6	0.2	<0.1	<0.1	< 0.1
:472.7	0.2	55.1	0.3	<0.1	-	0.1
"	-	55.2	0.2	0.2	-	< 0.1
:489.5	0.1	55.3	0.4	< 0.1	< 0.1	-
"	0.1	54.8	0.3	< 0.1	< -	< 0.1
:544.6	<0.1	55.9	0.3	< 0.1	< 0.1	< 0.1
"	0.2	55.9	0.3	< 0.1	-	< 0.1
:641.0	0.1	55.2	0.3	< 0.1	< 0.1	-
"	-	55.4	0.3	0.1	-	0.1
:690.4	0.1	55.1	0.3	0.1	< 0.1	-
"	0.1	55.4	0.3	< 0.1	< 0.1	0.1
Gi 4: 28.8	-	55.4	0.3	0.1	-	-
"	-	55.5	0.4	< 0.1	< 0.1	< 0.1
:321.6	-	55.6	0.4	0.1	< 0.1	0.1
"	-	55.8	0.4	0.1	0.1	0.1

Table 3. Analyses of laumontite from Gideå, Finnsjön (Tullborg & Larson, 1982). Sespe Hot Springs (Mc Culloh et al., 1981), New Zeeland (Coombs, 1952) and Japan (Seki et al., 1969). Contents in weight -%.

	Gideå Gi 2:559.2	Finnsjön Fi 5:264.4	Sespe Hot Springs (hydrothermal)	New Zeeland (metamorphic)	Japan (hydrothermal)
SiO_2	55.3	51.2	50.6	50.6	51.0
Al_2O_3	21.3	22.0	22.0	21.5	21.5
CaO	11.3	11.2	11.5	10.7	12.2
FeO	-	-	>0.1	0.7	0.1
K_2O	0.1	0.5	0.3	0.5	0.1
Na_2O_3	-	0.3	0.2	1.0	0.3

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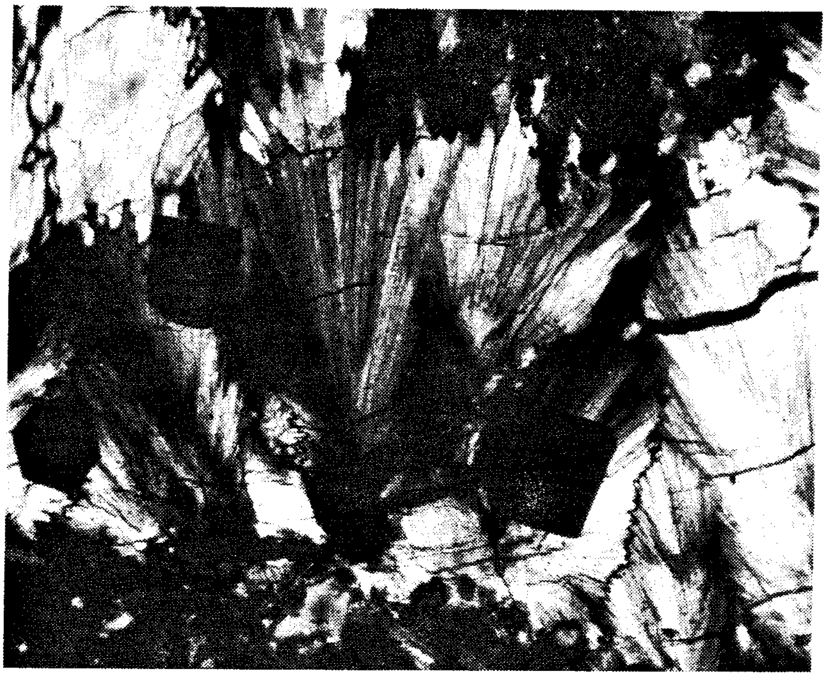
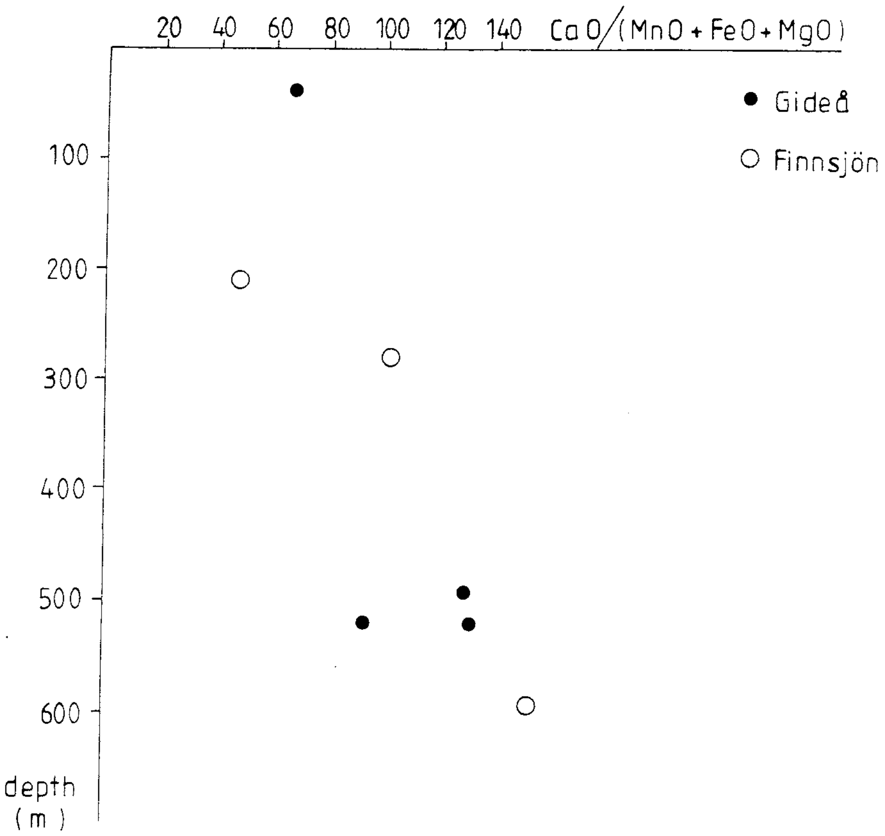


4. Idiomorphic pyrite crystals in fissure-filling lauomontite from Gi 2:280.



5. Variation in the ratio CaO/(MgO + FeO + MnO) for calcites taken from different depths. All samples are from calcites considered to be of hydrothermal origin.

gradually depleted in magnesium as the surface water penetrates to greater depth in the rock.

Only one laumontite sample has been analyzed (table 3). This sample has been compared with laumontite analyses from Finnsjön (Tullborg & Larson, 1982), Sespe Hot Springs, U.S.A. (McCulloh et al, 1981), New Zealand (Coombs, 1952) and Japan (Seki et al, 1969). These comparisons show that the laumontite from Gideå is much richer in silicon than other laumontites, which have low sodium and potassium contents (Other fissure-filling minerals at Gideå have also been found to have anomalously high silicon contents).

One of the samples (Gi4:28.8) was identified as laumontite on the X-ray diffractogram, but the analyzed crystal from the sample proved to have a chemistry similar to that of other stilbites analyzed. The probable explanation for this is that the sample scraped for X-ray analysis contained both phases, but with a heavy preponderance of laumontite.

Stilbite is a zeolite mineral with a relatively high water content and can be formed at relatively low temperatures from silicon-rich solutions. Four stilbite samples were analyzed (Table 4). Three of these samples were taken from fissures in Gi2 and one sample from Gi4. The SiO_2/Al_2O_3 contents are found to be low overall (cf. Kostov, 1968).

Tables 5 and 6 show analyses (performed by J. Duplay, Strassbourg) of chlorite and smectite from five fractures from Gi2 and Gi3. One of the fractures from Gi2:199.5 (samples 1-6) is thin but contains both chlorite and smectite. The other fracture is thicker and contains chlorite and smectite in an edge zone (samples 7-8) while the central portion (samples 9-12) contains an unidentified clay mineral. The chlorite is Al- and Mg-rich and the smectite is Mg-rich.

Table 4. Microprobe analyses of stilbite. Contents are given in weight-%.

	Gi2:199.5	Gi2: 544.6	Gi2:641.0	Gi4:28.8
SiO_2	59.5	61.8	62.0	61.1
Al_2O_3	16.8	16.8	16.9	16.8
CaO	8.7	8.1	8.4	8.6
FeO	-	0.5	0.1	-
K_2O	< 0.1	<0.1	<0.1	0.1
Na_2O	0.6	0.6	0.3	0.2

Table 5. Microprobe analyses of chlorites. Elements are given in weight-%.

	Si	Al	Fe	Mg	Ca	K
Gi 2:199.5-1	39.30	31.4	10.7	18.6	0.1	-
Gi 2:199.5-2	38.3	29.8	10.1	20.2	0.1	1.5
Gi 2:199.5-6	39.5	31.1	9.2	20.1	0.1	-
Gi 2:199.5-7	40.3	24.4	8.0	27.3	0.1	-
Gi 2:223-1	34.9	13.4	34.9	16.3	0.2	0.4
Gi 2:223-2	42.2	25.8	10.5	21.5	-	-
Gi 2:200.5-1	36.3	17.6	25.6	20.5	-	-
Gi 2:200.5-2	37.3	16.4	25.9	20.2	0.2	-
Gi 2:200.5-3	39.8	14.6	23.0	22.3	0.4	-
Gi 2:200.5-4	42.6	20.1	7.1	30.1	0.1	
Gi 3:462.3-1	40.3	34.5	13.4	11.9	-	-
Gi 3:462.3-2	36.2	17.8	37.6	7.5	0.1	0.1
Gi 3:462.3-3	37.4	17.5	32.8	11.1	0.2	1.0
Gi 3:462.3-4	34.6	16.7	37.9	9.7	-	1.1
Gi 3:462.3-5	41.1	27.9	13.7	17.3	0.1	-

(Samples 199.5-1 to 6 belong to a single fissure and 199.5-7 to 8 to a small fissure perpendicular to the other one).

