NGU Rapport 93.118

Groundwater in bedrock - Hvaler project. Investigations at Testsite Reffsgård.

NORGES GEOLOGISKE UNDERSØKELSE

Postboks 3006 - Lade
7002 TRONDHEIM
Tlf. (07) 90 40 11
Telefax (07) 92 16 20

RAPPORT

Rapport nr. 93.118	ISSN 0800-3416	Gradering: Åpen

Tittel:
Groundwater in bedrock - Hvaler project. Investigations at Testsite Reffsgård.
Grunnvann i fast fjell - Hvalerprosjektet. Undersøkelser ved Teststed Reffsgård.

Forfatter: D.Banks, T. Lauritsen, E.Rohr-Torp, J.S. Rønning, H.Skarphagen	Oppdragsgiver: NGU/Norsk Hydrologisk Komité
Fylke: Østfold	Kommune: Hvaler
Kartbladnavn (M=1:250.000) Oslo	Kartbladnr. og -navn (M=1:50.000) 1913-III
Forekomstens navn og koordinater: Reffsgård, Kirkeøy, [6]161 [65]494	Sidetall: 65 Pris: 95,- Kartbilag:

Feltarbeid utført:	Rapportdato:	Prosjektnr.:	Ansvarlig:
1992-1993	31.12.93	63.2462.00	Tor Erik Finne

Sammendrag:

Three 3" boreholes have been drilled to c. 42 m in relatively massive bedrock at Reffsgård. In-situ stress measurement, using hydraulic fracturing, was carried out in all holes, giving an effective maximum principal stress in a NNE direction. The three holes gave short-term yields of <0.1, 19 and 0.7 l/hr respectively (before hydraulic fracturing). To test whether orientation in a stress-field may have a significant effect on borehole yield, three 5½" boreholes were drilled to 70m into smaller fracture zones (boreholes B & C) and into a suspected dolerite dyke (borehole A). The boreholes were disappointing, yielding only c.5 l/hr (borehole A), 0.22 l/hr (B) and 0.27 l/hr (C). The low yields are believed to be related to exceptionally high in-situ stresses in the rock.

Tre stk. 3" borehull ble boret til ca. 42 m i forholdsvis massivt fjell ved Reffsgård for å måle in-situ spenning med hydraulisk trykking. En NNØ hovedspenningsretning ble konkludert. Hullene ga henholdsvis <0.1, 19 og 0.7 l/t vann under korttidsprøvepumping, før trykking. For å undersøke effekten av borehullsorientering i spenningsfeltet på vannytelse ble det boret 3 stk. 5½" borehull til 70 m; ett (hull A) i en forventet diabasgang, og to (B & C) i mindre sprekkesoner. Borehullene ga lite vann under korttidstesting; henholdsvis c.5, 0,22 og 0,27 l/t. De lave ytelsene synes å skyldes ekstremt høy in-situ spenning i fjellet ved den lokaliteten.

Emneord: Hydrogeologi	Sprekkesone	Grunnvann
Berggrunn	Grunnvannskvalitet	Borhullslogging
Geofysikk	Spenningsmålinger	Fagrapport

Table of Contents

1 Introduction - The Hvaler Study

The Geological Survey of Norway (NGU) have, since 1989, used Hvaler as a research area. The objective has been to investigate the practical, water resources aspects of the hydrogeology of a coastal granite aquifer, namely the Iddefjord granite. The area was chosen for the following reasons:

- it is near Oslo, with good road connections
- excellent bedrock exposure
- there are real problems with water resources on the islands
- the climate is mild, allowing a long field season
- the fracture pattern appeared (at first sight) to be relatively straightforward
- it's a pleasant place !

The investigations undertaken at Hvaler so far have included

- literature study
- mapping of fracture systems from aerial photos, topographic maps and field surveys
- survey of hydrochemistry
- assessment of various geophysical methods for detection of transmissive fractures (VLF, magnetometry and georadar have proved to be particularly interesting).
- establishment of 4 test boreholes at Pulservik to investigate two major fracture zones
- development of test-pumping methods
- investigation of methods to artificially enhance yields
- establishment of 6 boreholes at a second testsite at Reffsgård
- measurement of in-situ stresses and investigation of borehole yield in relation to these.

2. Hvaler - Geology and Tectonics

2.1 Geology

The Hvaler municipality consists of a group of islands (*Hvaler*ø*yene*) in the mouth of Oslofjord in south-east Norway (Fig. 1). The dominant lithology is the Precambrian Iddefjord Granite, described by Oxaal (1916). The granite is typically grey in colour when fresh, but tends to weather to the characteristic red colour of the islands' exposed coastline. The granite has been extensively worked for building and ornamental stone in numerous small quarries, some of which are still in operation today. Well-known Iddefjord Granite structures include the quay at Dover, England and the statues at the Vigeland Sculpture Park in Oslo.

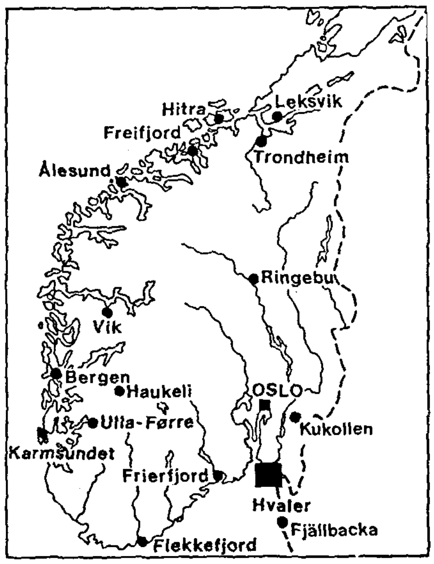


Figure 1. Location map of Southern Norway, showing Hvaler and other sites named in text

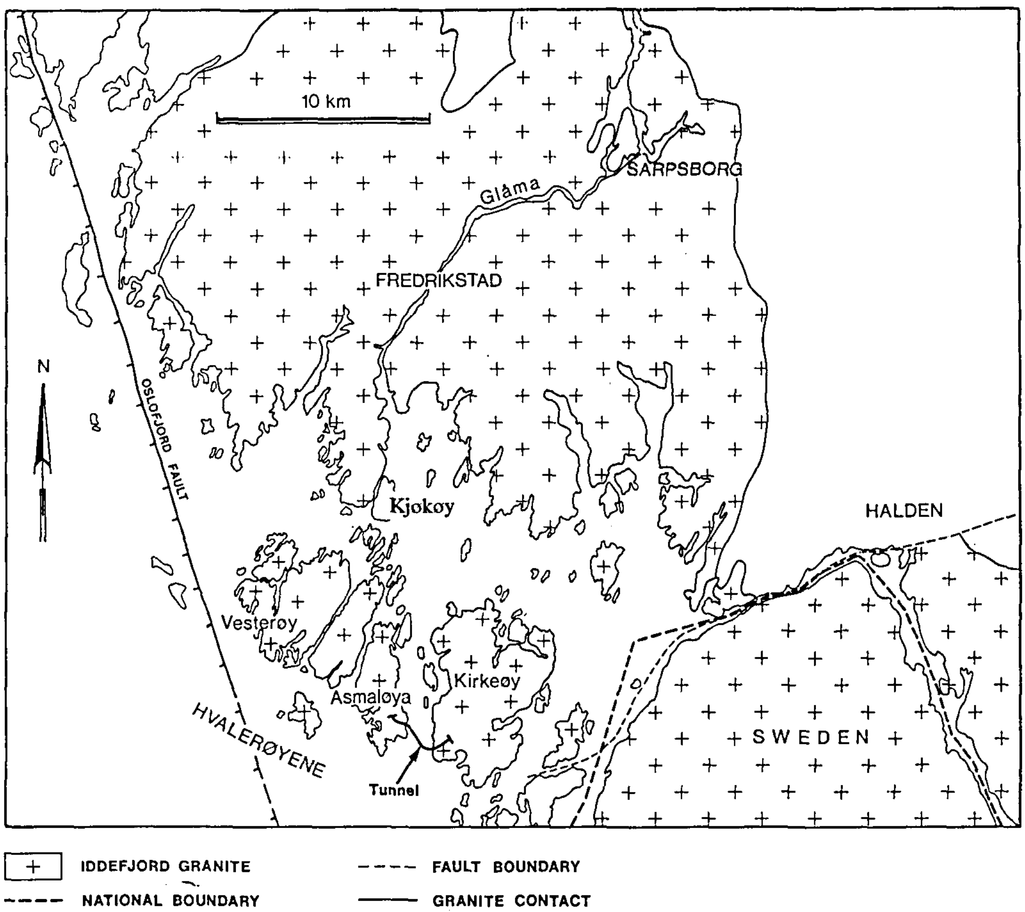


Figure 2. The Iddefjord Granite area, showing outcrop of Iddefjord granite and tunnel location. The bedrock surrounding the granite consists of Precambrian gneiss.

The Iddefjord Granite forms the northern extension of the Swedish Bohus batholith. The Iddefjord granite consists of 13 separate plutons (Pedersen & Maaløe 1990), ranging in composition from diorite to true granite, some of the youngest of which yield a Rb/Sr age of 918 $\pm$ 7 million years, corresponding to the end of the Sveconorwegian orogeny. Quartz, microcline and plagioclase are the dominant minerals in the granite. Accessory minerals include biotite, hornblende, muscovite, iron-oxides, chlorite, apatite, titanite & zircon (Pedersen & Maaløe 1990) and occasionally garnet. The granite commonly includes basic clots, pegmatites and xenoliths of gneissic host-rock. In some areas the xenolith content may be extremely high; in the new Hvaler tunnel the gneiss content reached some 55 % (Larsen 1990, Banks et al. 1992a). Ramberg & Smithson (1971) describe the Iddefjord granite as a tabular intrusion on the basis of geophysical evidence.

In common with most high latitude areas, the Hvaler area has no regional development of a heavily degraded layer of weathered granite. Relatively fresh bedrock outcrops over large areas of the islands, often showing signs of glacial scouring, or sub-glacial potholes.

The Hvaler islands' Quaternary deposits are to a large extent limited to the lineament-controlled valleys, and consist mainly of shallow marine (or littoral) sands, silts and clays (Olsen & Sørensen 1990). Limited deposits of peat, wind-blown sand, and coarser gravelly/pebbly beach deposits can be found on the southern part of Kirkeøy. The remains of one of the outermost terminal moraine trains from the last glaciation in Oslofjord can be found near Arekilen - the so-called Hvaler moraine train. The massive areas between the lineament valleys consist of bare bedrock or bedrock with a thin covering of humus.

The islands have undergone substantial isostatic uplift in the past 10,000 years or so. The highest marine limit is c. 170 m above current sea-level (Selmer-Olsen 1964). The islands have therefore only emerged from the sea within the last several thousand years. The hydrogeological environment of the rocks encountered onshore is thus only likely to have differed significantly from those in the Hvaler subsea tunnel (see later) during that period.

2.2 Tectonic situation

Hvaler is bounded to the west by the Oslo Graben boundary fault. The two islands *Nordre & Søndre Søstre* (North & South Sisters) lie to the west of the boundary fault and consist of rhomb porphyry conglomerates. Immediately west of the islands can also be found the so-called Hvaler Deep, a SW-NE graben structure believed to be seismically active today, and responsible for the magnitude 5.4 earthquake experienced in the region on October 23rd 1904 (Størmer 1935).

To the southeast the Hvaler area is bounded by the major Iddefjord fault, with the granite downthrown on the southern (Swedish) side (Pedersen & Maaløe 1990).

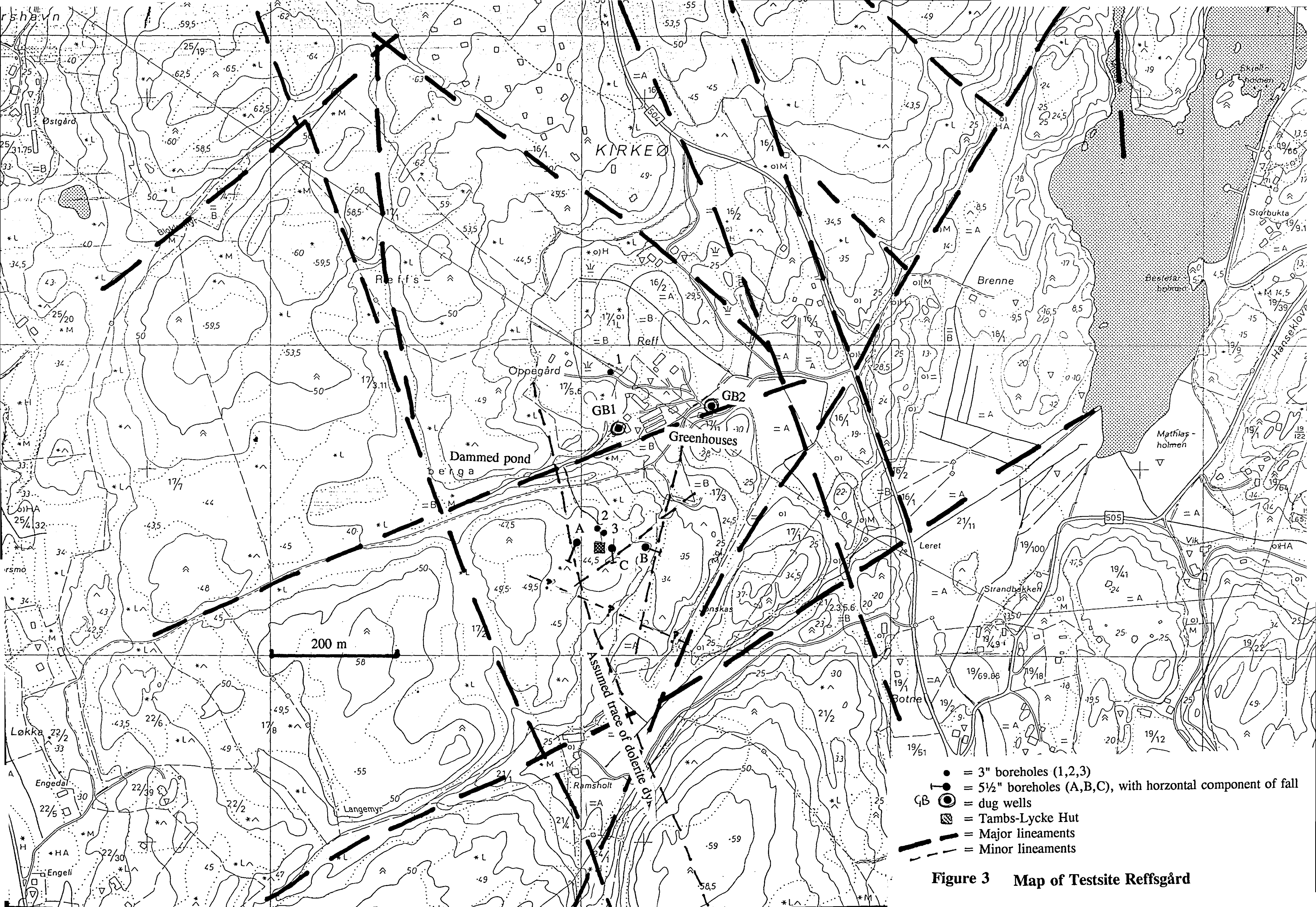


Figure 3 Map of Testsite Reffsgård

The Iddefjord granite area is dissected by a pattern of linear valleys resulting, at least in part, from preferential glacial erosion along zones of fractured and crushed rock. These valleys are usually partially infilled by Quaternary deposits, rendering the surface outcrops of the fracture zones unexaminable. The linear channels between the islands of the Hvaler group, such as the two straits between Vesterøy and Asmaløy and the channel between Asmaløy and Kirkeøy (Fig. 2), are also believed to have arisen by such a process. The origin of the fracture zones themselves is uncertain. It is likely, however, that they date from an early period of the granite's history, as a result of regional tectonic stresses or stresses related to emplacement and cooling of the granite. The fracture pattern is likely to have been reactivated or modified several times during its history; for example, during the Permian opening of the Oslo rift, post-rifting strike-slip movements along the Oslo graben boundary fault (Størmer 1935), and possibly even by glacial and post-glacial stresses.

The dominant lineament directions are NNE/NE-SSW/SW (primarily) and NNW/NW-SSE/SE. Ramberg & Larsen (1978) consider these directions to be typical of pre-Permian (i.e. pre-Oslo Graben) deformation of the Oslo region. Preferred orientations of lesser fractures (from field mapping) are primarily NW/NNW-SE/SSE and also NNE/NE-SSW/SW (Banks et al. 1992b).

Across the Swedish border, the continuation of the Iddefjord Granite (the Bohus Granite) has been investigated in great detail in connection with a geothermal energy project at Fjällbacka Fig. 1). The same dominant fracture directions were found here. Both at Fjällbacka (Eliasson et al. 1990) and Hvaler, fracture mineralisations consisting of calcite, fluorite, smectite, hematite, chlorite, quartz, biotite, muscovite, epidote and iron oxyhydroxide (rust) have been found; calcite, fluorite and epidote occur predominantly along NNE/NE-SSW/SW fractures (epidote also on NW-SE fractures), while clay fillings predominantly occur on NNW/NW-SSE/SE fractures (Banks & Rohr-Torp 1991, Kocheise unpubl.data [see Banks et al. 1993a], Sundquist et al. 1988). Eliasson et al. (1990) connect four major episodes of fracture generation/activation with four different types of mineral infilling: (1) pegmatites, quartz, $\pm$ epidote, related to cooling of granite; (2) haematite, chlorite, calcite $\pm$ quartz $\pm$ epidote, high temperature filling, post consolidation; (3) smectite, related to low-temperature ($< 80°C$) alteration, possibly during burial metamorphism in the late Palaeozoic; (4) iron oxyhydroxide deposition due to circulation of oxidizing groundwater (down to c. 250 m depth at Fjällbacka).

3 Testsite Reffsgård

Reffsgård (Fig. 3) lies towards the middle of the northwestern peninsula of Kirkeøy, one of the Hvaler island group, in the Precambrian Iddefjord granite group of plutons (Pedersen & Maaløe 1990). Work at the previous Pulservik testsite (Banks et al. 1991) had focussed on assessing the significance of topgraphically and geophysically prominant fracture zones on borehole yield. The results of work at Pulservik indicated that, at least on Hvaler, the presence of such a

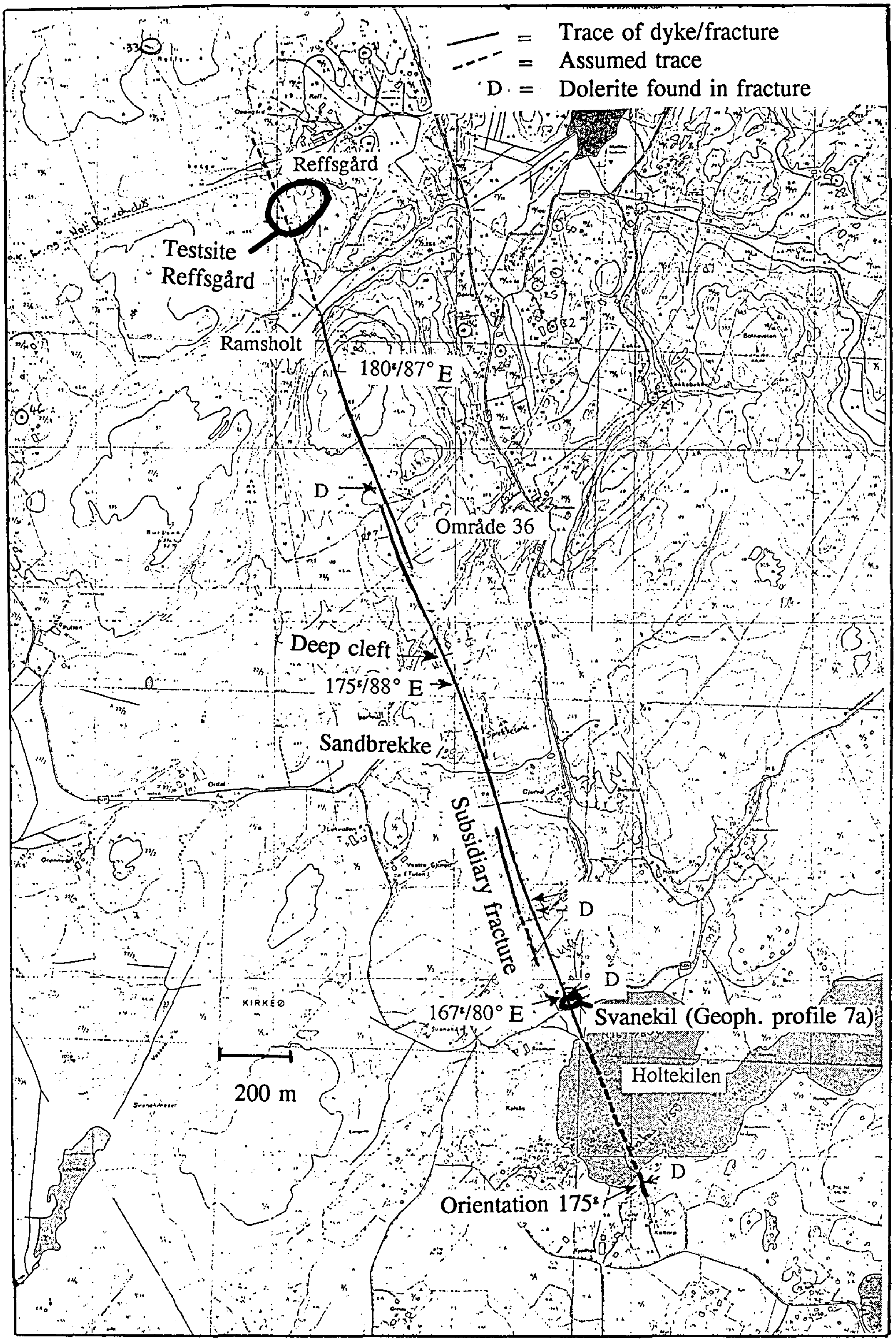


Figure 4. The "Skjernaa" dolerite dyke on Kirkeøy. N.B. 400g = 360°. After Banks and Rohr-Torp, 1991.