Table 6. Microprobe analyses of smectites. Elements are given in weight-%.

	Si	Al	Fe	Mg	Ca	K
Gi 2:199.5-3	51.4	21.2	5.6	21.6	0.2	-
199.5-4	51.7	18.7	5.6	23.8	0.1	-
199.5-5	56.6	21.1	5.4	16.7	0.2	-
199.5-8	52.9	18.2	6.6	22.1	0.2	-

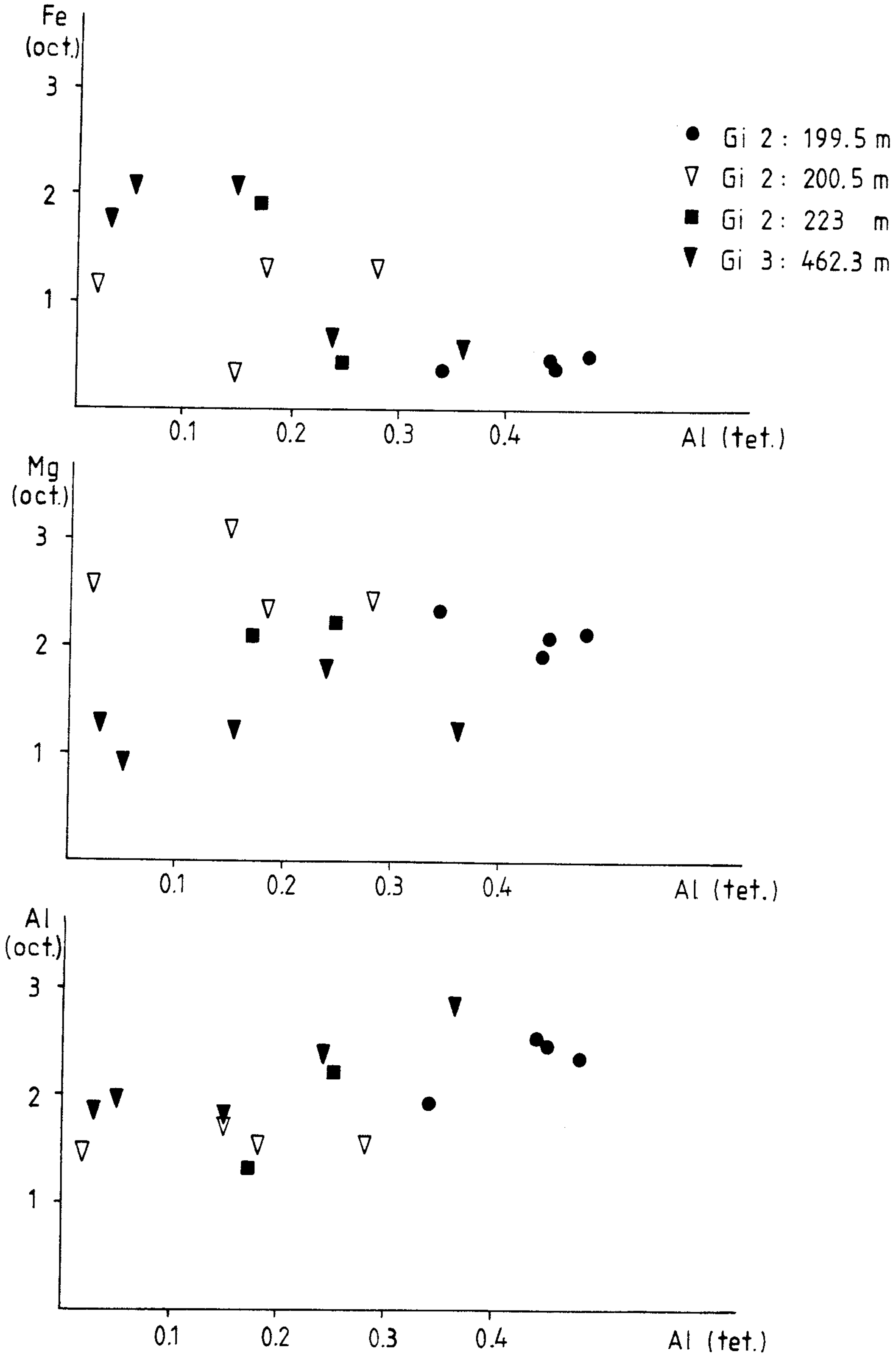
(Samples 199.5-3 to 5 belong to a single fissure and 199.8 belongs to a small fissure perpendicular to the other one).

Table 7. Structural formulas calculated for chlorite and smectite samples.

Sample no	Tetrahedral	Octahedral	Inter-layer
Gi 2: 199.5-1	$Si_{3.56}$ $Al_{0.44}$	$Al_{2.52}$ $Fe''_{0.49}$ $Mg_{1.945}$	$Ca_{0.004}$
Gi 2: 199.5-2	$Si_{3.52}$ $Al_{0.48}$	$Al_{2.38}$ $Fe''_{0.47}$ $Mg_{2.14}$	$Ca_{0.004}$
Gi 2: 199.5-3	$Si_{3.42}$ $Al_{0.58}$	$Al_{0.89}$ $Fe'''_{0.18}$ $Mg_{1.66}$	$Ca_{0.007}$
Gi 2: 199.5-4	$Si_{3.45}$ $Al_{0.55}$	$Al_{0.76}$ $Fe'''_{0.19}$ $Mg_{1.84}$	$Ca_{0.006}$
Gi 2: 199.5-5	$Si_{3.67}$ $Al_{0.33}$	$Al_{1.09}$ $Fe'''_{0.175}$ $Mg_{1.25}$	$Ca_{0.007}$
Gi 2: 199.5-6	$Si_{3.55}$ $Al_{0.45}$	$Al_{2.47}$ $Fe''_{0.42}$ $Mg_{2.09}$	$Ca_{0.004}$
Gi 2: 199.5-7	$Si_{3.66}$ $Al_{0.34}$	$Al_{1.96}$ $Fe''_{0.36}$ $Mg_{2.86}$	$Ca_{0.004}$
Gi 2: 199.5-8	$Si_{3.53}$ $Al_{0.47}$	$Al_{0.79}$ $Fe'''_{0.22}$ $Mg_{1.705}$	$Ca_{0.007}$
Gi 2: 223-1	$Si_{3.83}$ $Al_{0.17}$	$Al_{1.36}$ $Fe''_{1.93}$ $Mg_{2.07}$	$Ca_{0.02}$ $K_{0.03}$
Gi 2: 223-2	$Si_{3.75}$ $Al_{0.25}$	$Al_{2.24}$ $Fe''_{0.47}$ $Mg_{2.25}$	

Table 7. (cont.)

Sample	Tetrahedral		Octahedral			Inter-layer	
Gi 2: 200.5-1	$Si_{3.72}$	$Al_{0.28}$	$Al_{1.59}$	$Fe''_{1.32}$	$Mg_{2.425}$		
Gi 2: 200.5-2	$Si_{3.82}$	$Al_{0.18}$	$Al_{1.56}$	$Fe''_{1.335}$	$Mg_{2.40}$	$Ca_{0.01}$	
Gi 2: 200.5-3	$Si_{3.98}$	$Al_{0.02}$	$Al_{1.50}$	$Fe''_{1.16}$	$Mg_{2.57}$	$Ca_{0.028}$	
Gi 2: 200.5-4	$Si_{3.85}$	$Al_{0.15}$	$Al_{1.74}$	$Fe''_{0.32}$	$Mg_{3.14}$	$Ca_{0.004}$	
Gi 3: 462.3-1	$Si_{3.64}$	$Al_{0.36}$	$Al_{2.89}$	$Fe''_{0.60}$	$Mg_{1.24}$		
Gi 3: 462.3-2	$Si_{3.95}$	$Al_{0.05}$	$Al_{1.98}$	$Fe''_{2.07}$	$Mg_{0.95}$	$Ca_{0.004}$	$K_{0.06}$
Gi 3: 462.3-3	$Si_{3.97}$	$Al_{0.03}$	$Al_{1.90}$	$Fe''_{1.75}$	$Mg_{1.36}$	$Ca_{0.01}$	$K_{0.07}$
Gi 3: 462.3-4	$Si_{3.85}$	$Al_{0.15}$	$Al_{1.78}$	$Fe''_{2.21}$	$Mg_{1.24}$		$K_{0.08}$
Gi 3: 462.3-5	$Si_{3.77}$	$Al_{0.24}$	$Al_{2.43}$	$Fe''_{0.63}$	$Mg_{1.83}$	$Ca_{0.005}$	



6. Octahedral Fe, Mg and Al plotted versus tetrahedral Al for some chlorite samples from Gideå.

The fissure Gi2:200.5 contains chlorite with a very high SiO_2 content in places. This is also the case in sample Gi2:223.

The chlorite from fracture Gi3:462.3 is SiO_2-rich, like the other analyzed chlorites. The relatively high K content indicates, however, that a mixed phase of both illite and chlorite has been analyzed. Proposed structural formulas for identified phases are given in table 7.