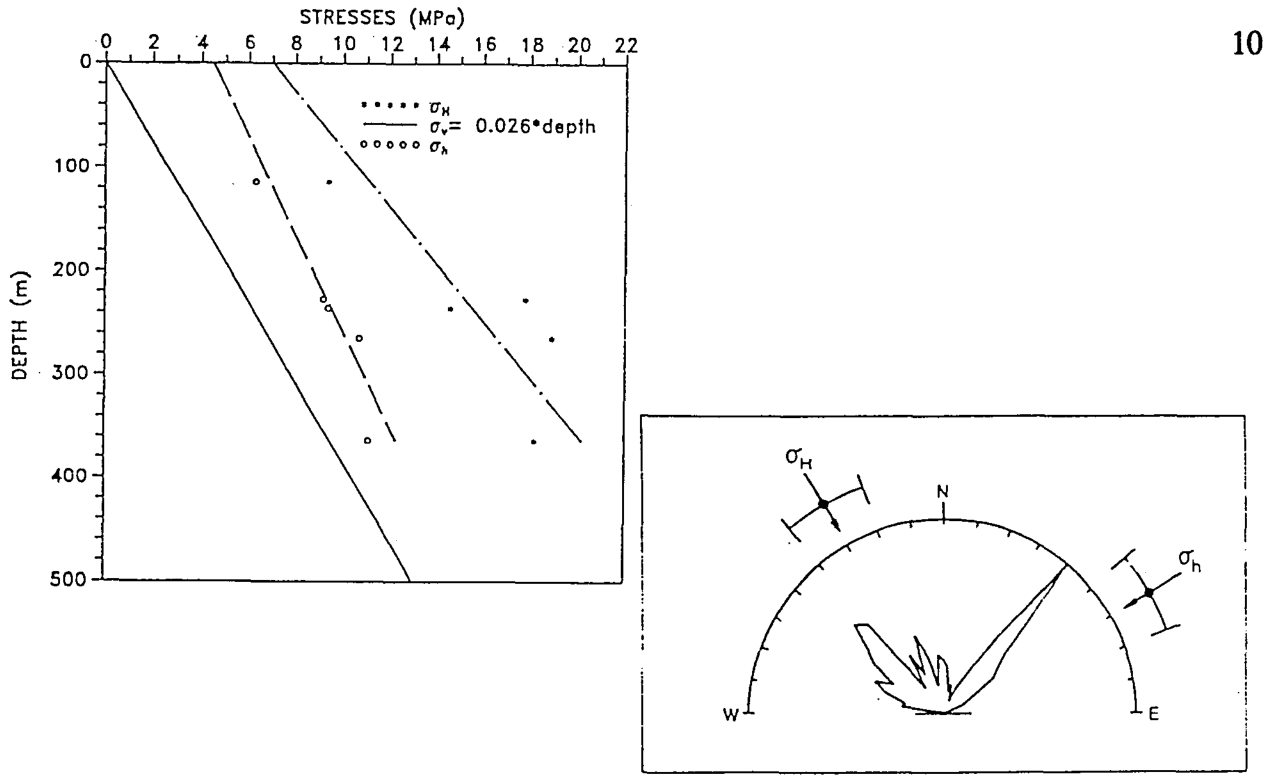


Figure 5a. Magnitude of horizontal principal stresses, from hydraulic fracturing, at Fjällbacka, Sweden. Figure 5b. Vertical and subvertical joints mapped at Fjällbacka, Sweden, and the horizontal principal stress directions (after Wallroth 1992).

fracture zone was no guarantee of high yield, partly due to the fact that many fracture zones are "tightened" by secondary clay mineralisations.

The Reffsgård site has been chosen for three purposes:

- to examine the water resources aspects of more massive granite, away from major fracture zones.
- to investigate the effects of in-situ stress and borehole orientation on borehole yield.
- to investigate the hydrogeological properties of a probable dolerite dyke.

This last objective is related to the presence of a fracture believed to be a continuation of a small (ca. 30 cm wide) dolerite dyke, mapped at Svanekil and Sandbrekke (Banks & Rohr-Torp 1991), Fig. 4. At Reffsgård, however, no dolerite filling has been demonstrated in the fracture, the nearest dolerite having been proven between Ramsholt and Sandbrekke, further south-east.

4 In-situ stress and borehole yield

A few hydrogeologists have gone beyond the "biggest is best" hypothesis for fracture zone transmissivity, and have investigated the effects of tectonic stress. Some workers (Larsson 1972,

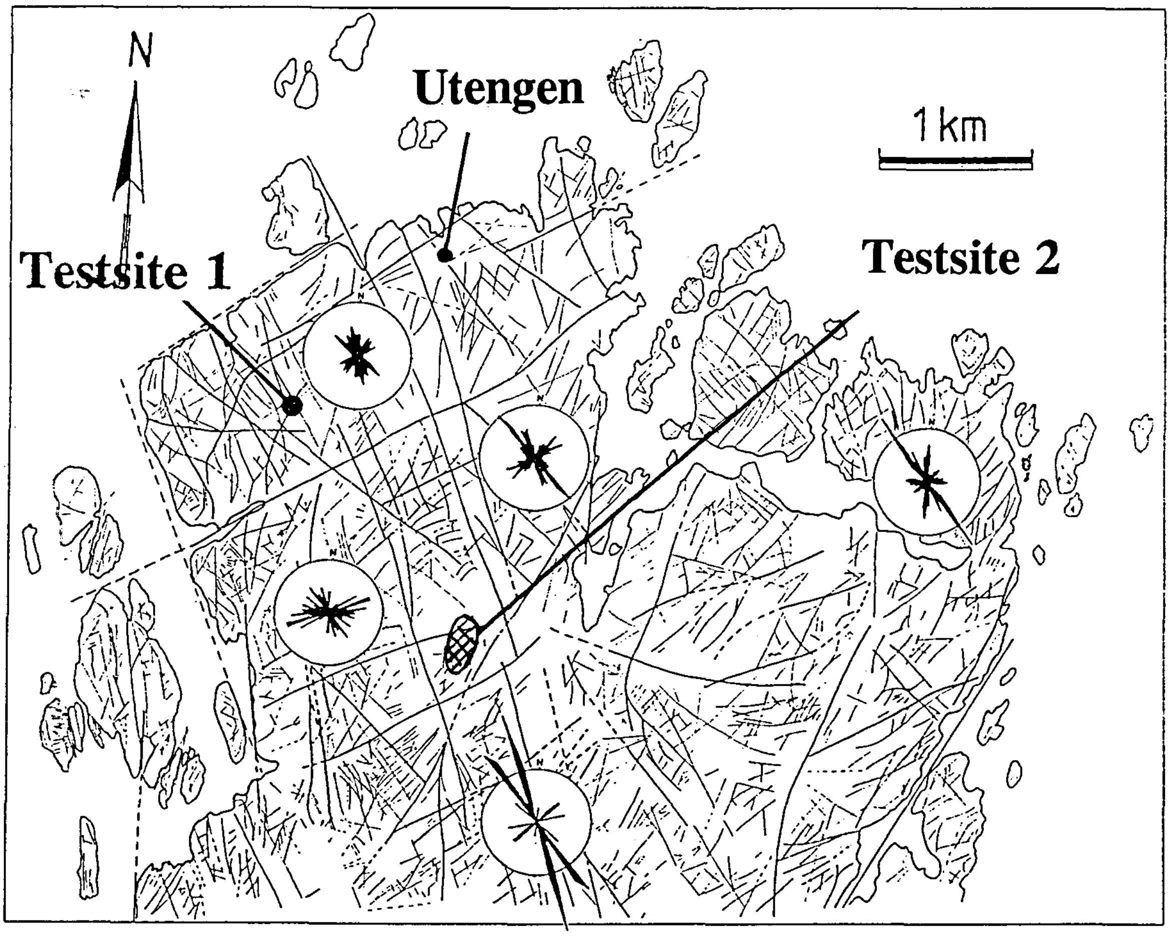


Figure 6. The northern part of Kirkeøy, showing lineaments identified from aerial photos. Rose diagrams show fracture strikes identified from field measurements (only fractures with dip ≥45° are included). N = 1167, 31 localities. Testsite 1 = Pulservik, Testsite 2 = Reffsgård.

Huntoon 1986, Rohr-Torp 1987) have identified a regional correlation between the past tectonic stresses which created or reactivated a particular fracture pattern and the permeability of the constituent fractures/fracture zones, whereas others (Olsson 1979, Selmer-Olsen 1981, Carlsson & Christiansson 1987) have found a correlation between permeability and the current stress field within the rock.

In-situ stress determinations have been carried out at testsite Reffsgård. It was then planned to ascertain if there is any relationship between the orientation of significantly yielding fractures/-fracture zones and the current state of stress, which might be expected to affect the degree of fracture openness. Such investigations have already been carried out at the Fjällbacka site, across the Swedish border, and a variety of methods indicated that the maximum horizontal *in-situ* stress (σ_H) was orientated NW/NNW-SE/SSE. The minimum principle stress was vertically orientated down to depths of c. 500 m (Wallroth 1992) - Fig. 5. By examining water leakages and mineralisations which appear to have formed in open fractures, it was also concluded, at

Fjällbacka, that the NW/NNW-SE/SSE fractures were the most hydraulically open set, followed by the subhorizontal fracture set (Sundquist et al. 1988).

In addition, the transmissivity of fractures or fracture zones may still reflect *palaeostress* conditions. Fracture mapping (Banks & Rohr-Torp 1991 - Fig. 6) has not been able to produce a totally unequivocal interpretation of the origin of Kirkeøy's fracture pattern, but it seems likely that the major fracture zones date from an early period of the granite's history. The fracture pattern has almost certainly been reactivated or modified several times during its history; for example, during the Permian opening of the Oslo rift, post-rifting strike-slip movements along the Oslo graben boundary fault (Størmer 1935 - see Fig.2), and possibly even by glacial and post-glacial stresses (Lagerbäck 1979). Three major dolerite dykes have hitherto been found on Hvaler, one striking ca. 160° across Kirkeøy past Holtekilen and Sandbrekke, one at Skams Klove on Kjøkøy and one on Asmaløy, all with similar orientations. The dykes appear to give a Permian palaeostress direction for σ_H (NNW-SSE) which is consistent with the current in-situ σ_H at Fjällbacka, and consistent with the main Oslo Graben tectonic grain (Ramberg & Larsen 1978). Their strike is similar to the major fracture direction on Kirkeøy (Banks & Rohr-Torp 1991), including the major fracture zone at testsite Pulservik, and the fracture zones in the Hvaler tunnel. The NNW-SSE σ_H is consistent with the hydraulically open fractures mapped at Fjällbacka, and with the result from Pulservik (Banks et al. 1991).

5 Surface geophysics

In July 1993, four surface geophysical profiles were run at the Reffsgård testsite, in the vicinity of boreholes A, B and C (see Fig. 7), using both very low frequency (VLF) and total field magnetometry, two methods which have given promising results at other localities on Hvaler (Lauritsen & Rønning 1991). VLK-Re was measured as dip-angle with equipment made at NGU. Magnetometry was measured using Geometrics Unimag 836 with resolution $\pm$ 5 nT. The profiles are presented in Figs.8a-d.

The VLF results for profile 6A (Fig.8a) show a weak anomaly (dip in the Re-curve) at approx. position 52. A weak fall in the Im-curve at the same place indicates poor conductivity. The anomaly is coincident with the fracture zone which can be a continuation of the dolerite dyke mapped at Svanekilen and Sandbrekke. If this is the case, the dolerite is weathered and eroded away.

The magnetic results, for the same profile (Fig.8a), show two clear low magnetic anomalies at positions 55 m and 70 m. In addition, the section between these anomalies has a generally lower magnetic field than the rest of the profile. This anomaly area corresponds to the VLF-anomaly. Magnetic susceptibility measurements have been carried out on hand specimens from the dolerite dyke and surrounding granite at Svanekilen (Table 1). These measurements show that the dolerite has an average susceptibility value which is clearly higher than granite (c. 20 times higher). The low-magnetic section at Reffsgård appears thus to be a fracture zone and not an eroded dolerite dyke. Small negative magnetic anomalies are also detected at positions 36 m and 85-90 m, without fractures being observed in the terrain at the surface. The magnetic profile is, in addition, affected to some extent by a suspended electricity line at position 23 m.

Sample nr.:	Species of rock:	Susceptibility:
71a	Dolerite	0.12592
71b	Dolerite	0.11582
71c	Dolerite	0.12467
71d	Granite	0.00368
71e	Granite	0.00008
71f	Granite	0.01064
71g	Granite	0.00884
72a	Dolerite	0.11103
72b	Dolerite	0.10387

Table 1: Susceptibility of rock samples from Svanekilen.

The VLF-Re curve for profile 6B (Fig.8b) shows a very weak anomaly at approx. position 115. The Im curve corresponds to this and thus indicates poor conductivity. The anomaly lies at the centre of the main NNE-oriented fracture zone, which is crossed at an acute angle.

The magnetic curve for profile 6B (Fig.8b) shows a magnetic low area between positions 105 and 145. This corresponds with the NNE-oriented fracture zone's width, as apparent at the surface. A small negative magnetic anomaly at position 50 is coincident with a lesser NE-oriented fracture.

Profile 6C (Fig.8c) crosses the same fractures as profile 6B. VLF-measurements gave, however, no clear anomaly over the NNE-oriented main fracture zone, as was the case for profile 6B.

Magnetic measurements along profile 6C (Fig.8c) show low-magnetic anomalies at approx. positions 20, 50, 80 and 95 m. The anomaly at position 20 m corresponds with that for the previously discussed NE-oriented fracture, while the anomaly at position 50 m coincides with the NNE-oriented main fracture zone. At position 80 m a thin fracture can be seen at the surface, while the reason for the anomaly at position 95 m is somewhat uncertain. The section

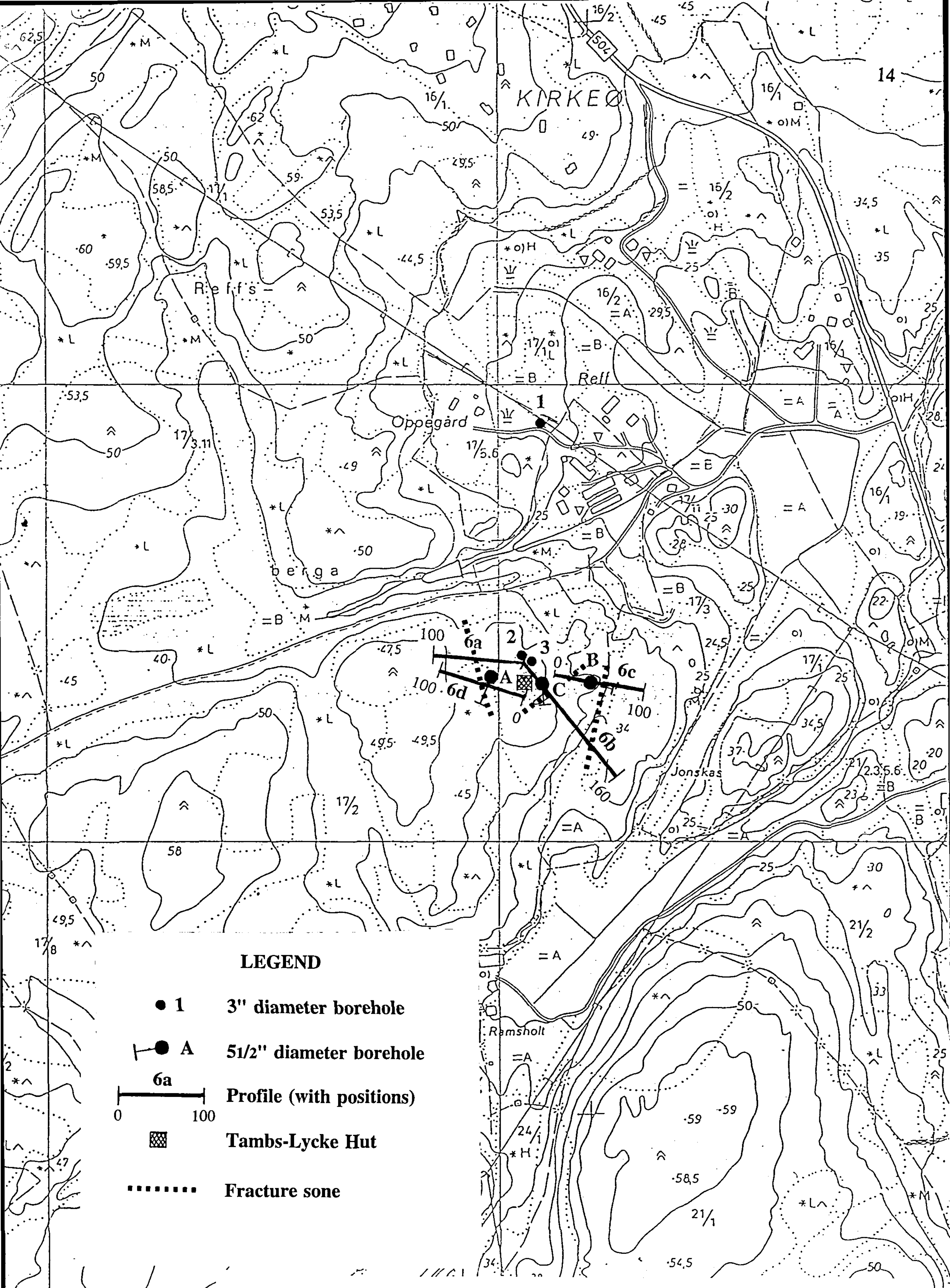
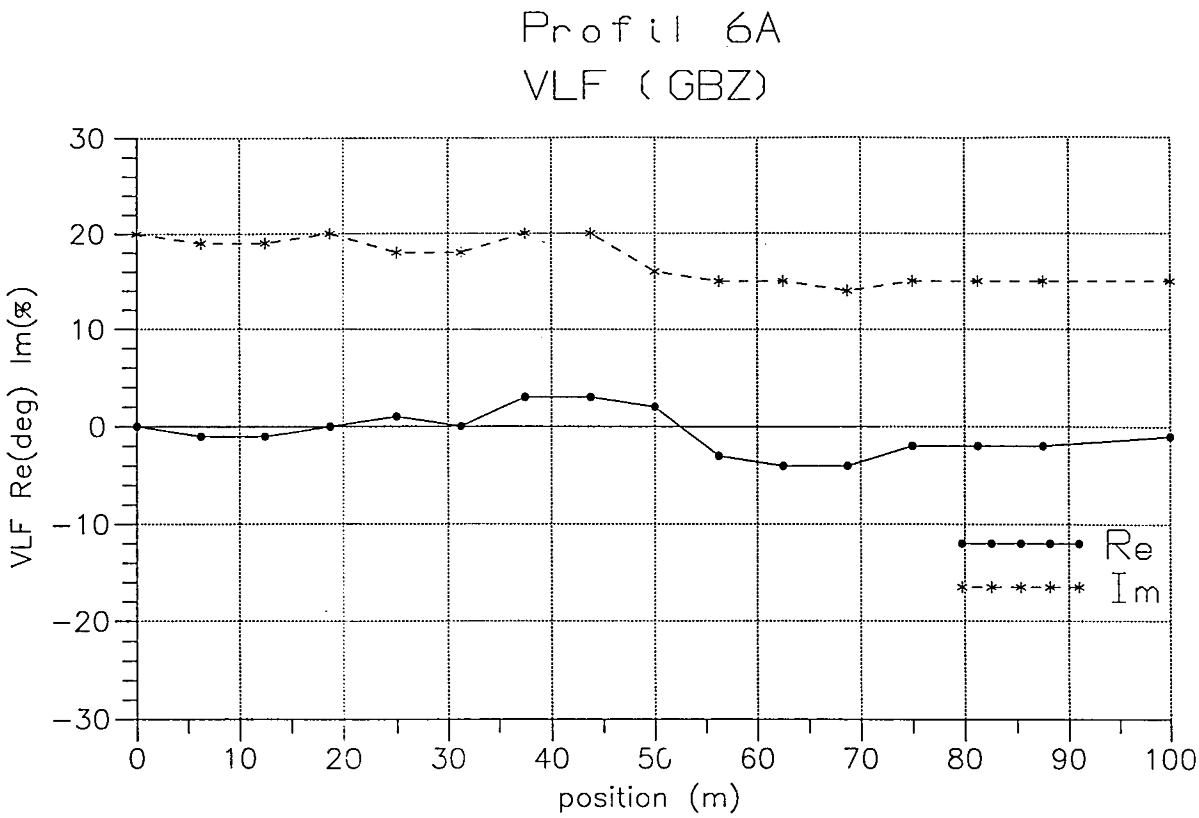