One way to differentiate "high-temperature" chlorite from "low-temperature" chlorite has been demonstrated by J. Duplay (1982). Tetrahedral Al is plotted against octahedral Mg and octahedral Fe. When the slope for Fe(oct)/Al(tet) is > 0 and the slope for Mg(oct)/Al(tet) is < 0 the chlorite is considered as "low-temperature type". If the opposite is true the chlorite is considered as "high-temperature type". When the few analyses that are available from one and the same sample are plotted in a graph, a picture is obtained that shows that several generations (types) of chlorite are present. In addition, the figures indicate that both "high-" and "low-temperature" chlorite are present (Fig. 6).

2.3 Stable isotopes

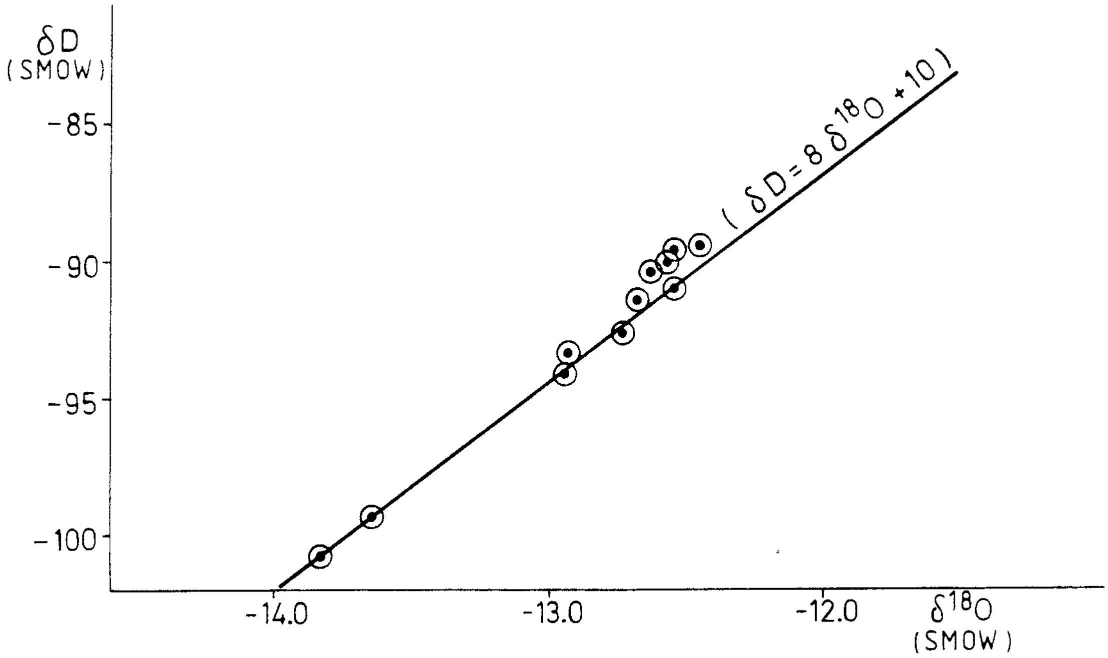
Analyses of the stable carbon and oxygen isotopes have been carried out on a total of 28 calcite samples from fissures in drill cores from the holes Gi2 and Gi4 (Table 8). Water from the same drill holes has been analyzed for oxygen and hydrogen isotopes.

In order to obtain an idea of the water´s origin, δD has been plotted against $\delta^{18}O$ in a graph. In an unaffected meteoric water, the plotted values will be described by the line $\delta D = k\delta^{18}O + \ell$, where $k \approx 8$ and $\ell \approx 10$ for "oceanic" precipitation (Craig, 1961). The analyzed waters from Gideå (Fig. 7) fall roughly along this line. This indicates that the waters analyzed at Gideå have not been affected to any appreciable degree by secondary processes (e.g. mineral-water exchange at elevated temperature etc.).

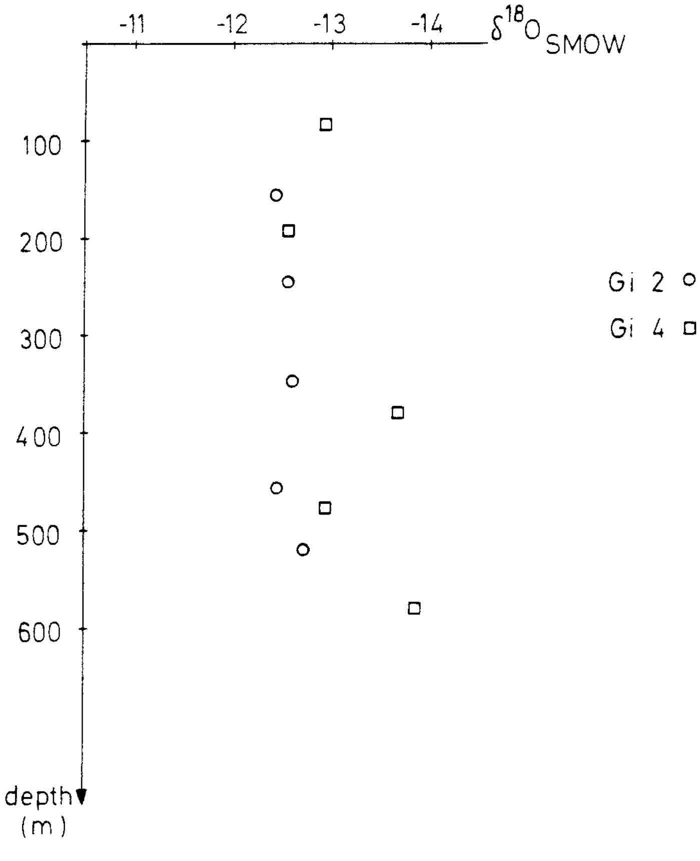
Table 8. $\delta^{13}C$ and $\delta^{18}O$ in fissure-filling calcites from drill holes Gi2 and Gi4.

Borehole: core length (m)	$\delta^{13}C$ PDB	$\delta^{18}O$ PDB	open/ sealed
Gi 2: 31.1-y	-12.1	-19.6	S
: 31.1-0	-11.5	-19.7	S
:199.5-y	+18.1	-14.4	S
:243.6-1	-13.4	-18.7	S
:243.6-3	-12.5	-12.0	S
:280.1	- 4.9	-11.6	S
:299.	- 5.5	-11.7	S
:400.7	-12.7	-13.7	S
:412.0-4	- 7.5	-12.3	OP
:412.0-0	- 5.6	-11.9	S
:463.7	-13.8	-17.1	S
:480.9-1	-14.7	-19.7	S
:480.9-2	-10.8	-13.4	OP
:489.5	- 7.0	-12.7	S
:544.6	- 4.8	-10.1	S
:637.8	- 5.5	-10.1	S
:641.0	- 4.7	-10.1	S
Gi 4: 8.0	- 1.1	-13.0	OP
: 28.7	-11.2	-10.1	S
: 47.0	-11.9	-12.2	OP
: 94.0	-13.3	-14.5	OP
:126.6	- 6.5	-11.42	S
:137.7	-13.6	-11.8	OP
:222.7	-11.7	-11.4	OP
:321.6	-11.6	-19.2	S
:445.5	- 2.2	-11.8	OP
:525.1	-13.9	-18.8	S
:690.4	-12.7	-19.6	S
Calcite fissure filling in Ulvö dolerite	- 7.8	-17.6	

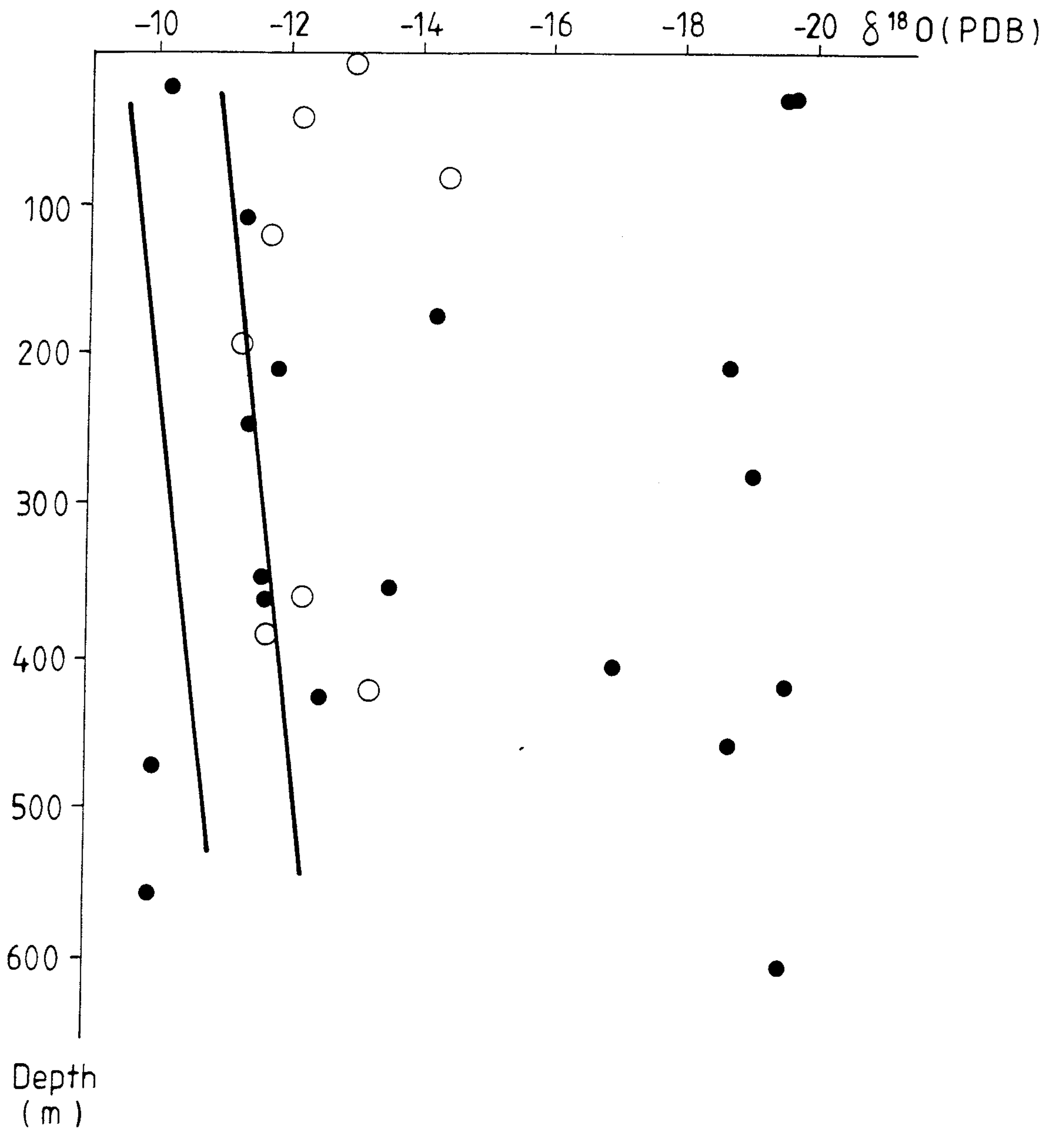
y = younger fissure
o = older fissure
1.2.3 = different generations of calcite in the same fissure (1 is the oldest etc).
S = sealed fissure OP = open