Figure 7 Geophysical profiles and boreholes location at Reffsgård



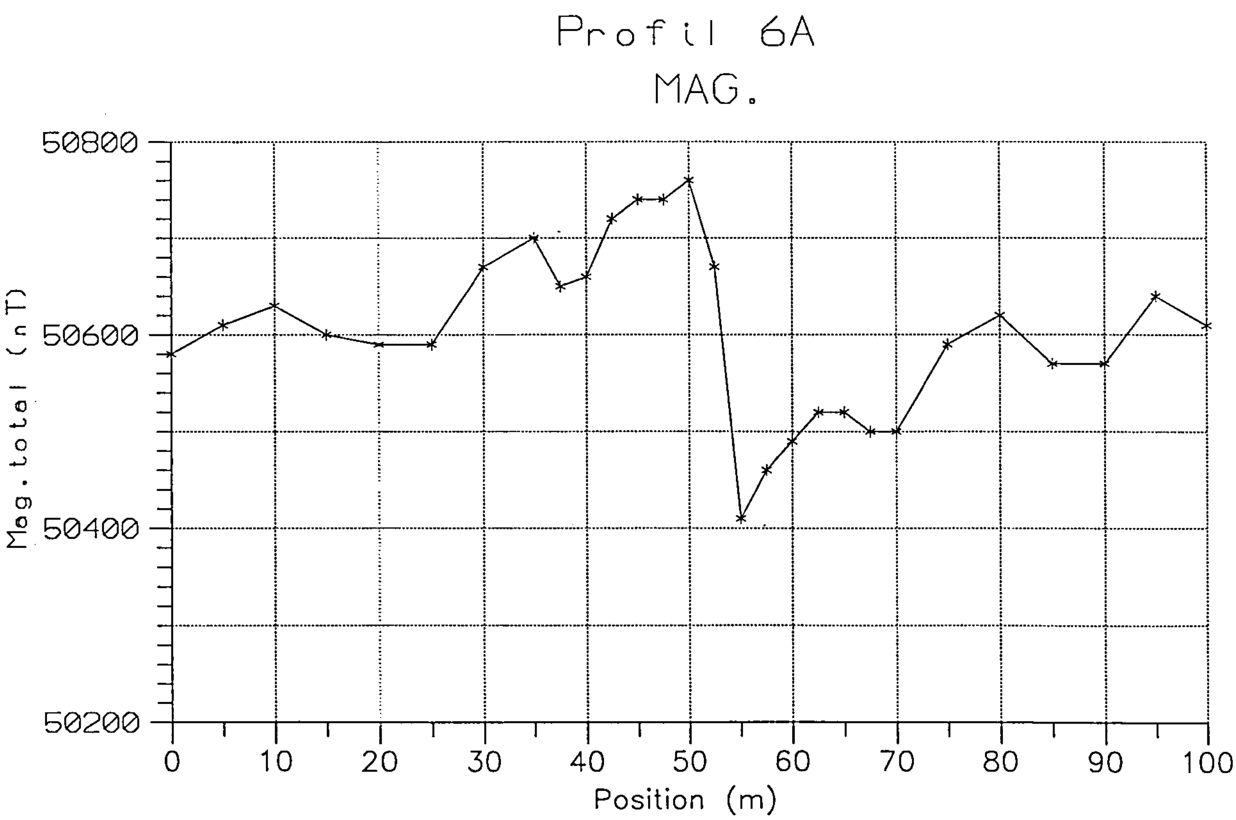
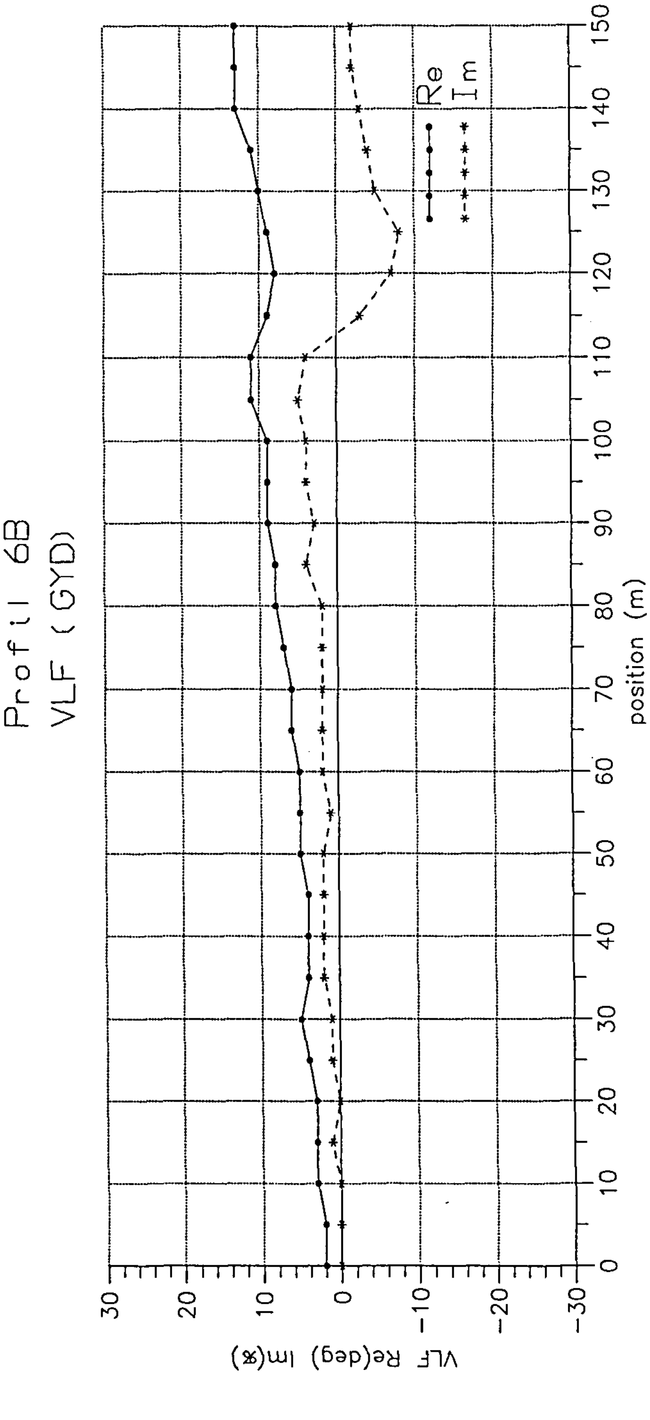


Figure 8a **Geophysical profile 6a from Reffsgård**



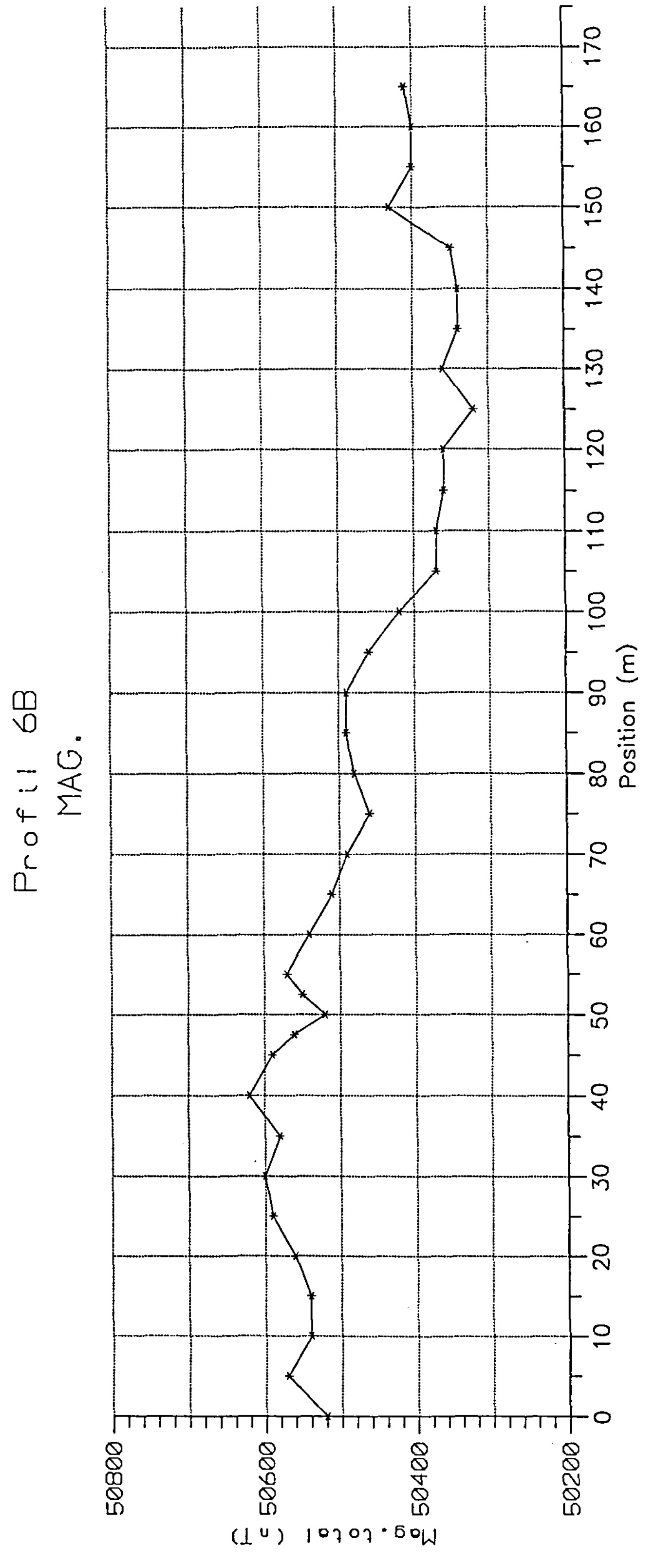
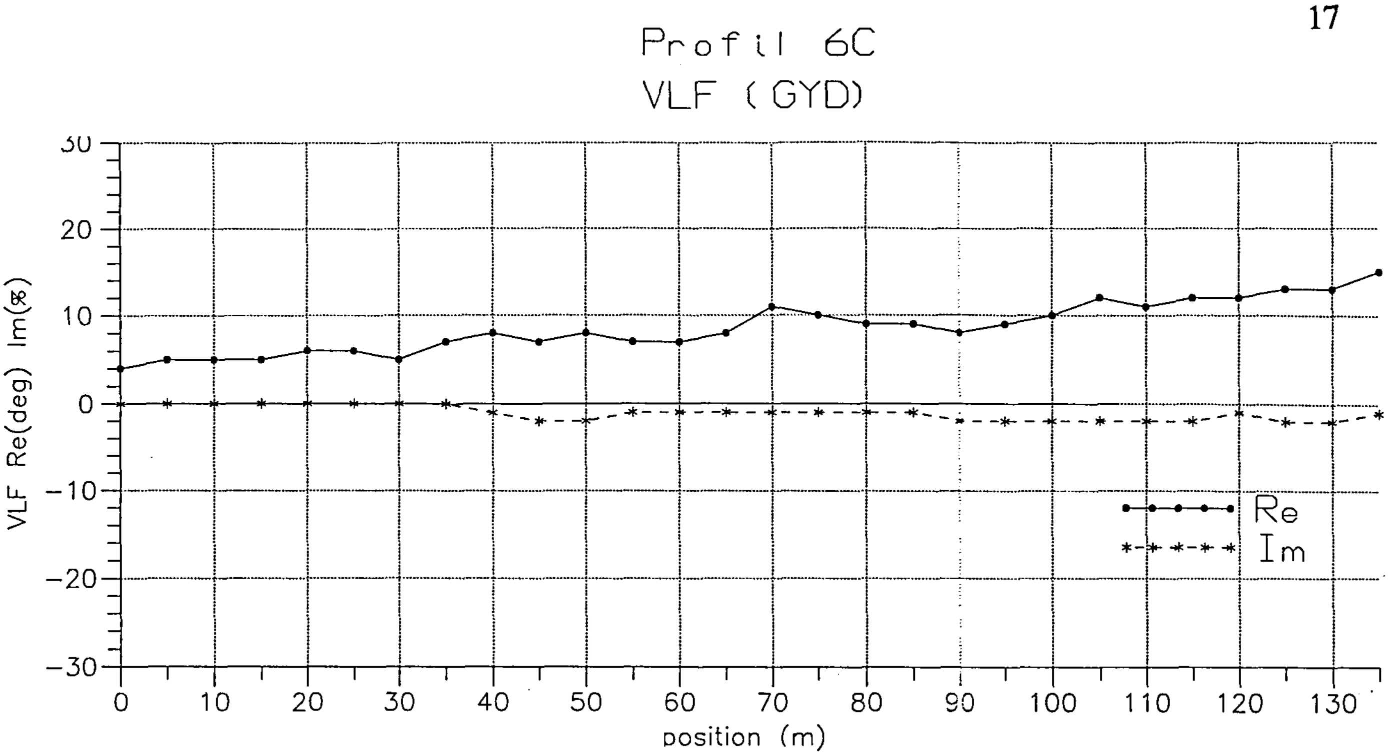


Figure 8b **Geophysical profile 6b from Reffsgård**



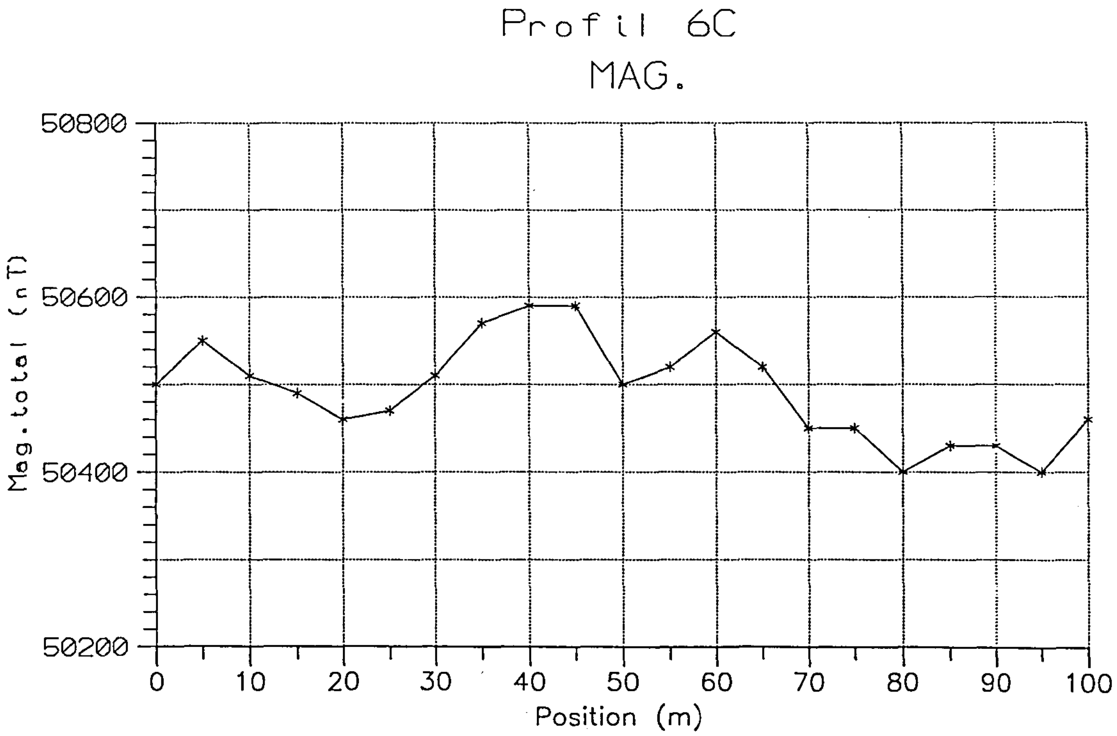
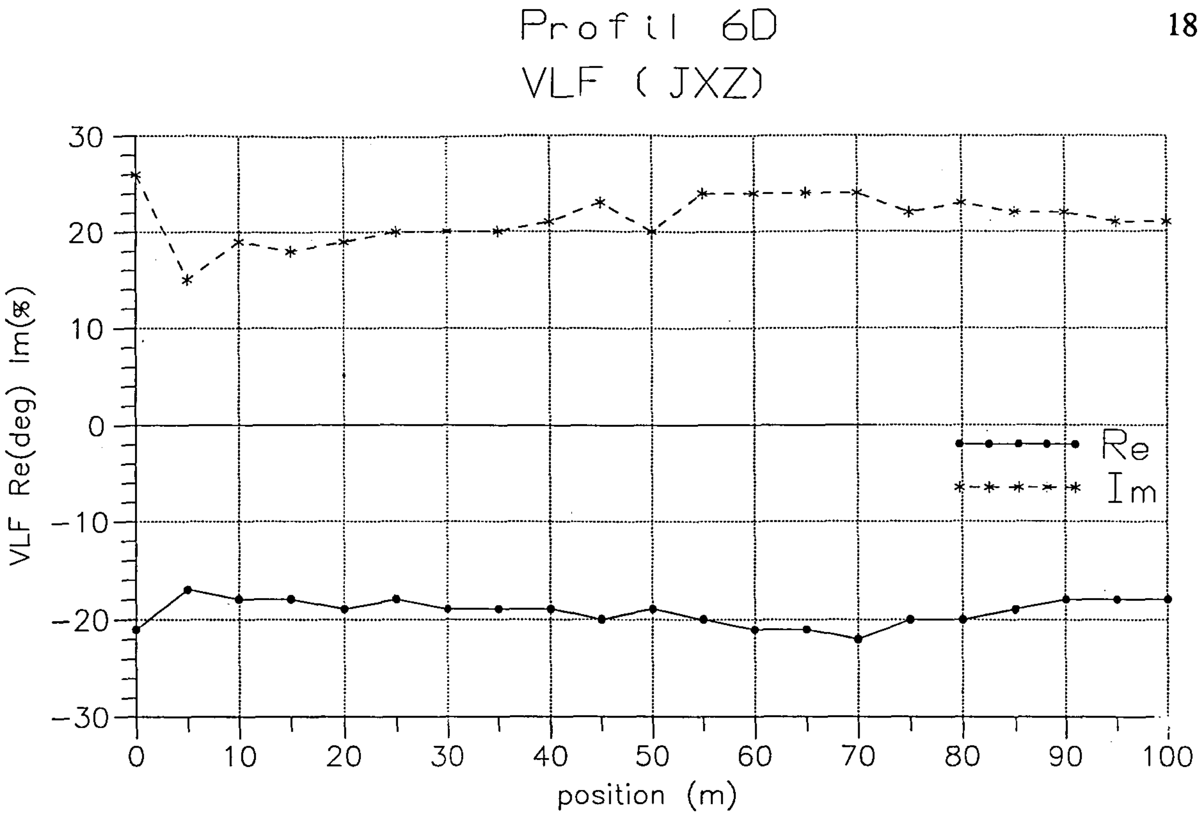