7. $\delta D/\delta^{18}O$ - graph for waters from Gideå. Meteoric water line from Craig (1961).



8. $\delta^{18}O$ (SMOW) for waters from Gideå at different sample depths.



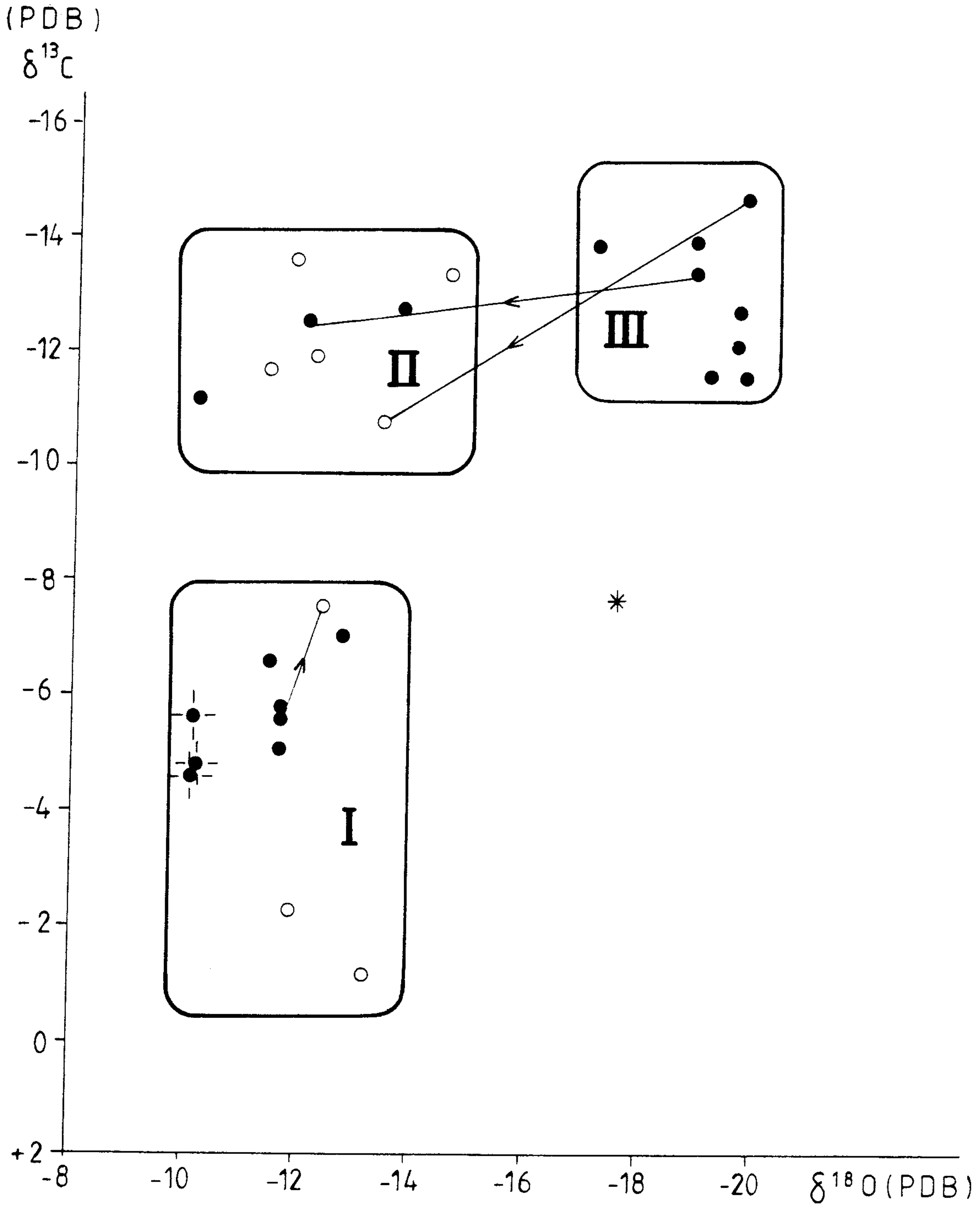
9. $\delta^{18}O$ PDB for fissure-filling calcite taken from different depths at Gideå. Circle = open fissure; dot = sealed fissure.

No clear-cut trend is obtained, when the $\delta^{18}O$ for water is plotted versus sample depth (Fig. 8). The $\delta^{18}O$ values normally vary between -12.6 o/oo and -12.9 o/oo, with the exception of two extreme values (-13.5 o/oo and -13.8 o/oo) in samples taken from borehole Gi4. These two samples exhibit an elevated salinity in comparison with the others.

The $\delta^{18}O$ for calcite varies between -10.1 o/oo and -19.7 o/oo. Calcites that exhibit the lowest $\delta^{18}O$ values always come from fissures that are sealed. The calcite´s $\delta^{18}O$ is plotted against sampling depth in Fig. 9. No correlation is obtained between depth and $\delta^{18}O$. The calcite that can be precipitated from today´s water in the drill holes should fall between the two solid lines. As is evident from the figure, only a few of the analyzed calcites fall within this interval. The majority of the calcites have thus been precipiated from a water which differs from present-day water with regard to isotope composition. It should be pointed out here that most calcites have probably been precipitated over a prolonged period of time, whereby some zoning in isotope chemical composition can occur. When such zoned crystals are scraped in connection with sampling, the analyses represent average values for the sample. This can partially explain why more "open fissure precipitations" do not fall within the interval for recent calcite.

In Fig. 10, the $\delta^{13}C$ of the calcite samples is plotted versus $\delta^{18}O$. The analyses fall into three groups. Group I in the figure has presumably been precipitated from a water that has been mixed with a marine component. This group includes the analyses that were carried out on calcites from fissures in dolerites. One sample from dolerite has not been included in the figure, however. This sample has a very extreme $\delta^{13}C$ (+ 18.0 o/oo) but a "normal" $\delta^{18}O$ (- 14.4 o/oo). The reason for the high $\delta^{13}C$ can be presumed to be a very local isotope exchange with surrounding phases under extreme conditions.

Analyses of a calcite sample from a fissure in Ulvö dolerite (about 30 km from Gideå) have also been included in the



10. $\delta^{13}C/\delta^{18}O$ graph for calcites from Gideå (see text). Star represents calcite from a fissure in Ulvö dolerite. Cross represents calcite from fissure in dolerite dykes at Gideå. Circle = open fissure; dot = sealed fissure.

figure. The calcite occurs here together with epidote, which indicates hydrothermal conditions of deposition. The Ulvö dolerite is dated to about 1 200 million years ("post-Jotnian") and is presumably roughly contemporary with the dolerite dykes at Gideå, from which the other calcite samples have been taken. It should be pointed out, however, that field observations show that the Ulvö dolerite has been intruded by steeply-dipping dolerite dykes with the same direction and of the same character as those at Gideå, so that the latter can be assumed to be younger than the Ulvö dolerite. This may explain the difference in isotope composition of precipitated calcites.