Figure 8c **Geophysical profile 6c from Reffsgård**



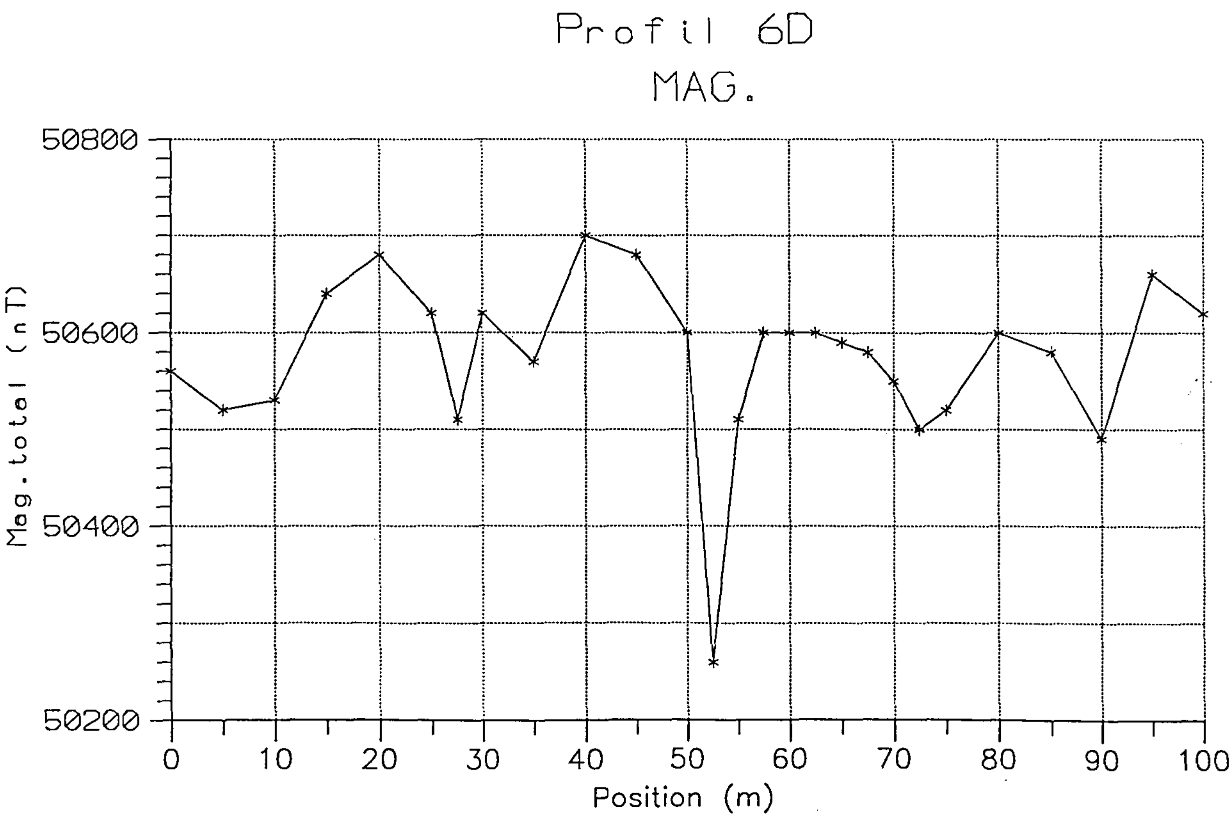
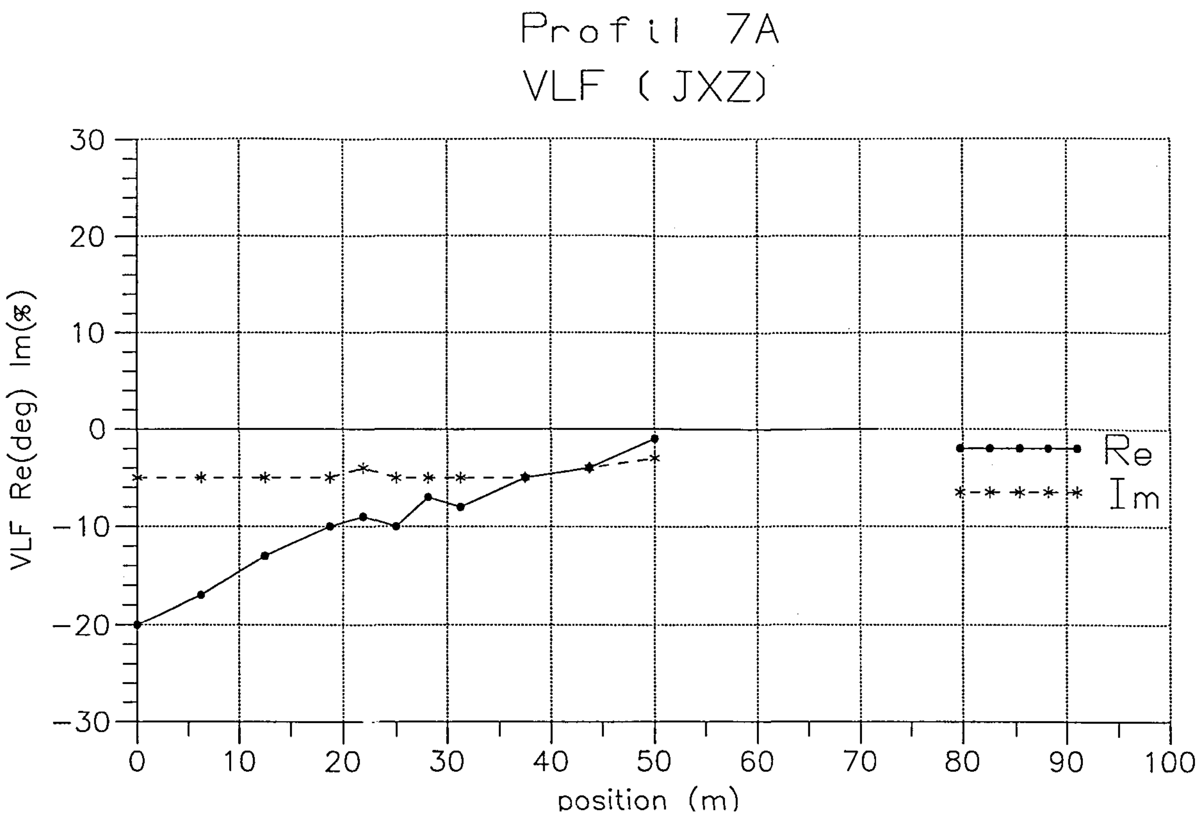


Figure 8d **Geophysical profile 6d from Reffsgård**



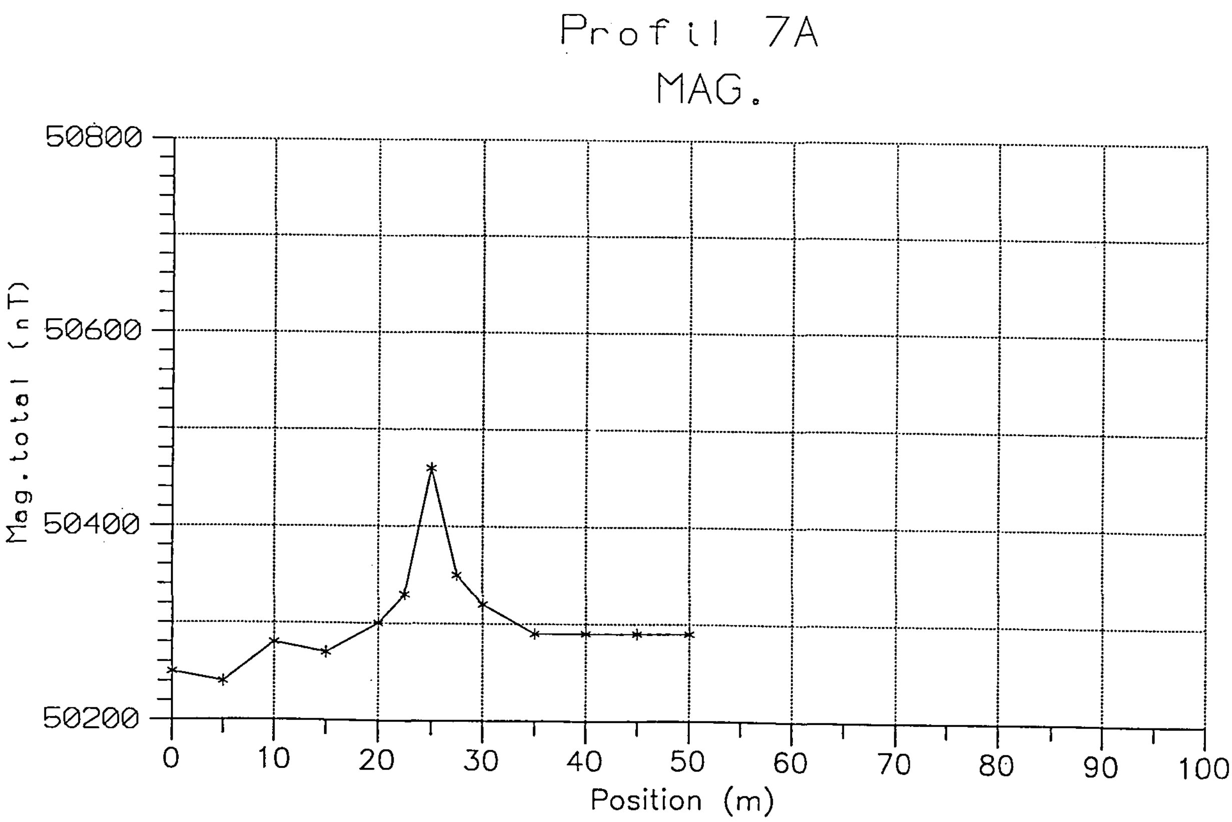


Figure 9 **Geophysical profile 7a from Svanekilen**

between positions 75 and 100 m is, however, charaterised by small, densely spaced, joint-controlled "benches".

Profile 6D (Fig.8d) lies almost parallel to profile 6A, but starts c. 30 m further south. Due to problems with reception, this profile was measured with a different VLF transmitter to profile 6A. The VLF-measuremets gave no clear indications of fracturing in the bedrock.

Magnetometric measurements show, however, several narrow negative magnetic anaomalies. The largest of these, at position 52 m, coincides with eastern edge of the NNW-oriented fracture zone, which was assumed to possibly be a continuation of the dolerite dyke. The western edge of that fracture zone is characterized by a weaker anomaly at position 73 m. No magnetic anomalies were found between these two anomalies. The section between positions 52 m and 73 m appears therefore not to be fractured. Anomalies at positions 27 m, 35 m and 90 m correspond to fractures which are exposed at the surface.

A profile was also run across the exposed dolerite dyke (ca. 30 cm wide) at Svanekil (Fig.9), to determine its characteristic geophysical response. Its response is most clearly seen by a sharp positive anomaly in the magnetic total field profile, due to its high magnetite content. The dyke produces a mild response in the VLF profile. Such a sharp positive magnetic anomaly is not noted on profiles 6A or 6D at Reffsgård, casting further doubt on whether the fracture-continuation of the dolerite dyke is in fact filled with dolerite at the Reffsgård locality.

6 Drilling and stress measurement

Towards the end of September 1992, three 3" diameter boreholes were drilled at Reffsgård (boreholes no. 1, 2, 3 - Figs. 3, 7) in apparently massive granite (away from prominent fracture zones) to a depth of c. 42 m by Brødrene Skolt of Moss, using a top-hammer, air flush percussion-type rig. Borehole details are shown in Table 2 below, and drilling logs are presented in Appendix 1. No casing was installed in the boreholes.

Prior to *in-situ* stress determination, borehole 1 was filled with water and the subsequent decline in water level measured. This simple "slug-test" indicated a negligible borehole yield, the decline, when full, being less than 0.5 cm in 15 mins (i.e. with over 11 m excess head). This would imply a short term yield not exceeding 0.1 l/hr with a similar drawdown.

	Borehole 1	Borehole 2	Borehole 3
Drilled length (along borehole axis)	42.4 m	42.4 m	42.4 m
Nominal Diameter	77 mm	77 mm	77 mm
Fall / Direction	90°	90°	90°
Yielding fractures (after drilling)	None	39.6 m (27.5 m)	8.3 m (+ deeper?)
Yield / drawdown (after drilling)	Negligible < 0.1 l/hr / 11 m	"Relatively good"	0.7 l/hr /20 m
Yield / drawdown (after hydrofraccing)	155 l/hr / 24 m	19 l/hr / 15 m	Not hydrofracced
Rest water level (Date)	11.79 mbgl (17/8/93)	8.72 mbgl (14/8/93)	4.05 mbgl (14/8/93)
		11.09 mbgl (11/6/93)	

Table 2: Borehole and short-term testing details; 3" boreholes at Reffsgård

The measurements of *in-situ* stress were carried out in boreholes 1 and 2 by Helge Ruistuen of SINTEF, Trondheim, in June 1993. The method employed involved hydraulic fracturing of the granite using water pressure applied between packers. The pressure at which the fracturing occurs is carefully recorded, and can be related to the magnitude of the *in-situ* stress plus the tensile strength of the rock. The directions of the principle stresses are obtained by using an oriented impression packer, which retains a "cast" of the newly created fracture. The fracture will typically be created perpendicular to the direction of minimum horizontal stress (Myrvang 1979, Fairhurst 1986).

The stress measurements were carried out in the period 10-16 June 1993 by Helge Ruistuen of SINTEF and Helge Skarphagen of NGU. Five borehole sections in 3" boreholes 1 and 2 were tested, giving the following results (Table 3):

BOREHOLE 1

Test depth (m)	P_b (MPa)	P_{isi1} (MPa)	P_{isi2} (MPa)	P_{o1} (MPa)	P_{o2} (MPa)	Fracture orientation
10	-	8.5	8.6	7.9	8.7	N173°E (somewhat uncertain)
20	-	8.1	-	10	-	N195°E
35	10.2	2.6	1.9	10.4	2.8	Non-vertical Poor impression

BOREHOLE 2

Test depth (m)	P_b (MPa)	P_{isi1} (MPa)	P_{isi2} (MPa)	P_{o1} (MPa)	P_{o2} (MPa)	Fracture orientation
10	-	-	8.4	8.8	9.0	No impression
17	-	8.6	-	11.5	-	N191°E

P_b = fracturing pressure
P_{isi} = instantaneous shut-in pressure
P_o = opening pressure

Table 3. Results of *in-situ* stress measurement, Testsite Reffsgård

The results indicate that the stress field can be considered constant between the two holes. Apart from the deepest section in borehole 1, only small variations in the stress parameters were noted. The reason that results from 35 m in borehole 1 deviated significantly from the other results was due to non-vertical fracturing. In addition, this section was the only one where fracturing of intact rock occurred (Ruistuen 1993, pers.comm.).

Results from stress measurement in boreholes 1 and 2 implied a minimum horizontal stress orientated c. 103° from north (i.e. ESE) and a maximum horizontal stress oriented at c. 13° (NNE). The shut-in and opening pressures (related to the minimum horzontal stress σ_h) of 8 - 11.5 MPa are also extremely high for such shallow depths.

Once in-situ stress was obtained at Reffsgård, oriented boreholes were drilled both perpendicular and parallel to the direction of maximum horizontal stress. One would expect permeability to be higher in fractures parallel to the maximum stress, and thus water yield to be greatest in boreholes oriented perpendicular to the most permeable fractures (Banks 1992) and thus to the maximum stress (all other factors being equal, which, of course, they're probably not - Odling 1993).

7 Drilling of 5½" test boreholes

During June 1993, three 5½" diameter test boreholes were drilled to c. 70 m in the vicinity of boreholes 2 and 3 by Brødrene Myhre of Hønefoss, using down-the-hole-hammer air flush techniques. These are referred to as boreholes A, B and C (Figs. 3, 7).

Borehole A was drilled parallel to maximum σ_H (SSW), into the suspected "dolerite dyke" fracture seen in the surface topography and in aerial photos, although no dolerite was observed in the drilling cuttings.

Borehole B was drilled parallel to σ_h (ESE) towards a minor fracture zone (oriented SSW), visible in the topography as a narrow valley filled with arable Quaternary deposits. No sign of any clear fracture zone was noted when drilling.

Borehole C was drilled nearly parallel (SSE) to σ_H towards another minor fracture zone (oriented NE). No sign of any clear fracture zone was noted when drilling. Borehole logs are given in Appendix 2, but all three boreholes were very disappointing, giving negligible yields. No casing was installed in the boreholes.

	Borehole A	Borehole B	Borehole C
Drilled length (along borehole axis)	73 m	70 m	70 m
Nominal Diameter	140 mm	140 mm	140 mm
Fall / Direction	65°/ 200°	70°/ 109°	70°/ 172°
Yielding fractures (after drilling)	c.35 mbgl (c.6-6.5 m)	None	None
Yield / drawdown (after drilling)	5 l/hr / 20 m	0.22 l/hr / 39 m	0.27 l/hr / 40 m
Rest water level (Date) (along borehole axis)	17.24 mbgl (13/8/93)	10.26 mbgl (13/8/93)	8.86 mbgl (13/8/93)

Table 4: Borehole and short-term testing details; 5½" boreholes at Reffsgård
(bgl = below ground level)

8 Geophysical logging

In October 1992 and July 1993, the 3" and 5½" boreholes respectively were geophysically logged by NGU. The logging was done using an ABEM Terrameter SAS 300 and an ABEM SASlog 200 which are able to measure formation resistivity at three configurations, fluid resistivity, temperature and self potential. In July 1993, boreholes A-C had still not recovered to their rest water level following drilling. Water was thus brought in by bowser and used to top up these three boreholes. It was thus not meaningful to measure Self Potential (SP) or fluid temperature in these boreholes.

	Borehole A	Borehole B	Borehole C
Water level prior to filling (mbgl)	33.5 m	69 m	70 m
Water level one day after filling (mbgl)	c. 10 m	ca. 3 m	ca. 2 m

Table 5 Condition of boreholes A-C during geophysical logging (ca. 5/7/93)

Borehole 1

Rest water level was c. 11½ m under ground level during logging. The temperature log (Fig. 10a) shows a section with stable or slightly decreasing temperature between 12½ and 17 m (c. 7.1°C). Below 17 m the temperature increases evenly, due to the prevailing geothermal gradient, from 7.1° at 17 m to 7.4°C at 42.5 m, a gradient of 0.012°/m. A rather small anomaly, possibly indicating inflow, can be noted at 34.5 m.

The fluid resistivity log reflects the ρ_f of the formation water, namely c. 50-60 ohmm which is equal to a conductivity of c. 170 -200 μS/cm. Anomalies can be seen at 15½ m, 36½ m and 41 m, possibly indicating minor inflows of formation water.

The resistivity logs display minima at c. 13½ m, c. 37 m and c. 41½ m, potentially indicating enhanced fracturing or mineralisation. The latter two depths agree well with anomalies on the fluid resistivity log. The anomaly at 37 m may correspond to a biotite-rich vein noted in the drilling log. The middle part of the log is rather featureless with ρ_a values around 15000 ohmm (short normal - SN) and 20000-30000 ohmm (long normal - LN) indicating unfractured bedrock.

Borehole 2

The temperature log (Fig. 10b) shows a "surficial" section with decreasing temperature between 11 and 20 m. Below 20 m the temperature increases evenly, due to the prevailing geothermal gradient, from 7.19° at 20 m to 7.22°C at 42 m, a gradient of 0.0014°/m, which is extremely low. Rather small anomalies, possibly indicating inflow, can be noted at 26½ m, 30 m, 35½ m and 37½ m.

The fluid resistivity log reflects the ρ_f of the formation water, namely c. 130-140 ohmm, which is equal to a conductivity of c. 70 - 77 μS/cm, above 39 m. Below 39 m, the ρ_f is clearly lower at 70-90 ohmm, corresponding to conductivity of 110-140 μS/cm. This could indicate inflow (and upflow along the borehole) of fresher groundwater at 39 m, while below this level is more "stagnant" higher conductivity water. This feature could also be due to a higher-conductivity "slurry" of drilling cuttings in the base of the borehole. Anomalies can also be seen at 16 m, 18 m, 21 m, 23 m and 28 m, possibly indicating minor inflows of formation water.

The resistivity log displays minima at 16 m, 18 m, 21 m, 23 m, 28 m and 39½ m, potentially indicating enhaced fracturing or mineralisation. These depths agree well with anomalies on the fluid resistivity log, and with fractures noted during drilling. The largest anomaly is noted at 39½ m, and is also noted as the main water-yielding horizon during drilling. The smaller anomalies are only prominent on the short normal (SN) log, indicating thin single fractures. The section of the log between 28 and 38 m is rather featureless with ρ_a values around 20000 ohmm (SN) and 20000-30000 ohmm (LN), indicating unfractured bedrock.

The self potential (SP) log also displays anomalies at 18 m, 21 m, 23 m, 28 m and 39½ m, confirming the anomalies registered on the previous logs.

Borehole 3

The temperature log (Fig. 10c) shows a "surficial" section with decreasing temperature (from 9.8° to c.7.45°C) between 5 and 25 m. Below 25 m the temperature is approximately constant at around 7.45°C, again indicating anomalous temperature conditions. A large anomaly can be observed around 10 m, and rather small anomalies, possibly indicating inflow, can be noted at 25½ m, 27½ m, 29½ m, 37 m and 40 m.

The fluid resistivity log reflects the ρ_f of the formation water, namely c. 50-90 ohmm, which corresponds to a conductivity of c. 110 - 200 μS/cm. Apart from the section from 5 - 9m, the fluid resistivity seems to increase in a "stepwise" manner, the steps occurring at c.21½ m, 30 m and c. 35½ m, possibly indicating inflows or outflows. Other anomalies occur at c. 9 m, 22½ m and 26½ m.

The resistivity log (SN) displays minima at 21 m, 30 m and 35 m, potentially indicating enhanced fracturing or mineralisation. The latter two are also seen on the LN log. These depths agree well with anomalies on the fluid resistivity log. Indeed, in a simliar manner to the fluid resistivity log, the ρ_a (SN) appears to increase in a stepwise manner downhole, from c. 4500 ohmm at 11 m to c.23,000 ohmm at c. 38 m. The large anomaly at 35 m may be significant in relation to the fact that between 35 and 39 m during drilling, all cuttings and drilling air circulation disappeared (see Appendix 1). Smaller features also occur at c. 9-10 m and 40½ m. The main water-yielding horizon encountered during drilling was at 8.3 m, possibly corresponding to anomalies noted on temperature, fluid resistivity and resistivity logs at around 9 - 10 m.

The self potential (SP) log is not easy to interpret, but displays a break in slope at c. 10 m and anomalies at 30 and 35 m. Other anomalies are found at 13 m, 19½ m, 22½ m, 25 m, 28 m, 33 m and around 40 m.

Borehole A

The fluid resistivity log (Fig.11a) reveals a boundary at c. 35 m between natural groundwater (ρ_f = 25 - 40 ohmm, σ_f = 250 - 400 μS/cm) and the added, apparently rather brackish, water (ρ_f = c. 10 ohmm, σ_f = c. 1000 μS/cm). Small anomalies can be seen at 14-15 m, 20 m, 24-32 m, 48 m, 52-54 m, 60 m, 62 m and 66 m, possibly indicating minor inflows of formation water. Any anomalies in the zone 30 - 38 m are rather masked by the transition from natural to added water, although a possible inflow anomaly is visible at c. 34 m.

The short normal (SN), long normal (LN) and laterolog (LL) resistivity logs all reveal some degree of lowered apparent resistivity, implying enhanced fracturing, between 25 and 37 m. The minimum ρ_a is around 35 m, with a value of c. 380 ohmm (SN) and c. 950 ohmm (LN), the location agreeing well with observations of fracturing during drilling. Smaller minima can also be seen around 45m, 54 m, 61 m and 66 m. Few features can be distinguished above 25 m, and the rather high resistivity indicates very low porosity.

Borehole B

The fluid resistivity (Fig.11b) log reflects the ρ_f of the added water, namely c. 10 ohmm = c. 1000 μS/cm. Small anomalies can be seen at 10-11 m, 31-32 m, 51 m and 67 m, possibly indicating minor inflows of formation water. The largest anomaly is at c. 10-11 m.