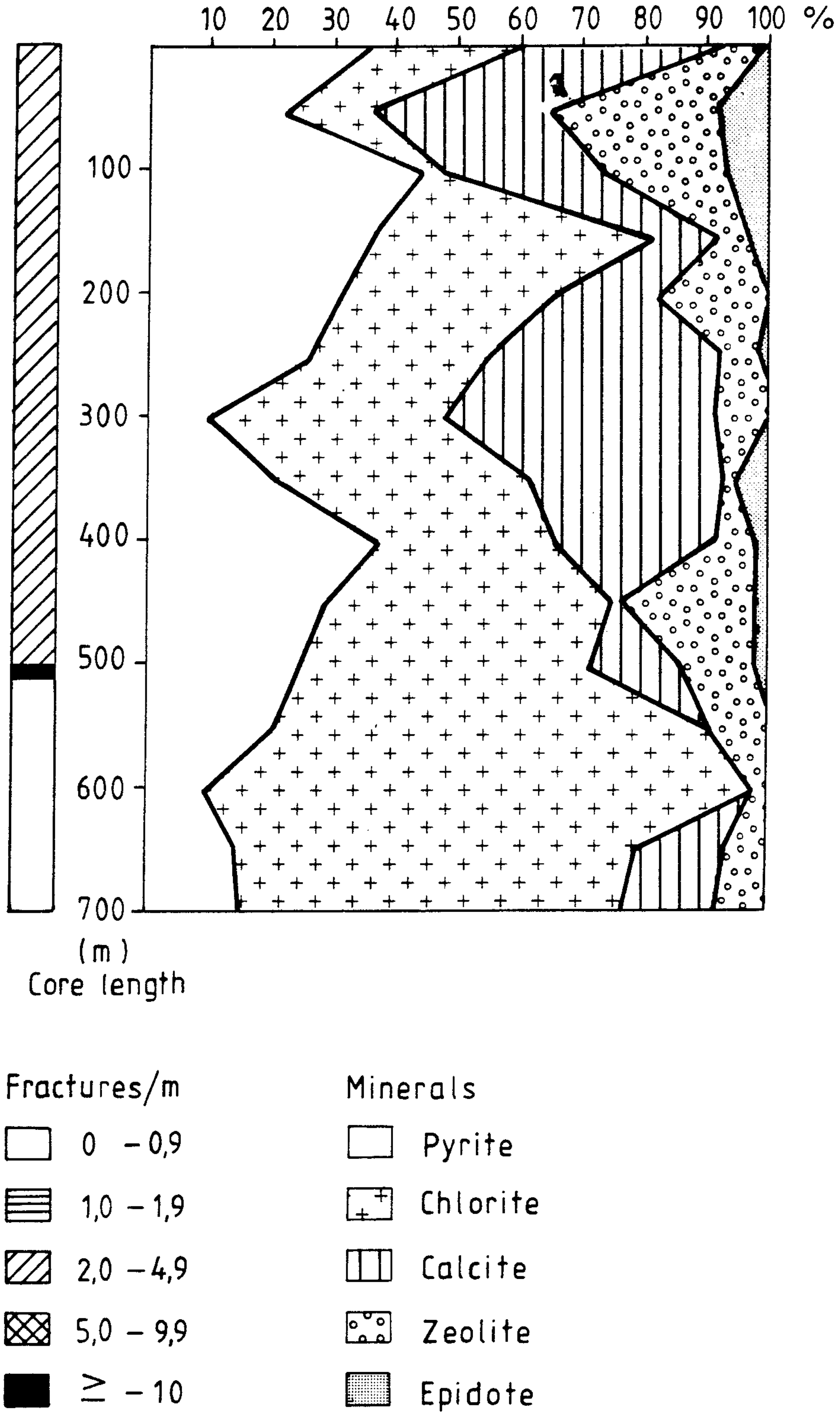
The majority of the calcites taken from open fissures fall in group II. This group includes samples that have been precipitated from a meteoric water under prevailing temperature conditions. Texturally, these calcites exhibit small or no deformation twins.

Group III includes only calcites from sealed fissures. Deformation twins are common in these calcites. Parageneses and textural studies show that the group comprises older (Precambrian) calcite generations. Thus, in many cases, the calcites have been precipitated under hydrothermal conditions. In some samples, these calcite sealings have fractured and been sealed by younger calcite (e.g. Gi2:243.6 and Gi2:480.9). The sample Gi2:480.9 exhibits a marked difference in deformation between the two generations. The arrows in Fig. 10 indicate change in isotope composition between an older and a younger generation of calcite in a single fissure. This shows that calcite sealings from group III are fractured and sealed by calcite from group II. It can also be seen that an older calcite in group I is intersected by a calcite-coated open fracture with a somewhat lower $\delta^{13}C$ content than in the older calcite (sample Gi2:412.0), i.e. more affected by biogenic carbon.

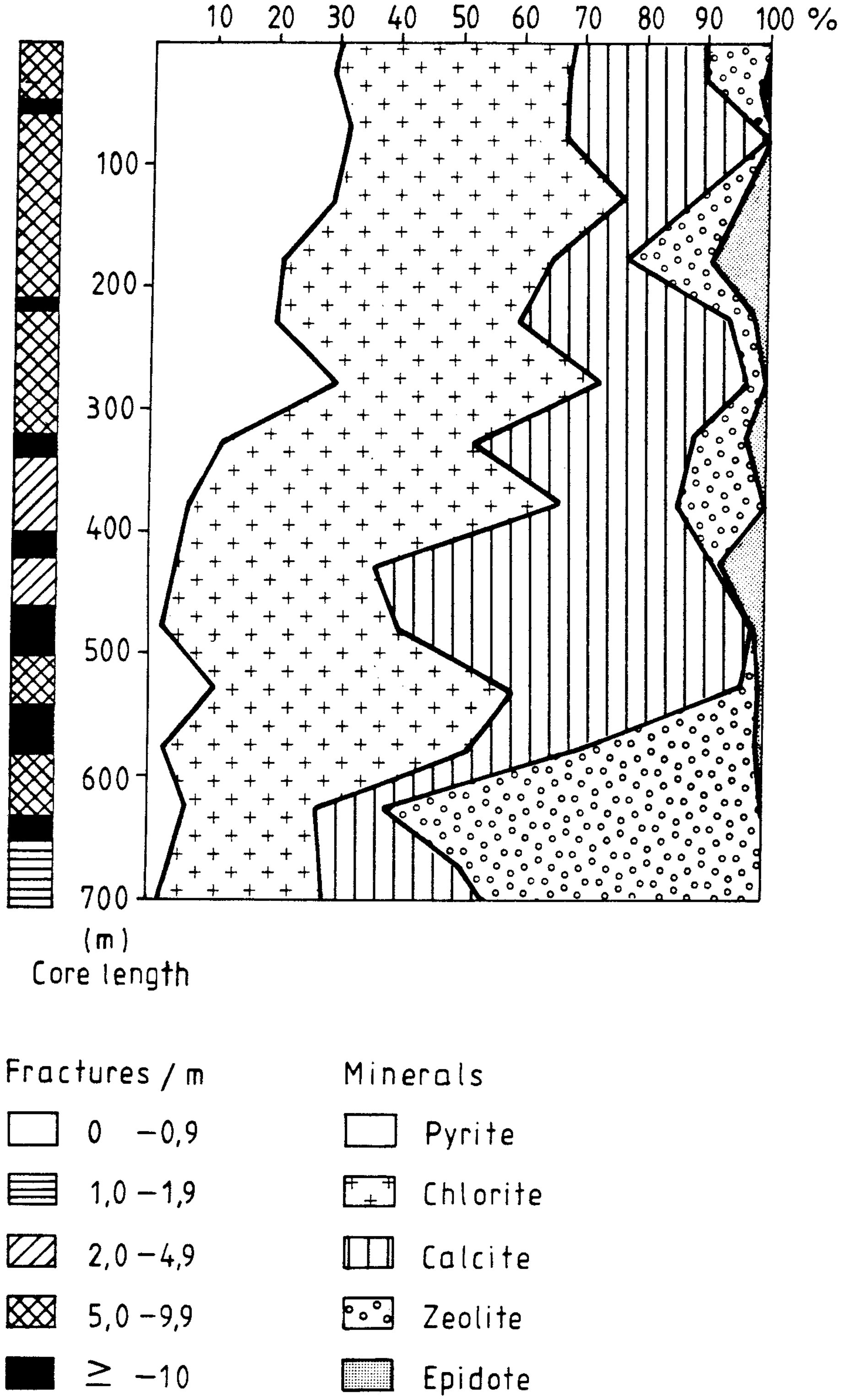
3. FRACTURE STATISTICS

Of the investigated drill holes Gi 1, Gi 2 and Gi 4, the largest number of fractures is exhibited by Gi 2 (5 205 fractures/700 m). These fractures are more or less evenly distributed over the 700 m length of the drill hole. When all drill holes at Gideå are taken into consideration, a declining fracture frequency is noticed at depth > 400 m (Ahlbom et al, 1983). However, an increased fracture frequency (greater than 10 fractures/m) occurs sporadically within the drill holes within zones with a thickness of a metre or so up to around 50 metres. The "surface fracturing" that can be discerned in places in the Swedish bedrock is not pronounced here. A very slight tendency towards increased fracture frequency may possibly be discerned in the upper part of drill hole Gi 1. Fracture frequency is plotted against drill hole length in figures 11-13. The strike of the fractures on the surface has been measured by Albino et al (1982). It can be concluded that the sealed fractures exhibit a different distribution of strike direction than the open fractures. The sealed fractures (Fig. 14) exhibit one pronounced strike direction in the N70W direction and another in N50E. In the case of the open fractures, a N-S direction dominates together with a direction in N30E (Fig. 15).