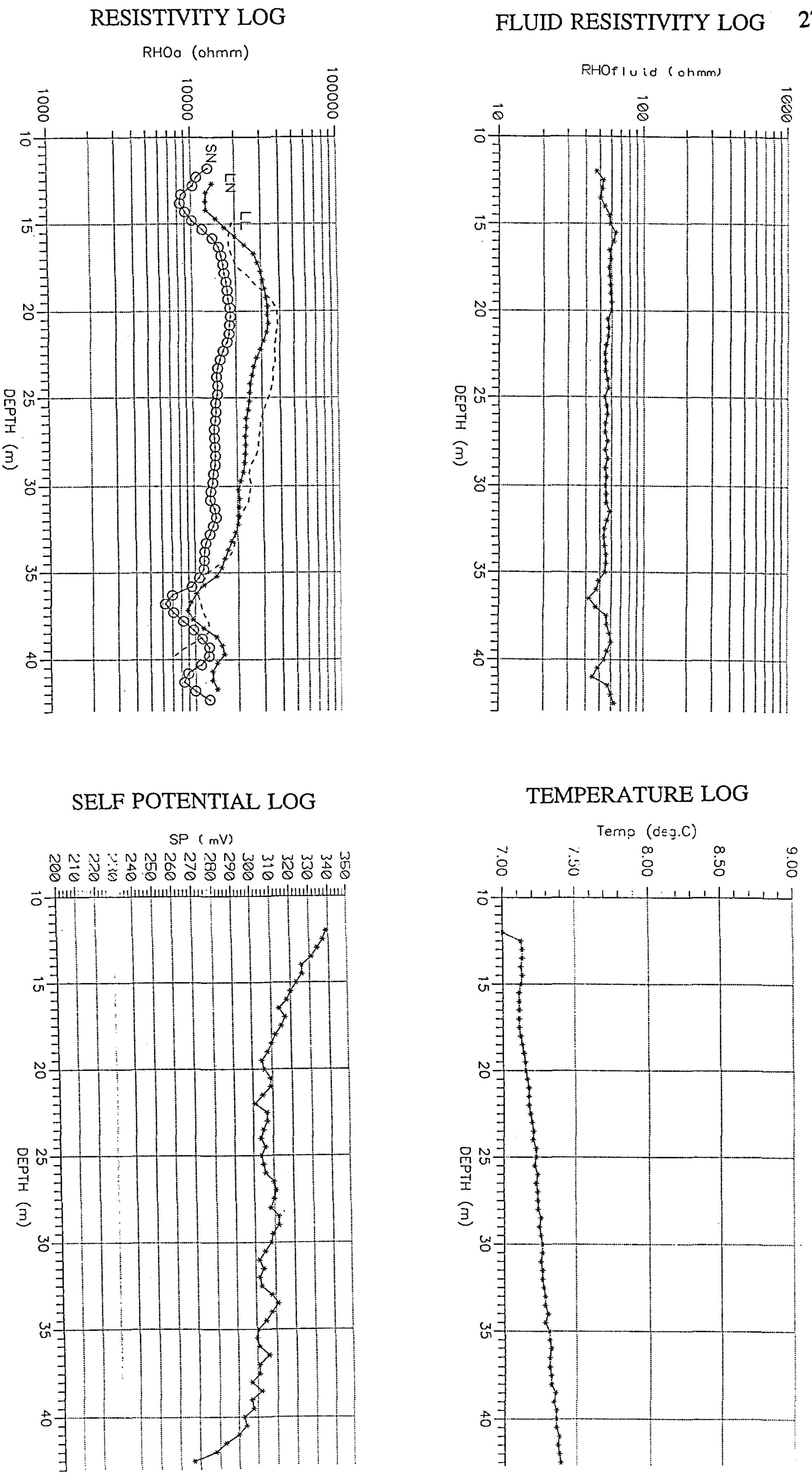
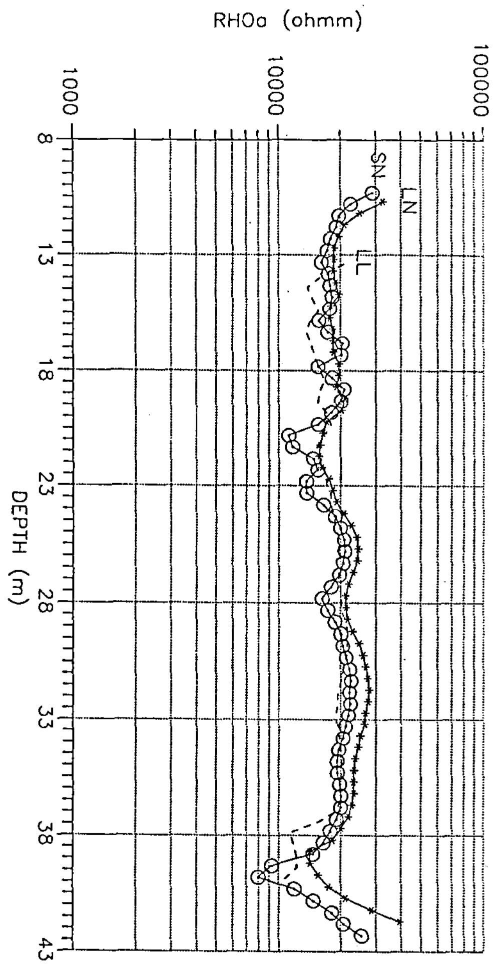
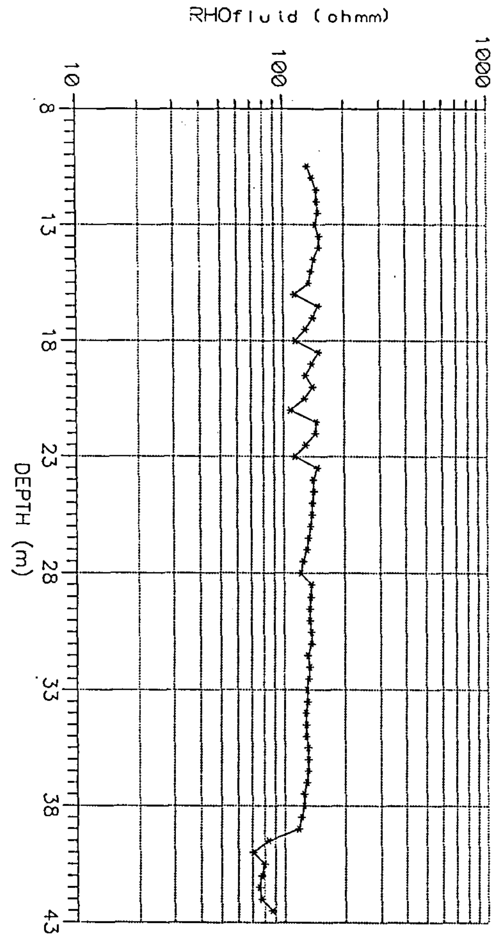


Figure 10a **Borehole logs from 3" borehole nr.1 at Reffsgård**

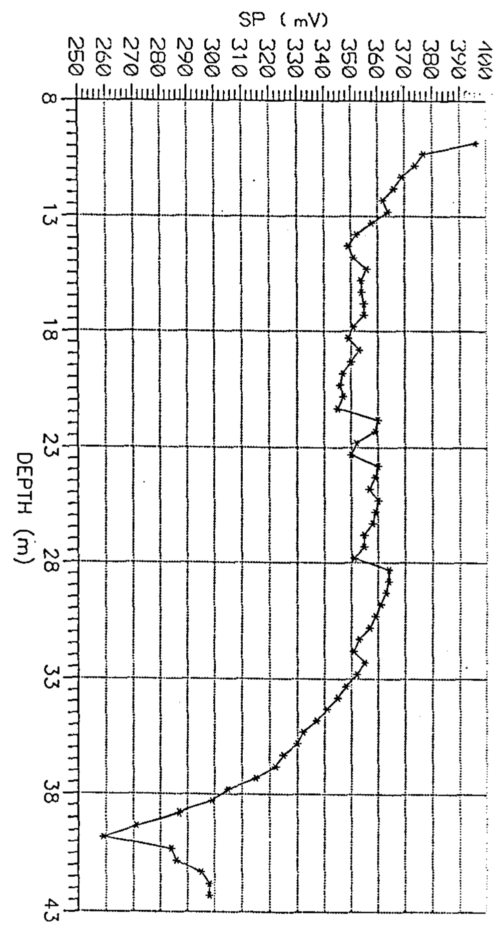
RESISTIVITY LOG



FLUID RESISTIVITY LOG



SELF POTENTIAL LOG



TEMPERATURE LOG

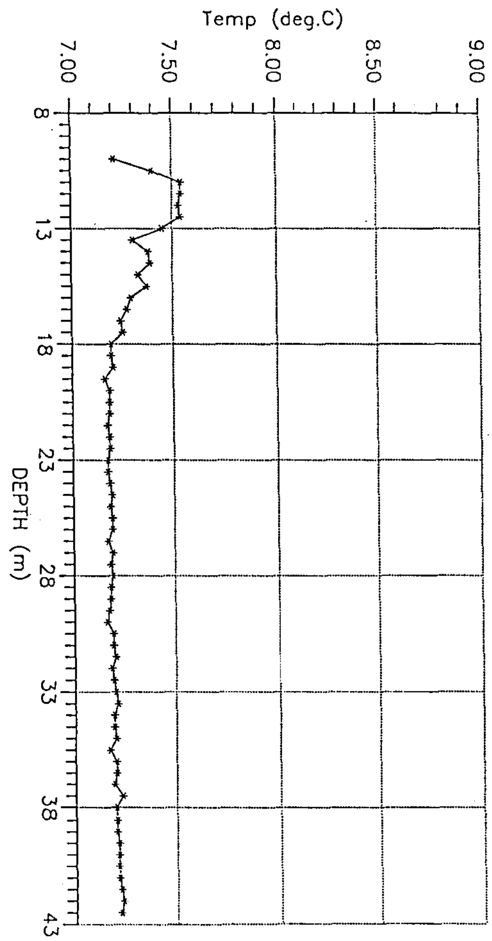
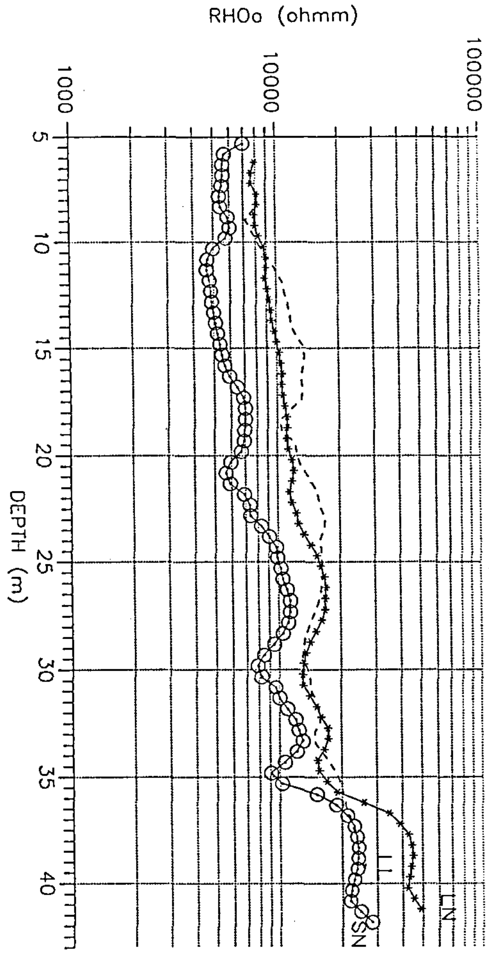
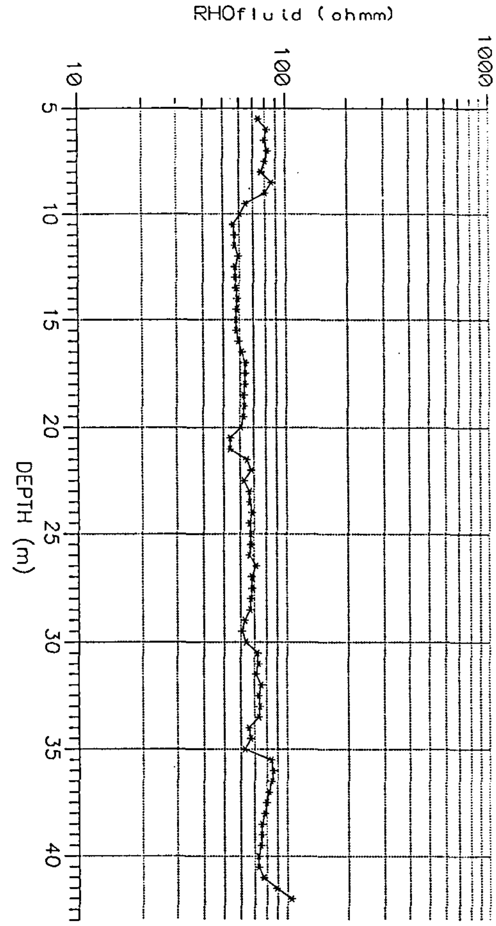


Figure 10b **Borehole logs from 3" borehole nr.2 at Reffsgård**

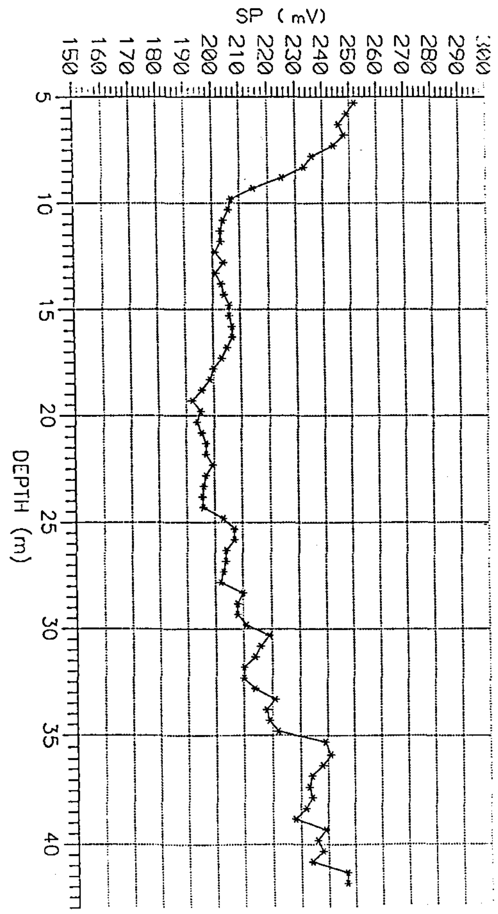
RESISTIVITY LOG



FLUID RESISTIVITY LOG



SELF POTENTIAL LOG



TEMPERATURE LOG

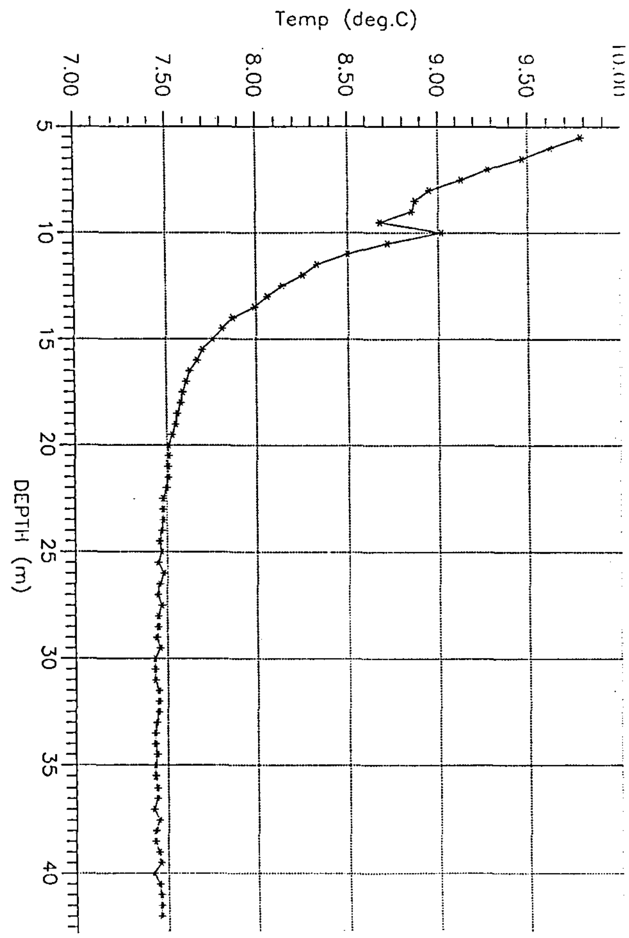
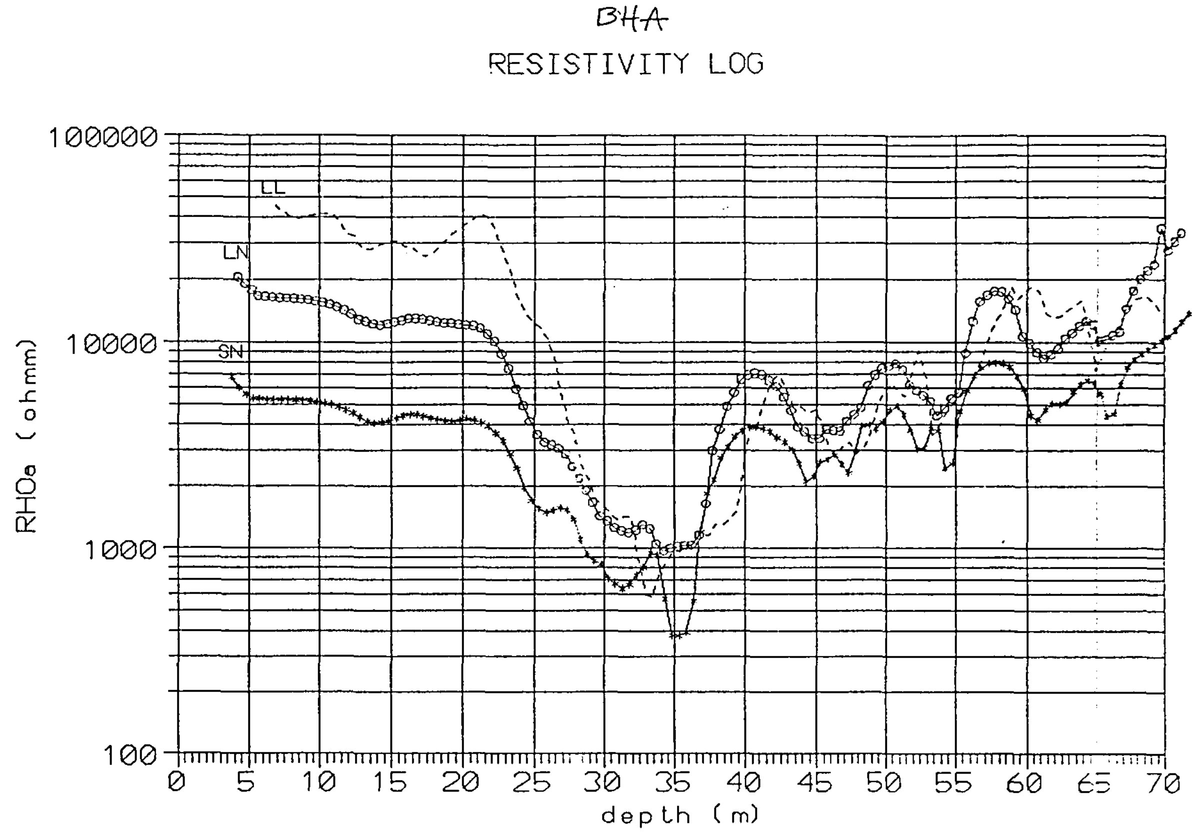


Figure 10c Borehole logs from 3" borehole nr.3 at Reffsgård



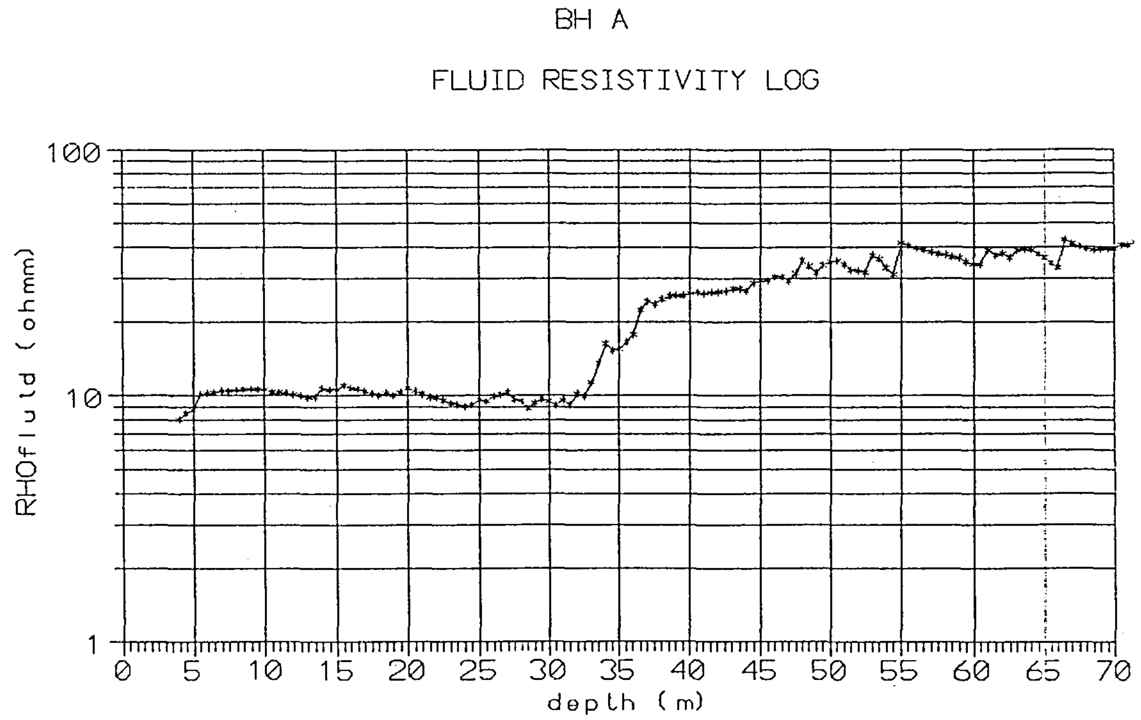
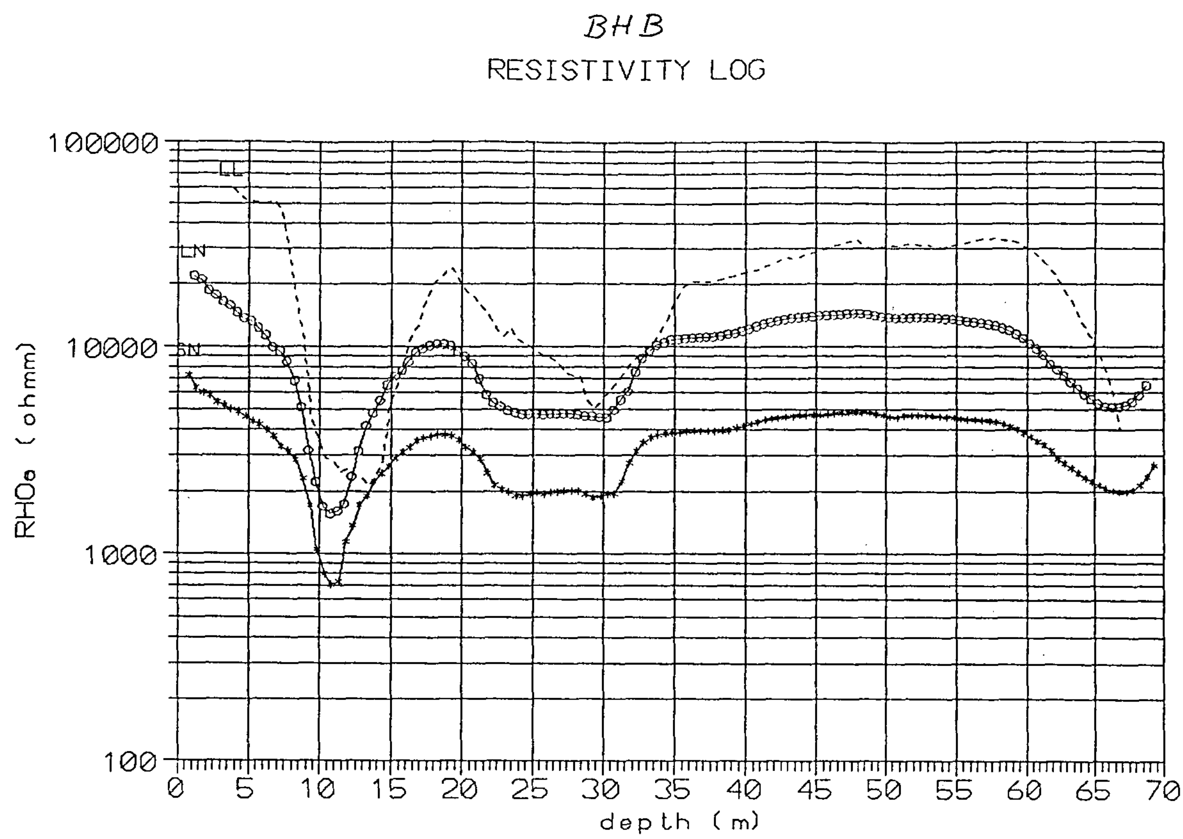


Figure 11a **Borehole logs from $5^1/_2$" borehole nr.A at Reffsgård**



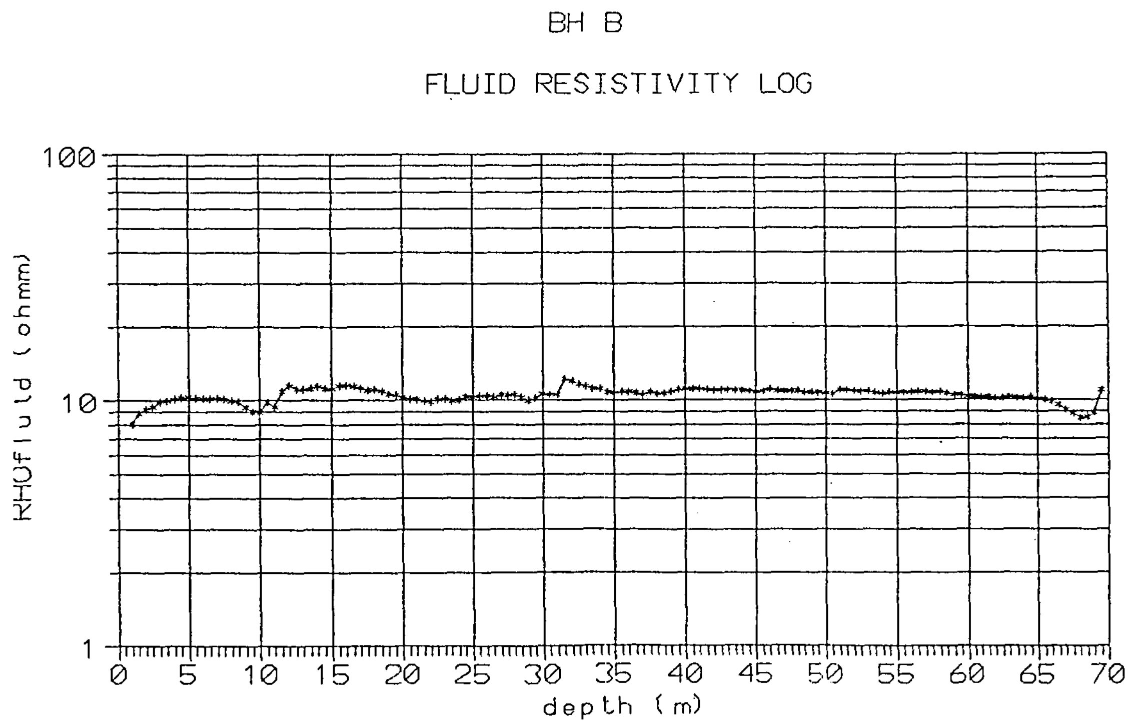
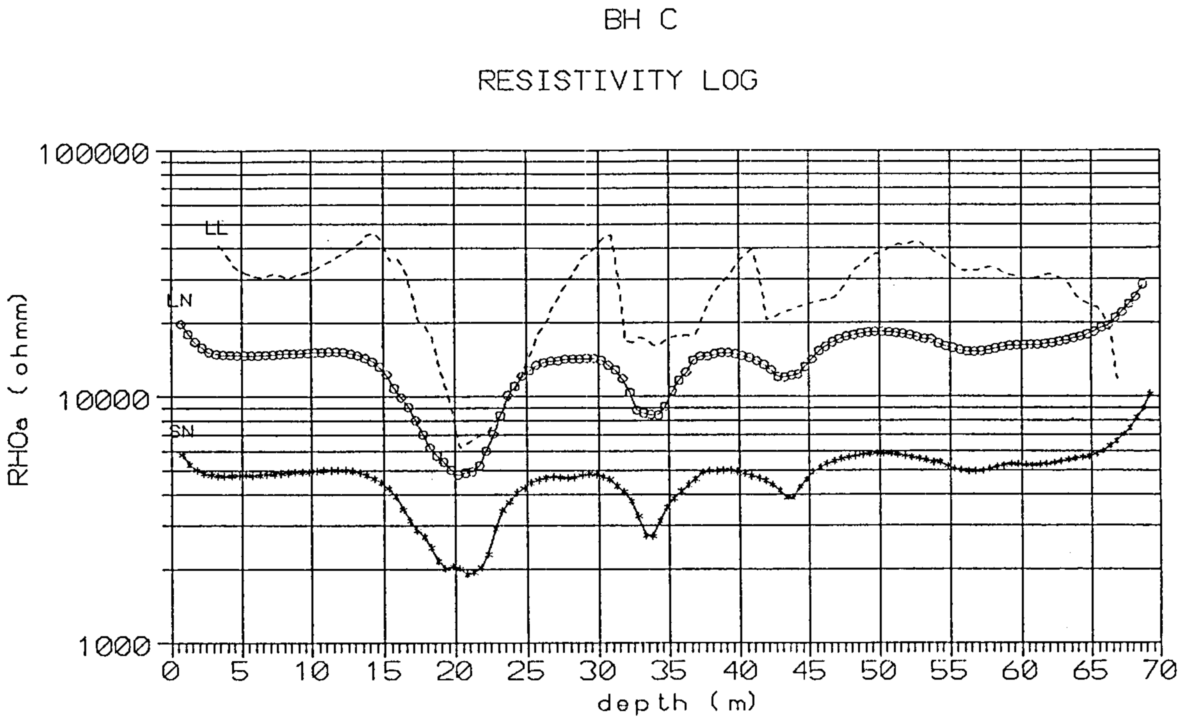


Figure 11b **Borehole logs from $5^1/_2$" borehole nr.B at Reffsgård**



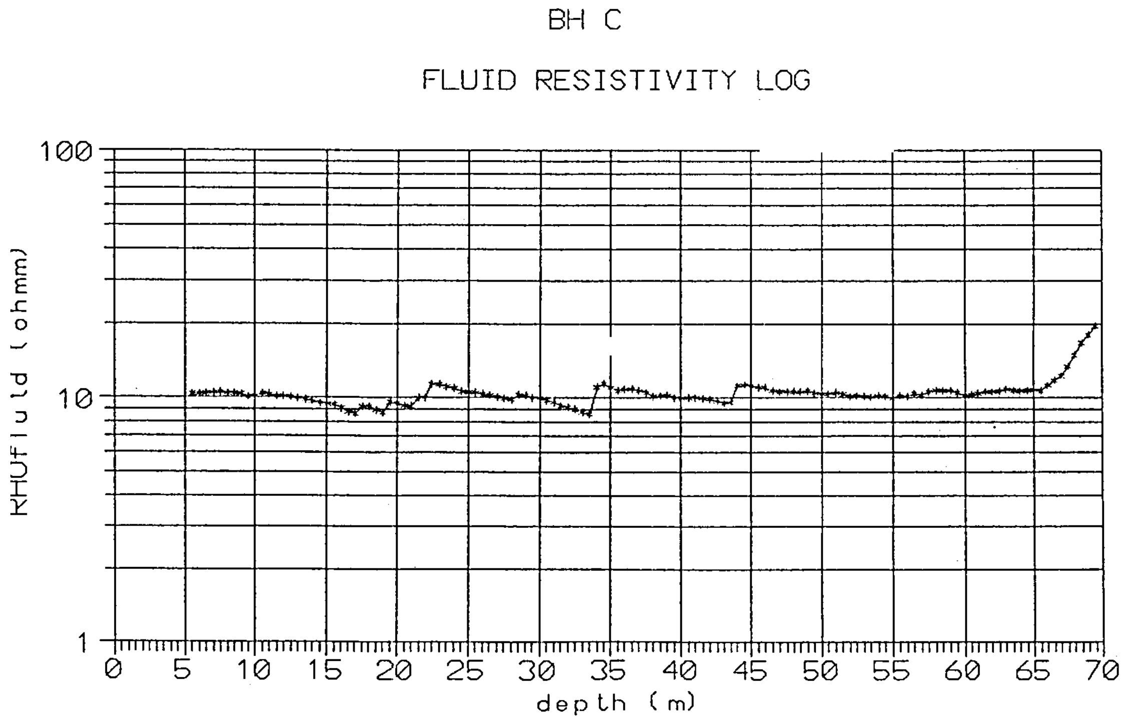


Figure 11c **Borehole logs from $5^1/_2$" borehole nr.C at Reffsgård**

The resistivity log reveals a fairly distinct minimum in ρ_a at 11 m (SN = 700 ohmm, LN = c. 1500 ohmm). A broad minimum, possibly implying enhanced fracturing or metasomatism, is observed between 22 and 32 m. The same effect are recognised below the depth of 60 m. The remainder of the log, below 32 m, is rather featureless with a uniform ρ_a of 4000-5000 (SN) and c. 14000 (LN), implying a negligible degree of fracturing.

Borehole C

The fluid resistivity log (Fig. 11c) is relatively uniform, reflecting the ρ_f of the added water, namely c. 10 ohmm = c. 1000 μS/cm. Small anomalies can be seen at 17 m, 19 m, 21-22 m, 28 m, 34 m and 44 m, possibly indicating minor inflows of formation water. The largest anomaly is at c. 34 m.

The resistivity logs show three broad minima, at c. 20 m, 33½ m and 43½ m, implying the possibility of enhanced fracturing. These levels agree well with potential inflows detected on the fluid resistivity logs.

9 Test pumping

All boreholes were short-term test-pumped during period 13-19 August 1993. The weather preceding this period has been very wet, and there were also several strong showers during the test-pumping period. As the yields of all holes were low, a small 2" diameter Grundfos MP1 pump was used. The techniques described by Banks (1993) were used for test-pumping and analysis. The pump was placed at a given level in the hole and the pump was switched on. The water level was drawn down to the pump intake level (taking typically 30-60 mins, depending on hole-diameter and yield). The pump was then taken out of the borehole and the recovery of the water level in the borehole was monitored using a manual dipper.

It was assumed that the holes' yield is limited by low-transmissivity feeder fractures (i.e. fractures linking the borehole to the wider fracture system) rather than aquifer storage. With this assumption, it is possible to calculate specific capacity, apparent transmissivity and fracture location from the rate of recovery in the borehole water level and the angle of the borehole (if non-vertical). The analytical method is described in Banks (1993), and the designation Q_a is used to describe the flow of groundwater from fracture (aquifer) to borehole.

9.1 Borehole 1

The borehole was cleaned of cuttings using a flowing hosepipe in connection with *in-situ* stress measurement in June 1993.

Borehole 1 was test-pumped on 17 August 1993. The well had not yielded significant amounts of water prior to the hydraulic fracturing carried out in connection with stress measurement. Now, the borehole yields up to 156 l/hr water with 24 m drawdown. The Q_a vs. water level curve is well-behaved, straight and intersects the x-axis at the rest water level (RWL) value. This implies that the yielding fractures are all below the lowest measured water level, namely 36 m. A repeat test-pumping (Skarphagen et al. 1993) allowed one to hear running water when the water level fell below 36.5 m, indicating a contributing fracture at that level. This is consistent with a significant anomaly noted on the geophysical logs.

The water pumped up was heavily loaded with drilling cuttings at the beginning of pumping (drawing in slurry from the base of the hole), then progressively clearer (drawing clean water from higher up the hole) then more turbid again (formation water from fractures loaded with cuttings).

3" Borehole 1	Date : 17/8/93
RWL (time)	11.79 mbgl (1524 hrs)
Pump level	40 mbgl
Pump switched on	1534 hrs
Approx. pump rate	3 - 7 l/min
Pump draws air (i.e. PWL at pump intake)	1646; 40 sec
Gradient of Q_a vs water level plot	6.5 l/hr/m
Fall of borehole	90°
Level of yielding fracture(s)	c.36.5 m (+ deeper ?)
Specific capacity of fracture(s)	0.156 m^2/d
Apparent transmissivity of fractures	0.17 m^2/d
Saturated borehole length	30.6 m
Apparent hydraul. conductivity of saturated borehole length	0.0057 m/d = 7 x 10^{-8} m/s
Yield / drawdown	156 l/hr with 24 m drawdown

Table 6. Summary of test-pumping analysis, borehole 1

On 18/9/93, when the water level had recovered to 11.93 m, at 0927 hrs, the pump was lowered to 35 m to obtain a sample of formation water (after pumping for 5 mins.).

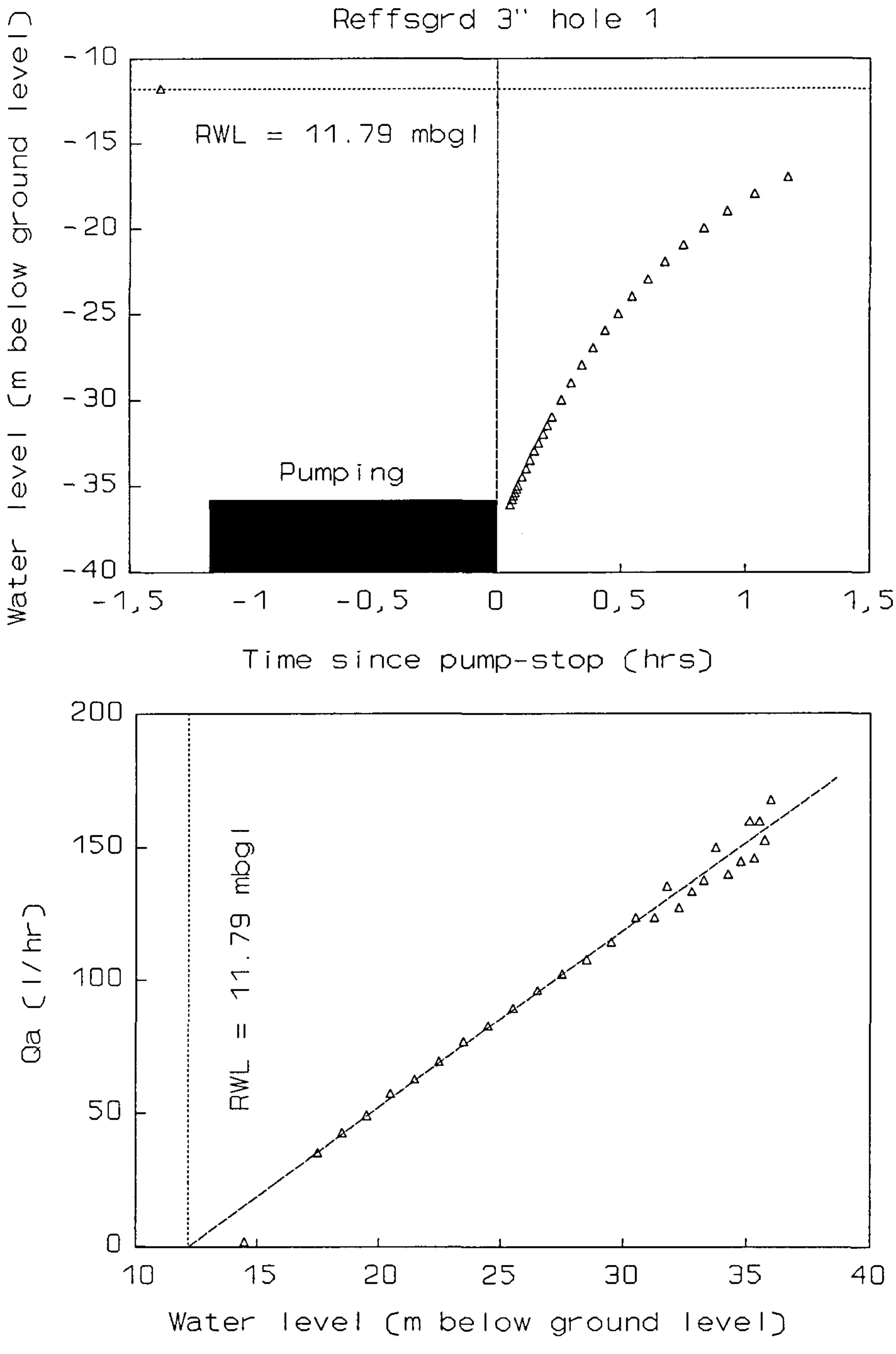


Figure 12. Short-term test-pumping of Reffsgård 3" borehole 1; 17/8/93. Plots of (a) water level vs. time and (b) yield from aquifer (Q_a) vs. water level during recovery.

9.2 Borehole 2

Borehole 2 was test-pumped on 14 August 1993. The well had appeared to yield a moderate amount of water during drilling (prior to the hydraulic fracturing carried out in connection with stress measurement). Now, after hydrofraccing, the borehole yields up to 18.6 l/hr water with 14.38 m drawdown. The earlier part (i.e. deepest part) of the Q_a vs. water level recovery curve is puzzling, values of only 5 to 10 l/hr being obtained with c. 17.8 m drawdown. No satisfactory explanation of this has been found, although it could conceivably be due to a large breakout in borehole diameter at that level (geophysical anomalies at 21 and 23 m), or a natural unclogging of contributing fractures. The data between 23 m and 16½ m appear fairly well-behaved and straight, a line through them intersecting the x-axis at the RWL-value. This implies that the yielding fractures are all below c.23.1 m (confirmed during drilling to be at ca. 39½ m. Around 15-16½ m, the Q_a vs. water level line appears displaced to the left by c. 1.3-1.4 m, while retaining approximately the same gradient. This may be due to rainfall recharge during that part of the recovery, a hypothesis supported by the fact that the final RWL (7.56 m) was around 1.2 m higher than the original (8.72 m). The anomaly at 15-16½ m could also be due to variations in borehole diameter (in connection with geophysical anomalies at c. 16 m?) or natural unclogging of fractures.

The water pumped up during the test was relatively clear in the beginning, but soon became heavily loaded with drilling cuttings.