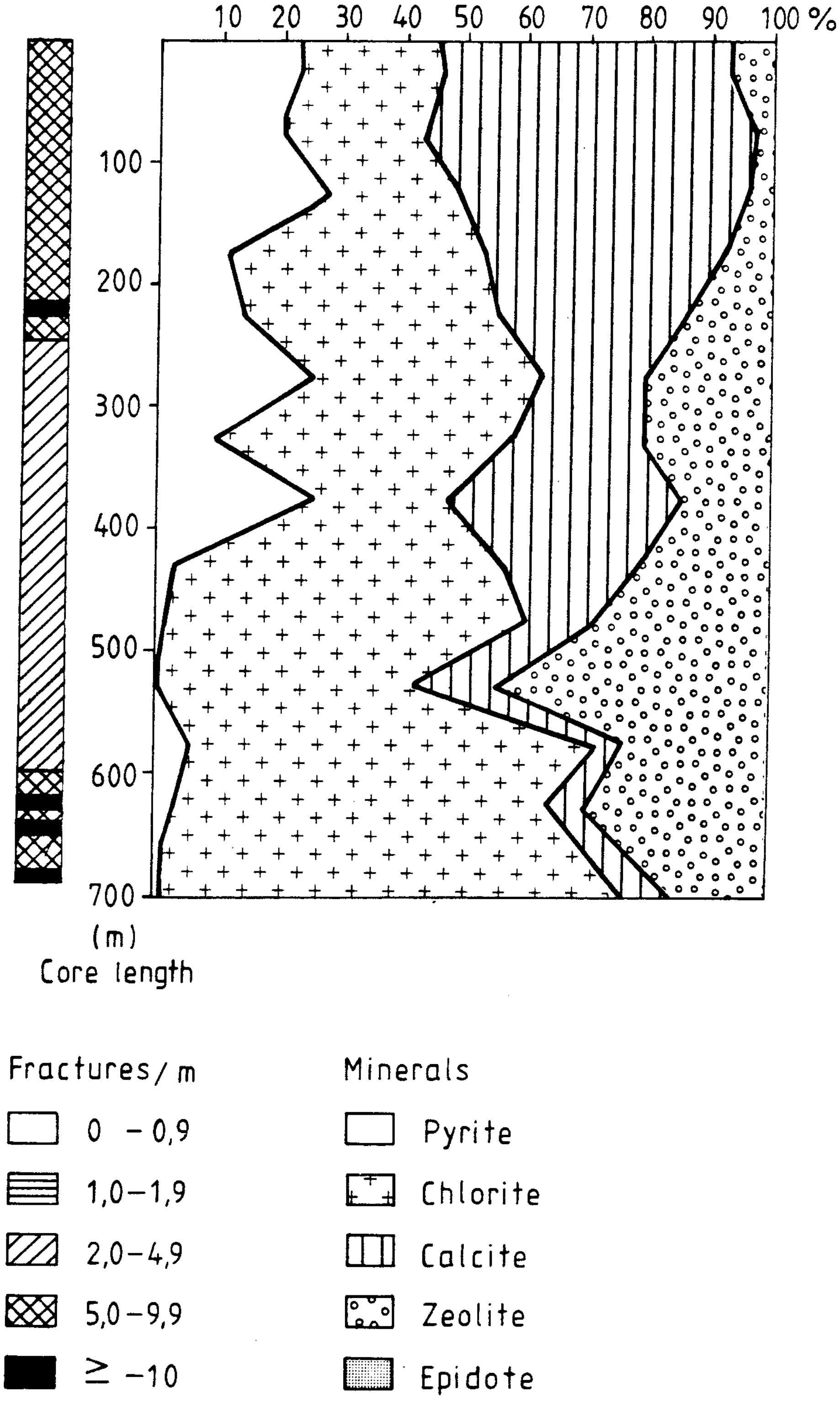
A fracture study in the surroundings of the test site including different rock types shows differences in the distribution of the fracture directions, although one of the aforementioned main directions always dominates. The shortage of studies of fracture directions from surface measurements is that the gently-dipping fracture are underrepresented unless a correction is made for the cross-section effect. The directions reported by Albino et al (1982) thus constitute a picture of how medium-steep and steep fractures tend to strike. The fracture directions measured in the post-Jotnian dolerite at Högvattberget (Albino et al 1982) coincide in particular with the preferred direction of the sealed fractures measured on the test site. It can be assumed that many of the sealed fractures on the test site are of post-Jotnian age. There is moreover reason to assume that the majority of the open fractures are



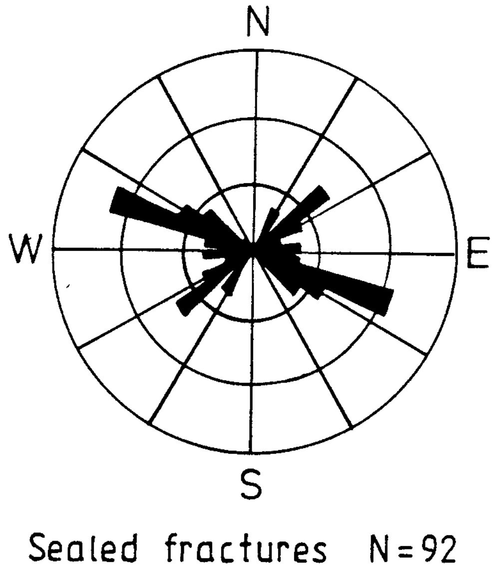
11. Relative variation of fracture-filling minerals with depth in Gi 1.



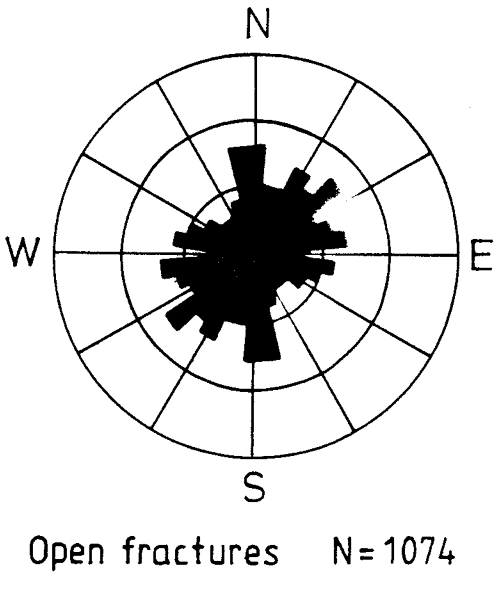
12. Relative variation of fracture-filling minerals with depth in Gi 2.



13. Relative variation of fracture-filling minerals with depth in Gi 4.



14. Strike of sealed fractures at Gideå (from Albino et al, 1982).



15. Strike of open fractures at Gideå (from Albino et al, 1982).

younger than the sealed fractures. The preferred directions of the open fractures do not coincide with the maximum direction of compression known from many measurements within different regions in Sweden. Thus, it is reasonable to suspect that the majority of the potentially "young" fractures (open) were not formed under the present-day stress field. This is confirmed by the fact that no "surface fracturing" has been observed.

In figure 16, the dip of all fractures within 100 m sections in drill hole Gi 1 is depicted graphically. Gi 1 is the only drill hole that is vertical, so it is the only one that could be used. Correction has been made for the fact that the hole is drilled vertically. As is evident from the figure, all sections show a dominance of relatively gently-dipping fractures (for the most part with a dip of 60-70^{o} towards the drill hole axis). There is no significant correlation between dip and depth.

In figure 17, the dips of fractures coated with a certain mineral are graphically depicted. The number of degrees gives the dip in relation to the drill hole axis. The frequency of each fracture-coating mineral is related to the number of fractures within each 10^{o} interval. Normally, the fractures are complex so that a single fracture can be represented by more than one mineral coating.

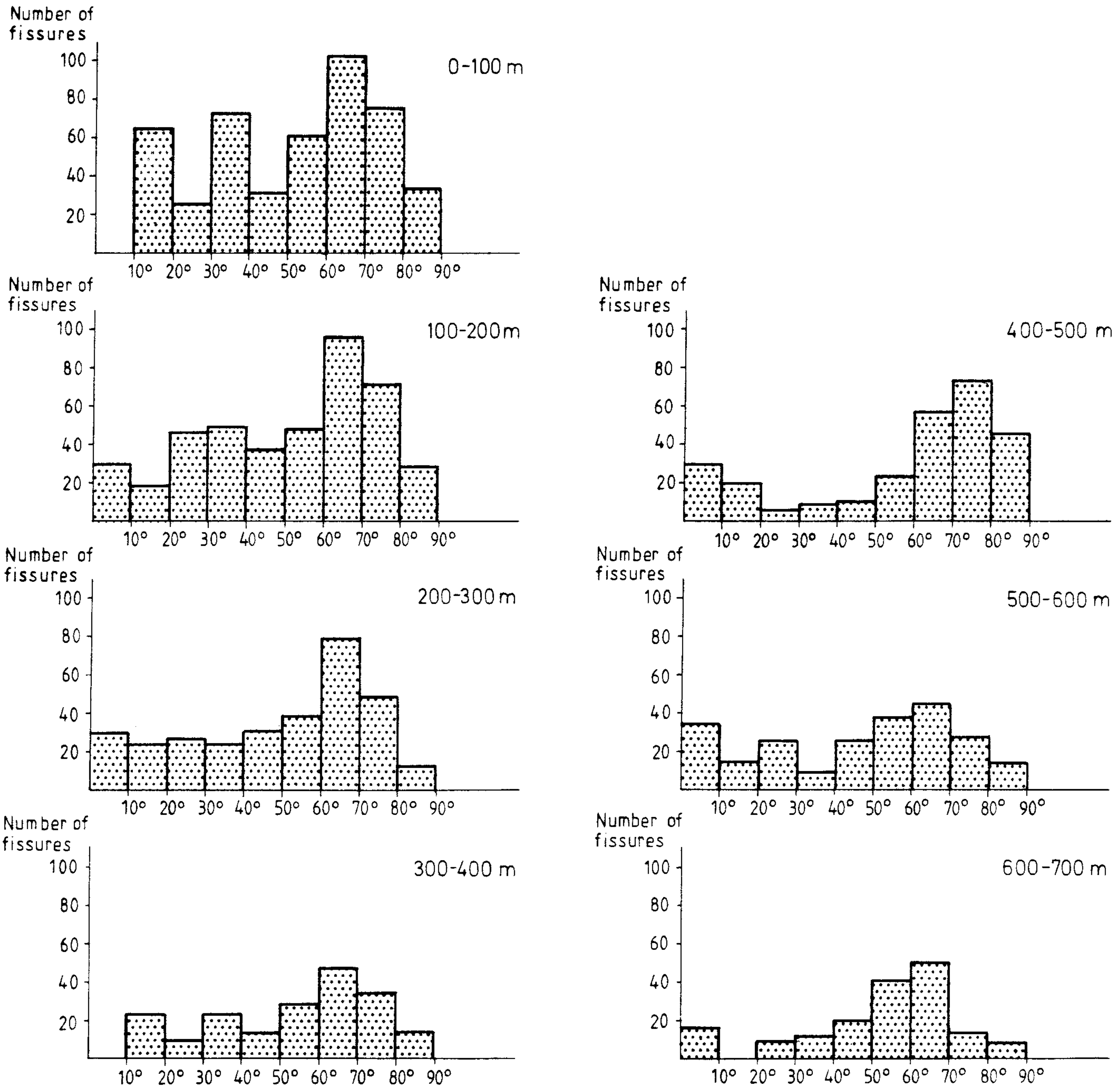
The figure show that epidote is relatively evenly distributed in fractures with different dips while laumontite and calcite are more common at certain dips. These dips are relatively steep, but is should be pointed out that relatively steep fractures are rare (Fig. 16) so significance for these fractures is less than for the gently-dipping fractures.

Figures 11-13 show the percentage distribution of fracture filling minerals with drill hole length in drill holes Gi 1, Gi 2 and Gi 4 within 50 m sections. The following trends can be discerned: the proportion of pyrite- and calcite-sealed fractures is greater towards the top of the drill holes, while the porportion of chlorite-sealed fractures is greater towards the bottom (with the exception of Gi 2). Moreover, the calcite and zeolite mineralizations appear to be associated with certain zones in the drill holes, although not the same zones.

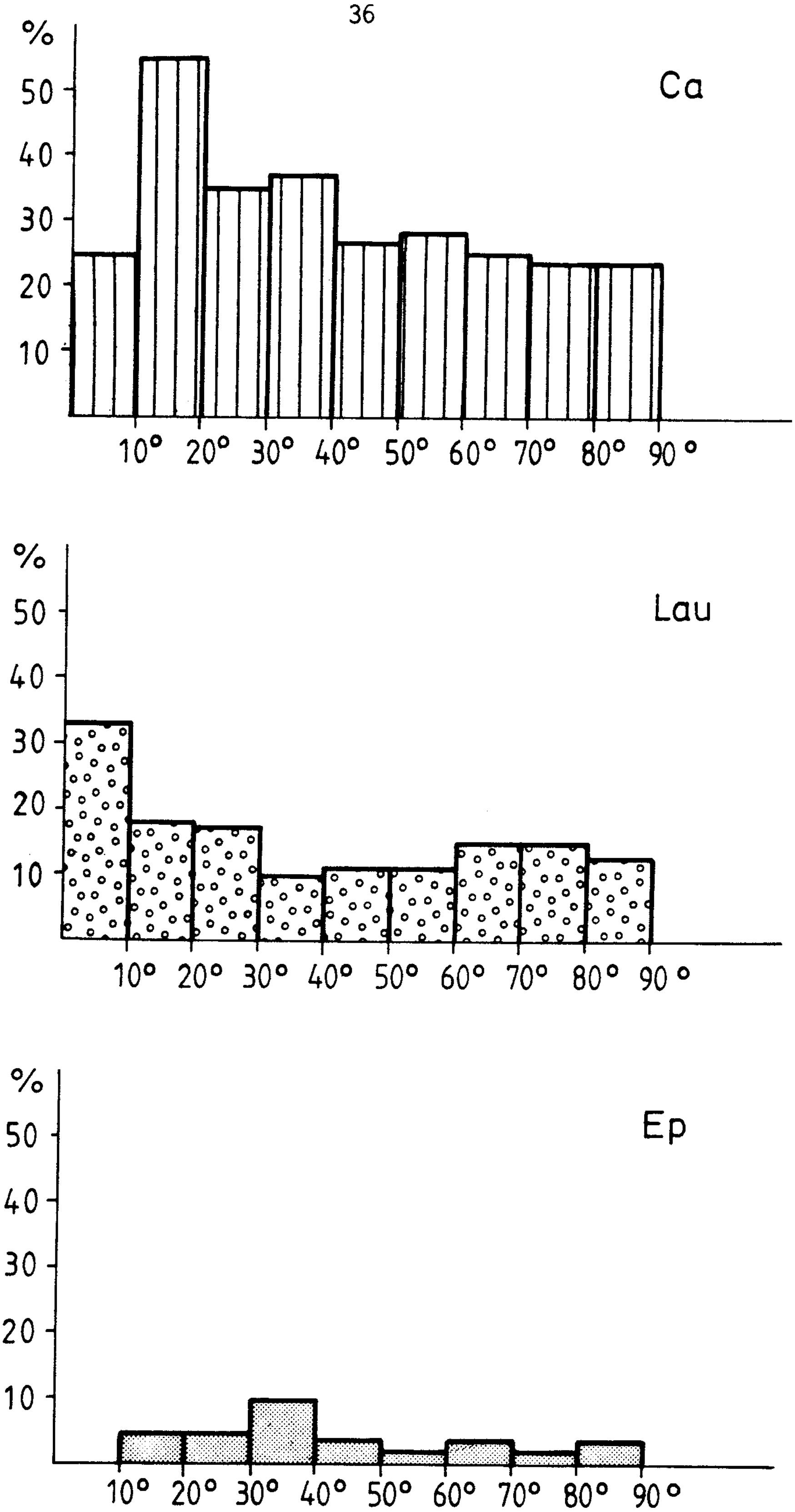
In summary, it can be said that the site is dominated by gently-dipping fractures. It can also be concluded that there is no pronounced surface fracturing and that a large number of fractures within the site at Gideå are of post-Jotnian age. Of the fracture-filling minerals, stilbite and smectite in particular may be post-Jotnian mineralizations, but other mineralizations of calcite, chlorite, laumontite, epidote and pyrite may also be post-Jotnian.

All drill holes (Gi 1, Gi 2 and Gi 4) are similar with regard to fracture mineralizations. The higher frequency of calcite in more superficial parts of the drill holes can presumably be correlated with present-day surface sections, why recent or relatively young calcite is present. The post-Jotnian dolerites have probably played a decisive role for the hydrothermal mineralizations in fractures on the site.

Drill hole Gi 2 is the only drill hole of the three that contains dolerite dykes. The sections where dolerite occurs simultaneously exhibit a higher fracture frequency. The poor hydraulic conductivity of the fractured dolerites must be due to the smectite alteration that has occured in these rocks, sealing the fractures.



16. Dip of all fractures within 100 m sections in drill hole Gi 1.



17. Dip of fractures (deviation from the axis of the drill hole) coated with a certain mineral. Related to number of fractures within each 10° interval.

4. WATER - MINERAL EQUILIBRIA

Water analyses (Allard et al, 1983) from drill holes Gi 2 and Gi 4 show that the waters are of the HCO_3-Na-Ca type. The salinities normally vary between 220 and 640 mg/l. The more saline waters have been observed in drill hole Gi 4 at levels 404 m and 616 m. The water at these levels is of the Cl-Na-Ca type. No difference has been found in fracture mineralizations or in the character of the fracture-filling minerals at these levels in comparison with other levels.

The analyses of waters from Gi 2 and Gi 4 were used in the computer program EQUIL (T) by Bertrand Fritz, Strasbourg, in order to estimate which mineral phases were in equilibrium or disequilibrium with the waters. In an initial calculation, all analyses as well as measured temperatures in the water were used. The result was a strong supersaturation of goethite. This was considered to be unreasonable, so Eh and Fe^{2+}/Fe^{3+} were corrected to goethite equilibium (B. Fritz, personal communication).

Analysis values for aluminium are partially lacking or of too poor precision to be able to be used in the equilibium calculations. In order to obtain an idea of the stability of the aluminium silicates, the assumption has been made that kaolinite equilibrium prevails. The results of the computer calculation are reported in table 9. From this it is evident that waters from drill hole Gi 2 are saturated with respect to calcite, quartz and smectite as well as, in some cases, illite and dolomite. Of the most common rock forming minerals, microcline and albite are stable, while anortite and biotite are unstable. The chemistry of the water varies much more in Gi 4, and the equilibrium calculations therefore give a more varying result. With regard to the fracture-filling minerals, fluorite, calcite, dolomite, quartz and smectite are the main stable ones. The waters from levels 404 and 616 m (saline type) give the same stable phases in the equilibium calculations as for the other levels.

With regard to rock-forming minerals, anortite, albite and biotite appear to be unstable, as do, in some cases, microcline and quartz.

The differences between Gi 2 and Gi 4 are probably due to the fact that the former drill hole is located in a discharge area and the latter in a recharge area (Timje, 1983). Thus, when the water has reached Gi 2, it has reached a greater equilibium with surrounding rock-forming minerals than in the case of drill hole Gi 4. It should be pointed out that even though the calculations show that more waters are saturated or very close to saturation with respect to flourite and magnetite, these minerals have not been encountered as fracture-filling minerals in the drill cores. This can be explained by the fact that the water exhibits greater supersaturation with respect to calcite, so that calcite precipitates more readily and thereby controls both the Ca-content and the HCO_3-content of the water.

Pyrite and chlorite, which are common fracture-filling minerals at Gideå, are unstable in the analyzed waters, with the exception of one of the saline waters from Gideå 4, which exhibits saturation with respect to Mg chlorite.

Table 9. Stability of minerals in waters (1-5) from drill holes Gi 2 and Gi 4.