3" Borehole 2	Date : 14/8/93
RWL (time)	8.72 mbgl (1002 hrs)
	7.555 mbgl (1000 hrs; 15/8/93)
Pump level	30 mbgl
Pump switched on	1012; 24 sec
Approx. pump rate	
Pump draws air (i.e. PWL at pump intake)	1054 hrs; (pump again 1140 to 1148 hrs).
Gradient of Q_a vs water level plot	1.29 l/hr/m
Fall of borehole	90°
Level of yielding fracture(s)	c.39½ m
Specific capacity of fracture(s)	0.031 m^2/d
Apparent transmissivity of fractures	0.034 m^2/d
Saturated borehole length	33.7 m
Apparent hydraul. conductivity of saturated borehole length	0.0010 m/d = 1×10^{-8} m/s
Yield / drawdown	18.6 l/hr with 14.38 m drawdown

Table 7. Summary of test-pumping analysis, borehole 2

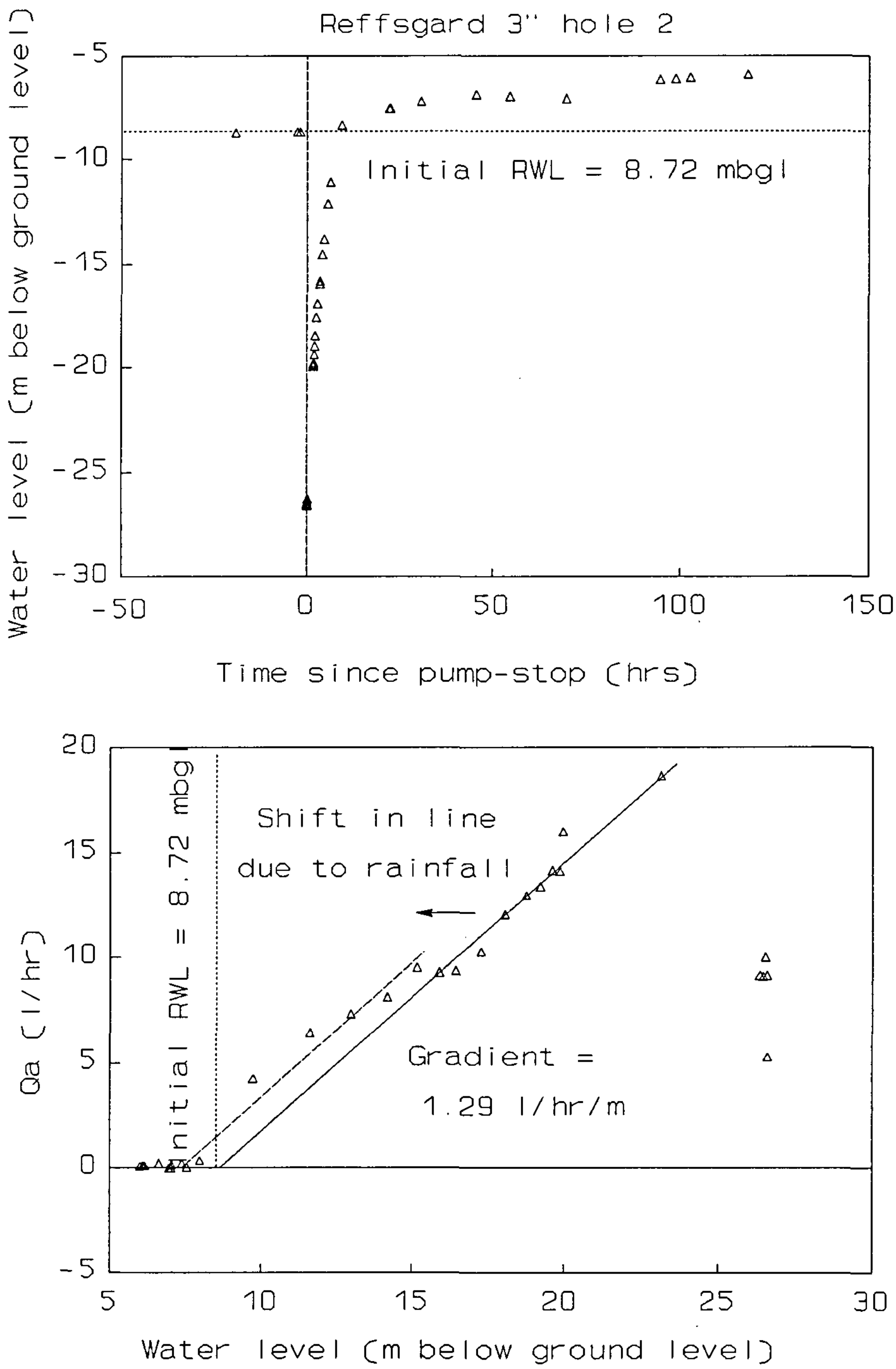


Figure 13. Short-term test-pumping of Reffsgård 3" borehole 2; 14/8/93. Plots of (a) water level vs. time and (b) yield from aquifer (Q_a) vs. water level during recovery.

9.3 Borehole 3

Borehole 3 was also test-pumped on 14 August 1993, immediately prior to testing of borehole 2. The borehole had not been subject to hydraulic fracturing in connection with stress measurement. The early (deep) data on the Q_a vs. water level plot at around 25 m, indicate a Q_a of c. 3 l/hr, which diminishes sharply to less than 1 l/hr. This steep part of the curve is believed to be due to drainage of small amounts (although large in the context of the borehole's true yield) of water from the borehole walls, and possibly a few minor blind fractures. After c.23 m, the data assume a more well-behaved, straight line nature, intersecting the x-axis as expected at the RWL of 4.05 m. This portion is believed to represent the borehole's minute, but "true" yield, from fractures below 23 m level, in accordance with the deeper anomalies observed in the resistivity logs. The yield is 0.69 l/hr for a drawdown of 19 m.

Although, during drilling, a water inflow appeared to come from c. 8½ m, the pumping test gives no indication of this, indicating that fractures here are "blind", possibly providing the short-term yield observed in the deep part of the Q_a vs. water level plot. This is backed up by the observation that running water from a fracture could be heard when the pumping water level (PWL) sunk below c. 11m, although this noise quickly diminished.

The water pumped up during the test was heavily loaded with grey drilling cuttings. Pumping of borehole 3 appeared to have no effect on the water level in borehole 2, prior to pumping of the latter borehole.

3" Borehole 3	Date : 14/8/93
RWL (time)	4.05 mbgl (0915 hrs)
Pump level	40 mbgl
Pump switched on	0932 hrs
Approx. pump rate	
Pump draws air (i.e. PWL at pump intake)	1002 hrs
Gradient of Q_a vs water level plot	0.036 l/hr/m
Fall of borehole	90°
Level of yielding fracture(s)	deeper than 23 m
Specific capacity of fracture(s)	8.7×10^{-4} m²/d
Apparent transmissivity of fractures	9.7×10^{-4} m²/d
Saturated borehole length	38.35 m
Apparent hydraul. conductivity of saturated borehole length	2.5×10^{-5} m/d = 3×10^{-10} m/s
Yield / drawdown	0.69 l/hr with 19 m drawdown

Table 8. Summary of test-pumping analysis, borehole 3

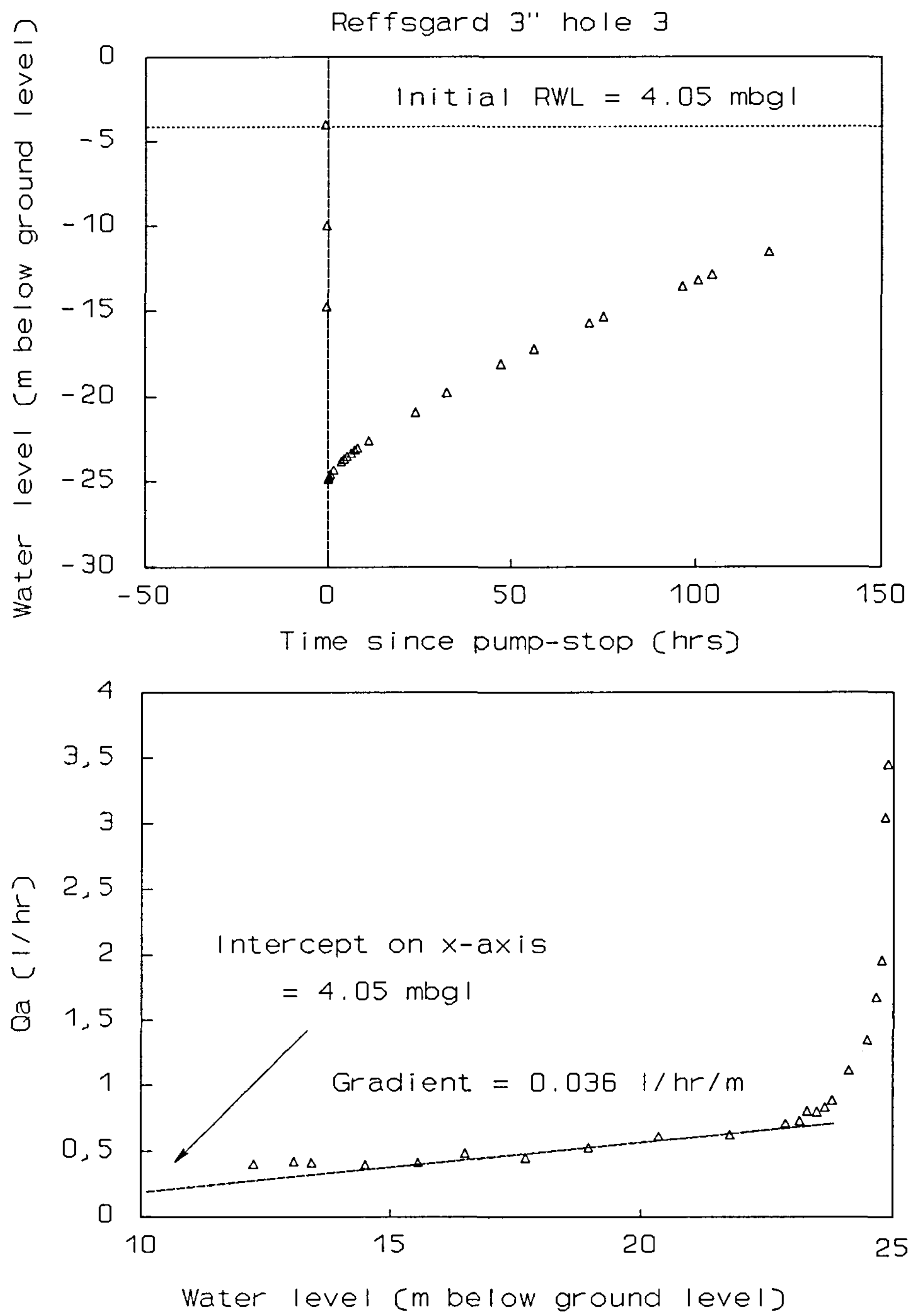


Figure 14. Short-term test-pumping of Reffsgård 3" borehole 3; 14/8/93. Plots of (a) water level vs. time and (b) yield from aquifer (Q_a) vs. water level during recovery.

9.4 Borehole A

Borehole A was also test-pumped on 14 August 1993, immediately after testing borehole 2. The Q_a vs. water level plot is not well-behaved, but has a concave shape indicating that, despite the small amounts of water involved, there is a significant storage depletion effect. Q_a values of up to 15 l/hr were obtained for early data, but a more representative short term specific capacity would be c. 3.5 l/hr for c. 17 m drawdown. This is used to estimate apparent transmissivity and hydraulic conductivity.

3" Borehole 3	Date : 14/8/93
RWL (time)	17.24 mbgl (c.1700 hrs, 13/8/93)
Pump level	45 mbgl
Pump switched on	1604 hrs
Approx. pump rate	
Pump draws air (i.e. PWL at pump intake)	1636; 50 sec.
Gradient of Q_a vs water level plot	Up to 0.282 l/hr/m; 0.206 l/hr/m used.
Fall of borehole	65°
Level of yielding fracture(s)	c. 35 m ?
Specific capacity of fracture(s)	5.5×10^{-3} m^2/d
Apparent transmissivity of fractures	6.1×10^{-3} m^2/d
Saturated borehole length	55.76 m
Apparent hydraul. conductivity of saturated borehole length	1.1×10^{-4} m/d = 1×10^{-9} m/s
Yield / drawdown	3.5 l/hr with 16.96 m drawdown = (15.4 vertical drawdown)

Table 9. Summary of test-pumping analysis, borehole A

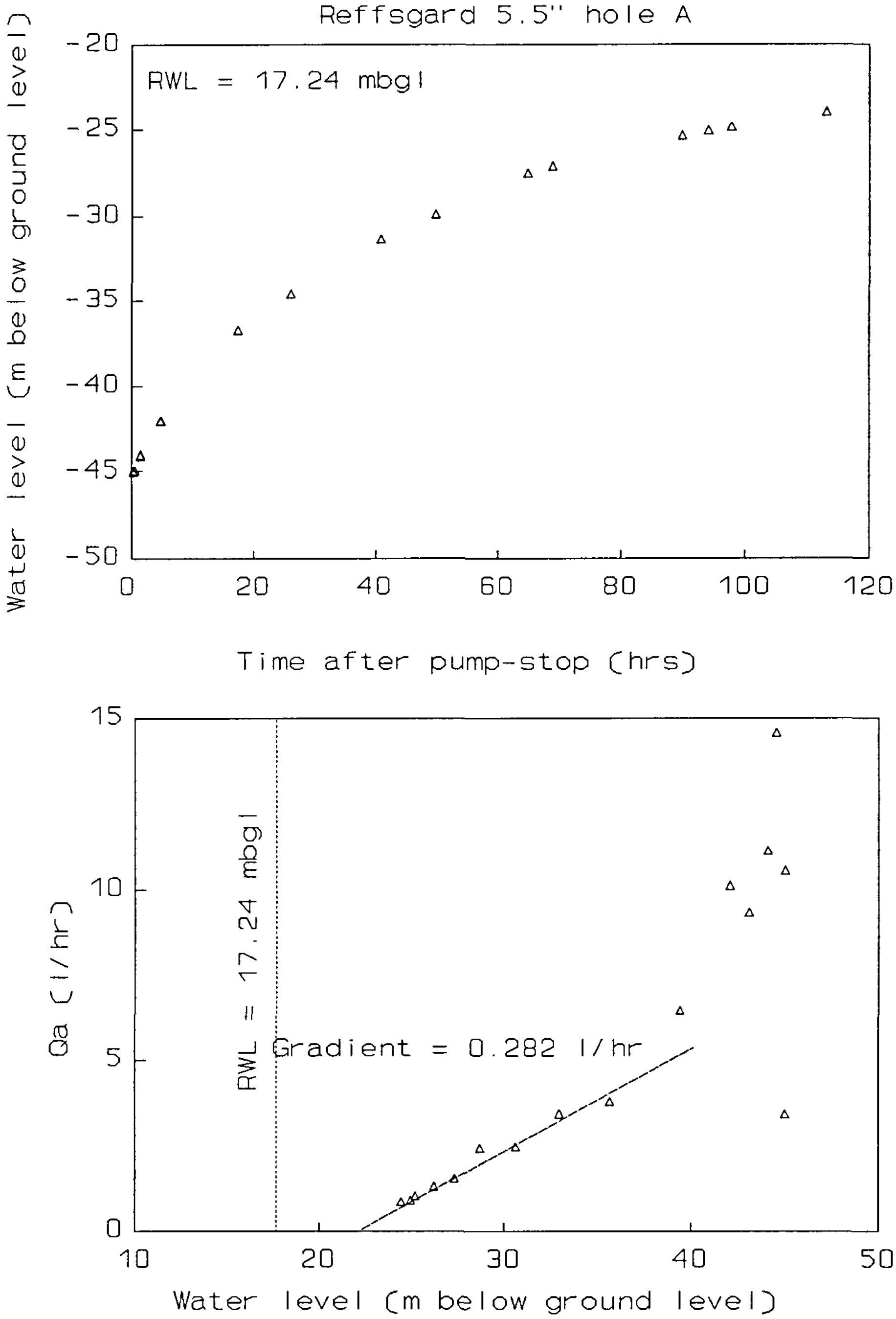


Figure 15. Short-term test-pumping of Reffsgård 5½" borehole A; 14/8/93. Plots of (a) water level vs. time and (b) yield from aquifer (Q_a) vs. water level during recovery.

9.5 Borehole B

Borehole B was test-pumped on 18 August 1993. The rate of recovery of the water level after pumping down to 50 m was so slow that a recovery of only c. 29.5 cm was observed during 20 hrs 50 mins, an average Q_a of 0.22 l/hr at a water level of 49.47 mbgl. The uncertainty in measurement (at least ± 1 cm with a manual dipper), leads to some uncertainty in this value.

The water pumped up during the test was moderately clear (borehole had been filled with imported water for geophysics).

3" Borehole 3	Date : 18/8/93
RWL (time)	10.70 mbgl (1029 hrs)
Pump level	50 mbgl
Pump switched on	1147; 30 sec.
Approx. pump rate	
Pump draws air (i.e. PWL at pump intake)	1228; 40 sec.
Gradient of Q_a vs water level plot	
Fall of borehole	70°
Level of yielding fracture(s)	?
Specific capacity of fracture(s)	1.4 x 10^{-4} m^2/d
Apparent transmissivity of fractures	1.6 x 10^{-4} m^2/d
Saturated borehole length	59.3 m
Apparent hydraul. conductivity of saturated borehole length	2.7 x 10^{-6} m/d = 3 x 10^{-11} m/s
Yield / drawdown	0.22 l/hr with 38.8 m drawdown = (36.4 m vertical drawdown)

Table 10. Summary of test-pumping analysis, borehole B.

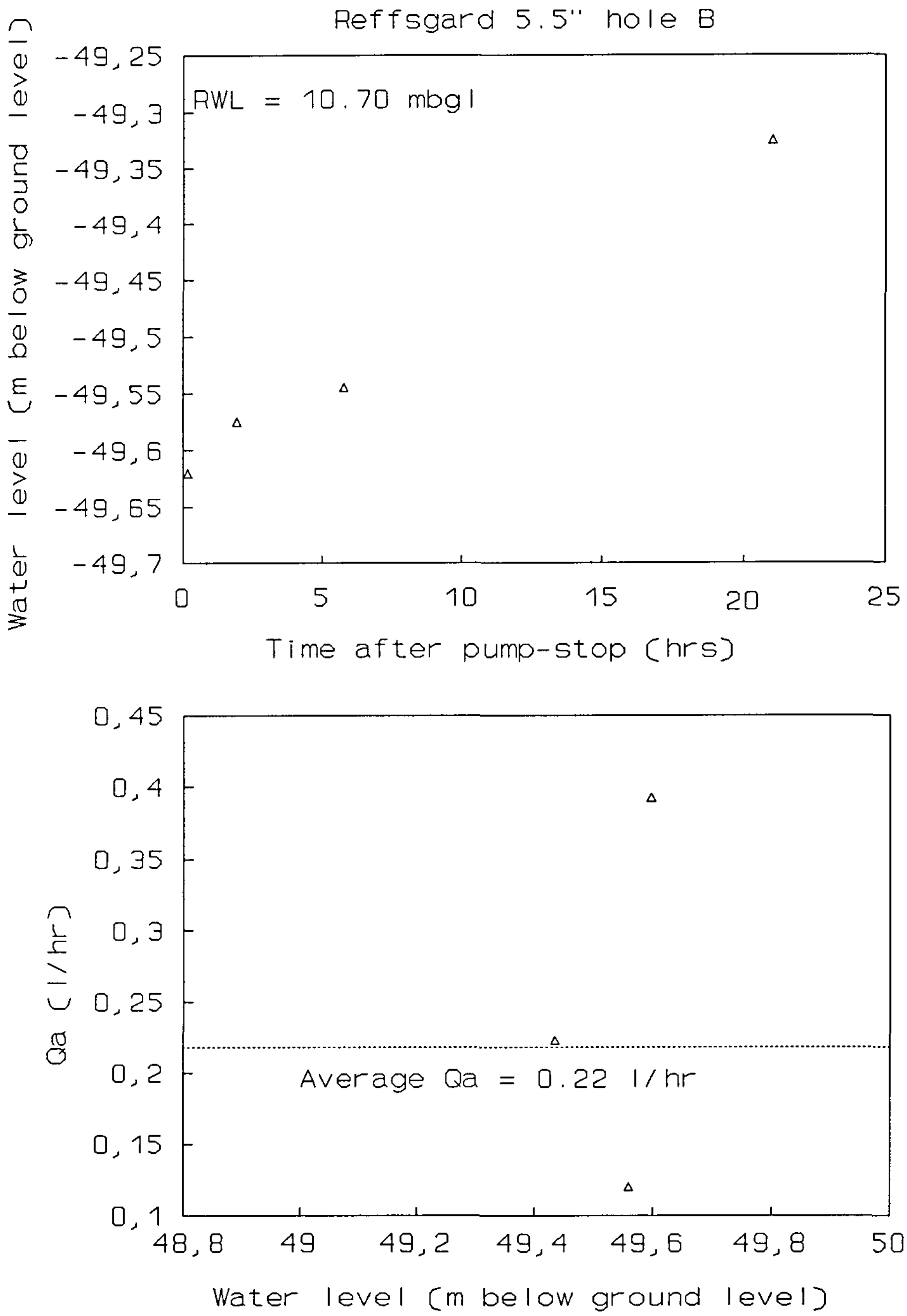


Figure 16. Short-term test-pumping of Reffsgård 5½" borehole B; 18/8/93. Plots of (a) water level vs. time and (b) yield from aquifer (Q_a) vs. water level during recovery.

9.6 Borehole C

Borehole C was test-pumped on 18 August 1993. The rate of recovery of the water level after pumping down to 50 m was so slow that a recovery of only c. 39 cm was observed during 22 hrs 27 mins, an average Q_a of 0.27 l/hr at a water level of 49.25 mbgl. The water pumped up during the test was moderately clear (borehole had been filled with imported water for geophysics), only becoming rather turbid towards the end.