Mineral	Unsaturated	Approx. saturated	Oversaturated
Gi 2 Fluorite		1, 2, 3, 4, 5	
Gi 4 Fluorite		1, 2, 3, 4, 5a,b,c	
Gi 2 Pyrite	2, 3, 4, 5	1	
Gi 4 "	1, 2, 3, 4, 5,a,b,c		
Gi 2 Calcite		1, 2, 3, 4, 5	
Gi 4 "	5a	1, 2, 3, 4, 5b,c	
Gi 2 Magnesite		1, 2, 3, 4, 5	
Gi 4 "	1, 3, 5a,b,c	2, 4	
Gi 2 Dolomite		1, 2, 3, 4, 5	
Gi 4 "	1, 5a,b	2, 3, 4, 5c	
Gi 2 Quartz		1, 2, 3, 4, 5	
Gi 4 "		1, 2, 3, 4, 5a,b,c	
Gi 2 Microcline			1, 2, 3, 4, 5
Gi 4 "		1, 4, 5a,b,c	2, 3
Gi 2 Albite		1, 2, 3, 4, 5	
Gi 4 "	1, 4, 5a,b,c	2, 3	
Gi 2 Anortite	1, 2, 3, 4, 5		
Gi 4 "	1, 2, 3, 4, 5a,b,c		
Gi 2 Biotite	1, 2, 3, 4, 5		
Gi 4 "	1, 2, 3, 4, 5a,b	5c	
Gi 2 Illite		1, 2, 3, 4, 5	
Gi 4 "	1, 5a,b,c	2, 3, 4	
Gi 2 Smectite			1, 2, 3, 4, 5
Gi 4 "		1, 4, 5a,b	2, 3, 5c
Gi 2 Mg-chlorite	1, 2, 3, 4, 5		
Gi 4 "	1, 2, 4, 5a,b,c		3

Following levels have been used in Gi 2 (core length): 1=178 m; 2=308 m; 3=400 m; 4=544 m; 5=602 m.

In Gi 4: 1=96 m; 2=222 m; 3=404 m; 4=512m; 5=616m (a,b and c are waters sampled from level 616 at different times).

5. DISCUSSION

Calcite, chlorite, pyrite, laumontite, stilbite, smectite, quartz and epidote are commonly occurring fissure-filling minerals. Of these, some can be distinguished as minerals formed at higher temperatures than those temperatures now prevailing on the site, i.e. hydrothermal formations. These minerals are predominantly laumontite, stilbite, pyrite and epidote, but also chlorite. Calcite and quartz are normally formed within a wider temperature range, which also includes low temperatures. Smectite is formed at low temperatures but is converted at elevated temperatures to chlorite and illite.

Both smectite and the zeolites (laumontite and stilbite) exhibit anomalously high ion exchange capacities. In addition, smectite exhibits the characteristics of absorbing water with considerable volume increase (swelling). The solubility of calcite deviates from that of other fracture-filling minerals, especially quartz, in that it decreases at elevated temperatures.

In the drill holes investigated, both calcite and the zeolite mineralizations appear to be associated with certain zones in the drill holes. In addition, calcite is less frequent in the lower part of the drill holes. This is probably due to the fact that carbonate-saturated water penetrating to such depths precipitated its calcite while infiltrating the more superficial portions of the bedrock and gradually achived an equilibium level towards greater depth. This process is associated with present-day surface i.e. a crustal level which has remained approximately constant for many million years. The declining frequency of calcite with depth is particularly noticeable in drill hole Gi 4. This is explained by the fact that Gi 4 is located within a recharge area and thereby supports the connection between calcite precipitation and present-day surface. The calcite that is associated with certain zones probably consists of, in addition to recent and younger calcite, also the oldest, Precambrian and hydrothermally formed calcite.

A large number of fractures can be concluded to be of post-Jotnian age. Stilbite, calcite and smectite are associated with these fractures. Laumontite can also be assumed to belong here.

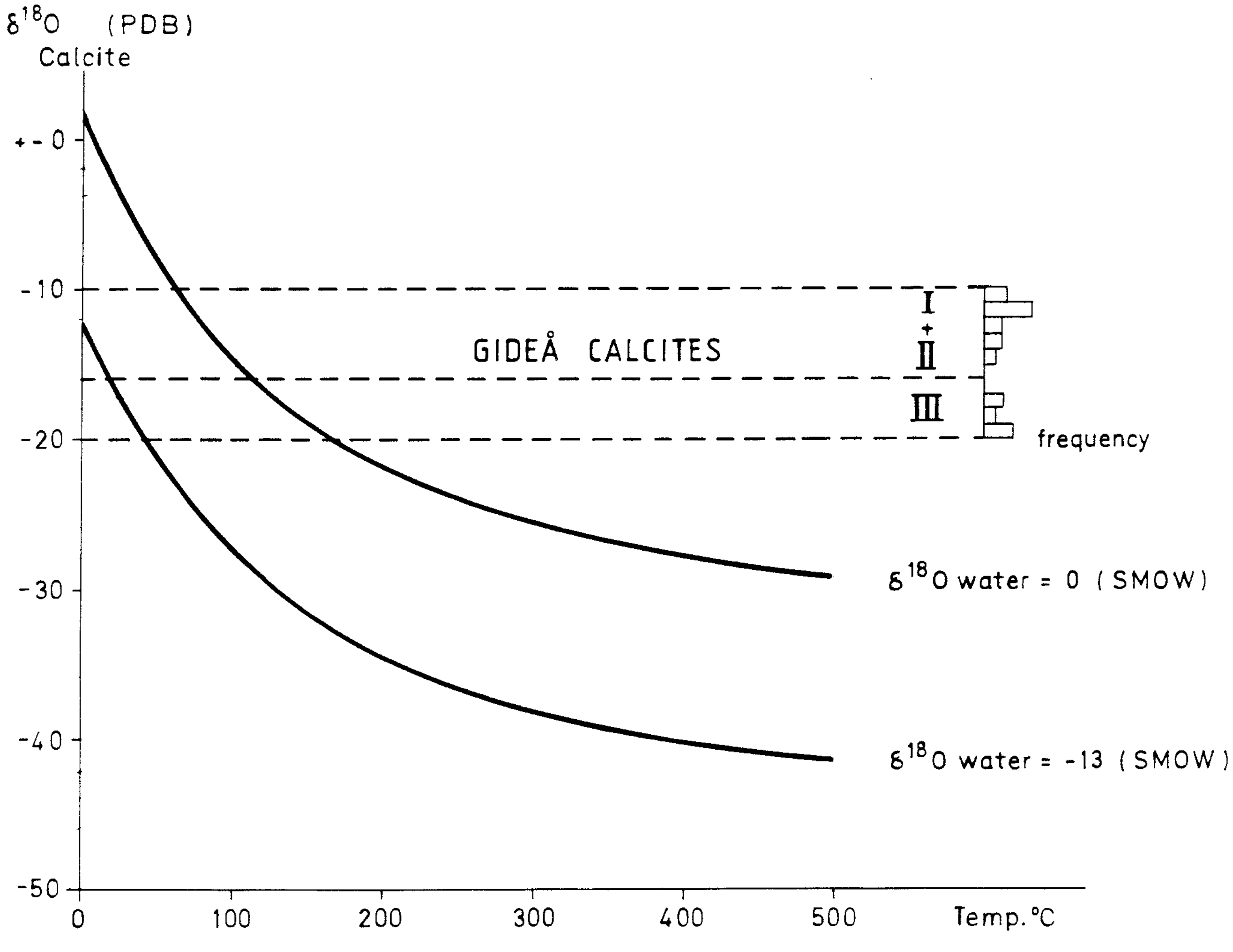
The dolerites in the area exhibit a high fracture frequency but a relatively low hydraulic conductivity. This is due to the fact that smectite is very prevalent in the dolerite fractures, sealing the fractures.

The fracture-sealing mineralizations are normally one to a few mm thick and have been found to have a simpler composition than those at e.g. Finnsjön. Several generations of fracture-filling minerals (above all calcite) have been found in a single fracture. Both textural and chemical properties distinguish them, which makes it likely that there are large age differences between them.

Figur 18 shows how calcite-water fractionation of $\delta^{18}O$ changes with temperature. Two waters have been selected. One is a marine water ($\delta^{18}O = 0$ o/oo) and the other is a water that coincides with the water pumped from the drill holes at Gideå ($\delta^{18}O = -13$ o/oo). The calcite that was analyzed is found within the intervals in the figure. Temperatures between about $50^{o}C$ and $180^{o}C$ are required in order for these calcites to be precipitated from a marine water, whereas many of the calcites could have been precipitated at temperatures < $50^{o}C$ from the water where $\delta^{18}O = -13$ o/oo.

The figure shows that most of the calcites from group I (cf Fig. 9) could not have been precipitated from water of present-day isotope composition at Gideå, whereas recent calcite may be found in group II. Group III could not have been precipitated under the temperature conditions that prevail on the site today, nor from the groundwater that occurs there. Moreover, these calcites occur together with typical hydrothermal minerals. The water that precipitated the calcite should therefore have had a higher $\delta^{18}O$ content than that which is found in a marine water.

Equilibrium calculations show that of the fracture-filling minerals present, calcite, quartz and smectite can be stable in the water analyzed from Gideå. Of the rock-forming minerals, not only quartz and microcline but also, albite is stable in some cases. Hole Gi 2 exhibits a water with a greater equilibium with existing minerals than water from Gi 4, which may be due to the fact that the former drill hole is located in a discharge area and the latter in a recharge area.



18. Calculated calcite-water fractionation of $\delta^{18}O$ versus temperature. The curves shown represent waters with a $\delta^{18}O$ content of 0 o/oo (SMOW) and -13 o/oo (analyzed water at Gideå).

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