3" Borehole 3	Date : 18/8/93
RWL (time)	9.31 mbgl (1004 hrs)
Pump level	50 mbgl
Pump switched on	1017; 30 sec.
Approx. pump rate	
Pump draws air (i.e. PWL at pump intake)	1057; 40 sec.
Gradient of Q_a vs water level plot	
Fall of borehole	70°
Level of yielding fracture(s)	?
Specific capacity of fracture(s)	1.7×10^{-4} m²/d
Apparent transmissivity of fractures	1.9×10^{-4} m²/d
Saturated borehole length	60.69 m
Apparent hydraul. conductivity of saturated borehole length	3.1×10^{-6} m/d = 4×10^{-11} m/s
Yield / drawdown	0.27 l/hr with 39.9 m drawdown = (37.5 m vertical drawdown)

Table 11. Summary of test-pumping analysis, borehole C.

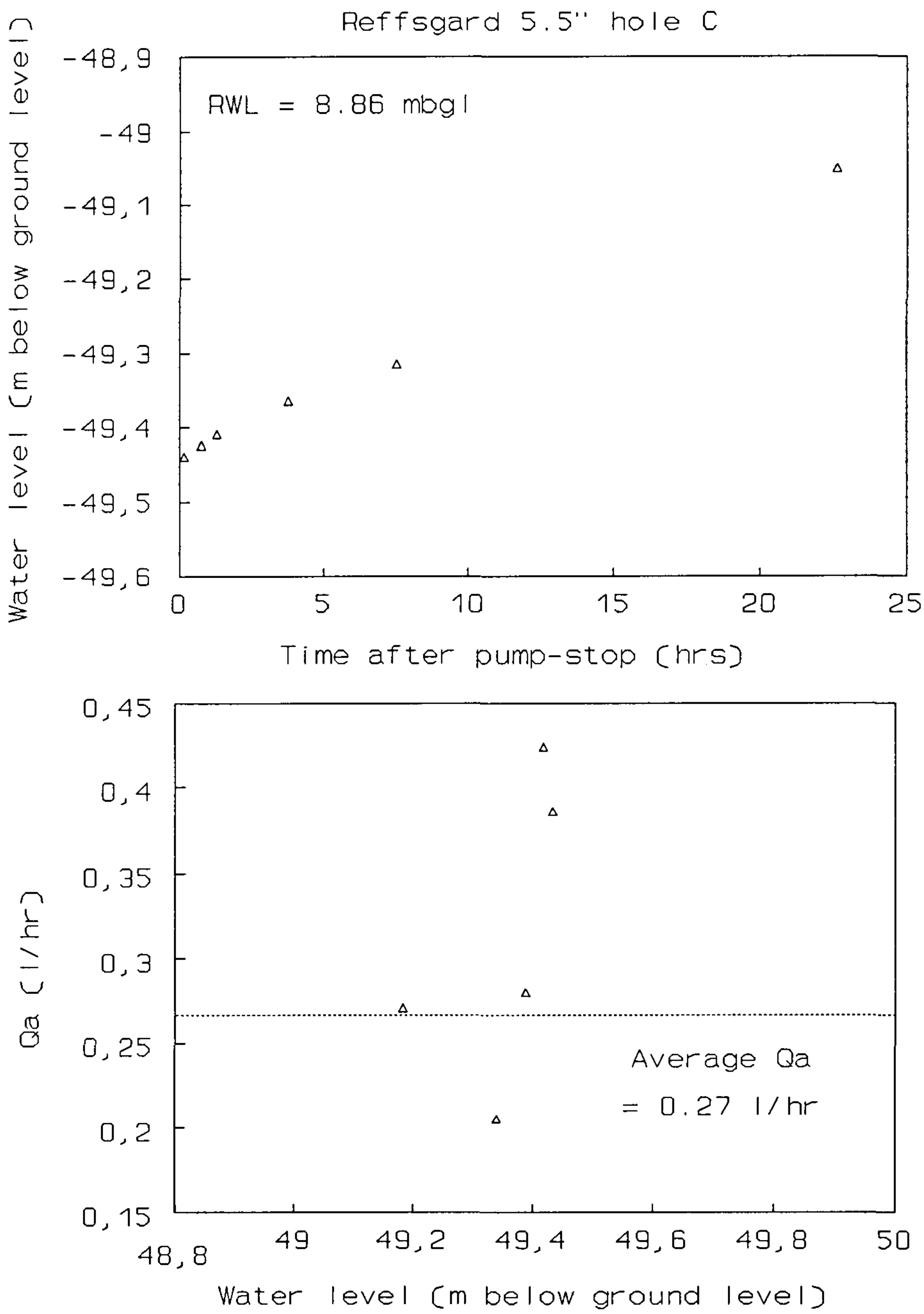


Figure 17. Short-term test-pumping of Reffsgård 5½" borehole C; 18/8/93. Plots of (a) water level vs. time and (b) yield from aquifer (Q_a) vs. water level during recovery.

10 Groundwater Chemistry

Groundwater samples were taken from the 3" boreholes during test pumping, and from Reffsgård's dug well in Quaternary deposits (GB1, see Fig. 3) as follows:

Sample No.	Borehole	Date	Time	Flask	Filtered	Analysis
R1a	Reffsgård 1	17/8/93	1634	1x500 ml	N	P
				1x100 ml	N	A,K
R1b	Reffsgård 1	18/8/93	0930	1x500 ml	N	P
				2x100 ml	N	A,K
TL2	Reffsgård 2	14/8/93	1148	1x500 ml	N	P,K,A
TL3	Reffsgård 3	14/8/93	0958	1x500 ml	N	P,K,A
RB	Reffsgård Dug Well	18/8/93	Evening	3x100 ml	N	P
				1x100 ml	Y	A,K,K*

P = pH, alkalinity, conductivity
A = anions (ion chromatography)
K = cations (ICP)
K* = standard acidisation of sample in flask (at NGU) by addition of Ultrapure HNO_3, prior to ICP analysis.

With the exception of sample RB, the samples were neither filtered nor acidified in the field, due to the high turbidity caused by drilling cuttings. One flask of sample RB was field filtered (but not acidified) using a 0.45μm Millipore filter. This sample was used for cation and anion analysis; one portion of it was acidified prior to ICP analysis to remobilise any precipitated or adsorbed cations/metals.

Results are summarised in Tables 12a,b and raw data is documented in Appendix 4.

Unfortunately, during transport to NGU, the samples were inadvertently placed near the vehicle ventilation system and subjected to upwarming. This, together with the fact that the samples (except RB) contained many particles in the form of drilling cuttings, renders the results for many of the parameters rather meaningless. The high surface area of the cuttings, together with the warmth, has resulted in extremely high concentrations of many litholgenic components, for example Si, Al, Fe, Ti, many heavy metals and possibly the major elements such as K, Mg, Ca and Na. This effect has been noticed in other samples from newly drilled boreholes (even filtered samples), despite having been preserved cool, although to a lesser degree (Banks et al. 1992b).

Comparing the analysis of R1a to R1b reveals a decline in the concentration of many elements, due to the less turbid nature of the latter sample. Interestingly, Na does not show this decline, indicating that the analysed value may be representative for the "true" groundwater, rather than derived from cuttings.

The samples from the dug well (RB) yield believable results, due to the fact that they are filtered and thus are not detrimentally affected (at least as regards metals, cations and anions such as F^-, Cl^- and Br^-) by any upwarming. The water from the well is revealed as a typical calcium bicarbonate water; not surprisingly as the silty/sandy Quaternary deposits at Reffsgård can be observed to contain abundant calcareous shells and shell fragments. A marine component is also indicated by the moderate Na and Cl contents, and the fact that Na $<$ Cl (indicating that Na is not derived to a great extent from mineral weathering). The sample also contains high nitrate concentrations, possibly indicative of agri-/horticultural contamination.

Locality: Reffsgård - Hvaler		**Table 12a**			
Sampled by: David Banks		**Date:** August 1993			
Analyzed by: NGU Trondheim. * = contains some particles, thus possibly inaccurate alkalinity.					
Parameter	Reffsgård 1 R1a	Reffsgård 1 R1b	Reffsgård 2 TL2	**SIFF(G)**	**SIFF(A)**
pH	7,34	7,53	6,53	7,5 - 8,5	6,5 - 9,0
Alkalinity (mmol/l)	2,48*	2,47*	0,71	0,6 - 1,0	
Conductivity (μS/cm)	338	332	223		
Silicon ppm	127	34	36		
Aluminium ppm	57	12.6	16.7		
Iron ppm	41	9.7	9.9	< 0.1	< 0.2
Magnesium ppm	9.5	2.5	4.9	< 10	< 20
Calcium ppm	4.7	2.5	6.3	15 - 25	
Sodium ppm	81	80	36	< 20	
Potassium ppm	21	5.1	8.4		
Manganese ppb	390	98	400	< 50	< 100
Copper ppb	58	20	30	< 100	< 300
Zinc ppb	198	46	56	< 300	
Lead ppb	51	< 50	< 50	< 5	< 20
Cadmium ppb	< 10	< 10	< 10	< 1	< 5
Barium ppb	360	85	166	< 1000	
Strontium ppb	60	25	56		
Chromium ppb	54	11.8	40		
Titanium ppb	2100	450	613		
Boron ppb	86	69	31		
Beryllium ppb	17	4.0	< 2		
Lithium ppb	31	5.3	19.2		
Fluoride ppb	3800	3400	1790	< 1500	
Chloride ppm	16.4	14.8	15.6	< 100	< 200
Nitrite ppb	< 1000	< 1000	< 1000	< 16	< 164
Nitrate ppb	762	332	81	< 11000	< 44000
Phosphate ppb	< 200	< 200	< 200		
Sulphate ppm	14.5	16.8	32	< 100	
Bromide ppb	< 100	< 100	< 100		

F = field filtered for ICP, FS = field filtered and acidified in flask in laboratory prior to ICP.
SIFF(G)/SIFF(A) = Good/acceptable quality according to SIFF (1987) requirements.

Locality: Reffsgård - Hvaler	**Table 12b**				
Sampled by: David Banks	**Date:** August 1993				
Analyzed by: NGU Trondheim. * = contains some particles, thus possibly inaccurate alkalinity.					
Parameter	Reffsgård 3 TL3	Reffsgård Well RB-F	Reffsgård Well RB-FS	SIFF(G)	SIFF(A)
pH	7,28	7,25	7,25	7,5 - 8,5	6,5 - 9,0
Alkalinity (mmol/l)	1,41*	1,84	1,84	0,6 - 1,0	
Conductivity (µS/cm)	251	335	335		
Silicon ppm	79	4.5	4.3		
Aluminium ppm	38	0.050	0.042		
Iron ppm	23	0.055	0.058	< 0.1	< 0.2
Magnesium ppm	5.7	3.1	3.1	< 10	< 20
Calcium ppm	3.1	48	48	15 - 25	
Sodium ppm	55	14.6	14.7	< 20	
Potassium ppm	14.3	2.5	2.7		
Manganese ppb	324	16.5	14.5	< 50	< 100
Copper ppb	53	8.2	10.6	< 100	< 300
Zinc ppb	220	15.4	19.3	< 300	
Lead ppb	< 50	< 50	< 50	< 5	< 20
Cadmium ppb	< 10	< 10	< 10	< 1	< 5
Barium ppb	270	13.5	13.2	< 1000	
Strontium ppb	33	230	230		
Chromium ppb	108	< 10	< 10		
Titanium ppb	1420	< 10	< 10		
Boron ppb	38	< 20	25		
Beryllium ppb	6.1	< 2	< 2		
Lithium ppb	42	< 2	< 2		
Fluoride ppb	3400	187		< 1500	
Chloride ppm	15.6	28		< 100	< 200
Nitrite ppb	< 1000	< 1000		< 16	< 164
Nitrate ppb	228	5130		< 11000	< 44000
Phosphate ppb	< 200	< 200			
Sulphate ppm	15.3	15.1		< 100	
Bromide ppb	< 100	< 100			

F = field filtered for ICP, FS = field filtered and acidified in flask in laboratory prior to ICP.
SIFF(G)/SIFF(A) = Good/acceptable quality according to SIFF (1987) requirements

11 Conclusions

Testsite Reffsgård has been chosen with the aim of examining the water resources aspects of a hard rock aquifer away from major fracture zones, and in particular to examine the effects of *in-situ* stress on borehole yield.

Three 3" boreholes have been drilled to 42,4 m, yielding between < 0,1 l/hr and 19 l/hr. Two of these were used to determine *in-situ* stress in the granite by hydraulic fracturing and use of impression packers. *In-situ* horizontal stresses, as indicated by instantaneous shut-in pressure and opening pressure were in the range 8 - 11 MPa. This is regarded as a high stress for such shallow depth. One of the boreholes showed an increased yield, from < 0,1 l/hr (11 m drawdown) to 156 l/hr (24 m drawdown) as a result of the hydraulic fracturing.

Three 5½" boreholes were then drilled. One of these was drilled into a suspected dolerite dyke, and yielded only around 5 l/hr water. Geophysics subsequently indicated that the suspected fracture feature was not filled with dolerite at this locality. The other two boreholes were drilled with 70° fall into minor lineaments approximately perpendicularly and parallel to σ_H. They yielded similar, very low water yields of 0,22 - 0,27 l/hr, indicating apparent bulk hydraulic conductivities of c. 3 - 4 x 10^{-11} m/s. Thus, no clear significance was found for the orientaion of the borehole with respect to orientation of *in-situ* stress.

The exceptionally low yields of all the boreholes appears could be due to the exceptionally high measured magnitudes of σ_h at the site, keeping the fractures tightly closed. Thus, the magnitude, rather than the orientation, of *in-situ* stress appears to be the controlling feature for borehole yield at this site.

12 References

General Geology of the Hvaler Area

Bjørlykke, H. 1939. Feldspat V - De sjeldne mineraler på de norske granittiske pegmatittganger. *(Feldspars V - rare minerals of Norwegian granitic pegmatites).* Nor.geol.unders. 154.

Hageskov, B. 1985. Hin Hånes harvespor *(Old Nick's furrows).* Varv, 2 (1985), 35-42 *(in Danish).*

NVE 1975. NVE nuclear power plants, Oslofjord. Oslo region tectonic map. Produced by Norwegian Geotechnical Institute (NGI) for Norges Vassdrags- og Energivesenet (NVE), 1975.

Olsen, L. & Sørensen, E. 1990: Fredrikstad. 1913 III. 1:50000 kvartærgeologisk kart. *(Fredrikstad map sheet 1913 III, 1:50,000 Quaternary geological map)* Nor.geol.unders. Unpublished manus form. Due for publication 1992.

Oxaal, J. 1916. Norsk granitt *(Norwegian granite).* Nor. geol. unders., 76.

Pedersen S. & Maaløe S. 1990. The Iddefjord Granite: geology and age. Nor. geol.unders., 417, 55-64.

Ramberg, I.B. & Larsen, B.T. 1978. Tectonomagmatic evolution. In "The Oslo Paleorift, a review and guide to excursions". Nor. geol. unders. 337, 55-73.

Ramberg, I.B. & Smithson S.B. 1971. Gravity interpretation of the southern Oslo graben and adjacent precambrian rocks, Norway. Tectonophysics, 11, 419-431.

Samuelsson, L. 1971. The relationship between Permian dikes of dolerite and rhomb porphyry along the Swedish Skagerrak coast. Sver. geol. unders. Series C, 663.

Størmer, L. 1935. Contribution to the geology of the southern part of the Oslofjord. Norsk geol.tidskr., 15, 43-114.

NGU Reports on Hvaler Hydrogeology

Banks, D., Lauritsen, T., Skarphagen, H. & Rohr-Torp, E. 1991. Hvaler-prosjekt -grunnvann i fast fjell. Boring og kapasitetstesting av fire hull, ved Pulservik, Kirkeøy *(Hvaler project, groundwater in bedrock. Drilling and capacity testing of four boreholes at Pulservik, Kirkeøy)* Nor.geol.unders. report 91.215.

Banks, D. & Rohr-Torp, E. 1991. Hvaler-prosjekt - grunnvann i fast fjell. Sprekkekartlegging: Iddefjordgranitten. *(Hvaler project, groundwater in bedrock. Fracture mapping in the Iddefjord granite)* Nor.geol.unders. report 91.214.

Banks, D., Lauritsen, T., Rohr-Torp, E., Rønning, J.S. & Skarphagen, H. 1993c. Groundwater in bedrock - Hvaler project. Investigations at testsite Utengen. Nor. geol. unders. report 93.117.

Klemetsrud, T. & Rohr-Torp, E. 1992. Grunnvannsforsyning Skjærhallen, Hvaler kommune. *(Groundwater supply for Skjærhallen, Hvaler kommune)* Nor. geol. unders. report 92.235.

Lauritsen, T. & Rønning, J.S. 1992. Geofysiske målinger over mulige vannførende sprekkesoner på Kjerkøy, Hvaler, Østfold. *(Geophysical measurements over potentially water-bearing fracture zones on Kirkeøy, Hvaler, Østfold)* Nor. geol. unders. report 92.173.

Rohr-Torp, E. 1991. Grunnvann i krystallin bergrunn. Sluttrapport av forprosjektet. *(Groundwater in crystalline bedrock. Final report from preliminary study)* Nor.geol. unders. report 91.189.

Rohr-Torp, E. & Nordahl-Olsen, T. 1992. Grunnvann i Hvaler kommune *(Groundwater in Hvaler kommune)*. Nor. geol. unders. report 92.050.

Skarphagen, H., Banks, D. & Rohr-Torp, E. 1993. Groundwater in bedrock - Hvaler project. Investigations at Testsite Reffsgård, borehole 1 (Capacity enhancement using EDTA). Nor. geol. unders. report 93.119.

Other Publications on Hvaler Hydrogeology

Banks, D. 1993. Estimation of apparent transmissivity from capacity-testing of boreholes in bedrock aquifers. Accepted for publication in Applied Hydrogeology.

Banks, D. & Rohr-Torp, E. 1990. Hvaler-prosjektet - et integrert studium av grunnvann i fast fjell *(The Hvaler project - an integrated study of groundwater in bedrock)*. Geonytt, 17, No.4, 25-26 & 59, Dec. 1990.

Banks, D., Solbjørg, M.L. & Rohr-Torp E. 1992a. Permeability of fracture zones in a Precambrian granite. Quart. J. Eng. Geol., London 25, 377-388.

Banks, D., Rohr-Torp, E., & Skarphagen, H. 1992b. An integrated study of a Precambrian granite aquifer, Hvaler, Southeastern Norway. Nor.Geol.Under. Bull., 422, 47-66.

Banks, D., Rohr-Torp, E., & Skarphagen, H. 1993a. Groundwater resources in hard rock - do any general rules exist ? Experiences from the Hvaler study, Southeastern Norway. In Banks, S.B. & Banks, D. (eds.) Proc. XXIVth Congress Int. Assoc. Hydrogeol. "Hydrogeology of Hard Rocks", Ås, 28/6/93-2/7/93.

Banks, D., Rohr-Torp, E. & Skarphagen, H. 1993b. Groundwater chemistry in a Precambrian granite island aquifer, Hvaler, Southeastern Norway. In Banks, S.B. & Banks, D. (eds.) Proc. XXIVth Congress Int. Assoc. Hydrogeol. "Hydrogeology of Hard Rocks", Ås, 28/6/93-2/7/93.

Banks, S.B. & Banks, D. 1993. Groundwater microbiology in Norwegian hard-rock aquifers. In Banks, S.B. & Banks, D. (eds.) Proc. XXIVth Congress Int. Assoc. Hydrogeol. "Hydrogeology of Hard Rocks", Ås, 28/6/93-2/7/93.

Gaut, A. (ed.) 1993. Field Excursion 2: The Oslofjord area. Excursion Guide, XXIV. Congress Intl. Assoc. Hydrogeol., Ås, Oslo, 1993, "Hydrogeology of Hard Rocks".

Larsen, M.L. 1990. Riksvei 108 Hvalertunnelen, geologisk sluttrapport *(Highway 108 Hvaler tunnel. Final geological report)*. Statens Vegvesen Østfold. Vegkontoret, report no. 88/3744, 31 pp.

Skjernaa, L. & Jørgensen, N.O. 1993. Detection of local fracture systems by azimuthal resistivity surveys: examples from South Norway. In Banks, S.B. & Banks, D. (eds.) Proc. XXIVth Congress Int. Assoc. Hydrogeol. "Hydrogeology of Hard Rocks", Ås, 28/6/93-2/7/93.

Storås, I. 1988. Ingeniørgeologisk analyse av vannlekkasjer og injeksjon i Hvalertunnelen *(Engineering geological analysis of water leakages and grout injection in the Hvaler tunnel)*. Unpublished thesis, Geologisk Institutt, Norges tekniske høyskole, Trondheim. 80 pp.

Taugbøl & Øverland A/S 1987: Ingeniørgeologisk rapport; Hvalertunnelen *(Engineering geological report - Hvaler tunnel)*. Report No. 2479.9, Taugbøl & Øverland A/S, Oslo, 8 pp. plus diagrams.

Publications on the Fjällbacka Research Site, Sweden

Eliasson, T.M., Tullborg, E.-L. & Landström, O. 1990. Fracture filling mineralogy and geochemistry at the Swedish HDR research site. In Baria, R. (ed.) "Hot Dry Rock", Proc. Camborne School of Mines Int. Conf., Robertson Sci. Publ., London. 425-435.

Sundquist, U., Wallroth, T. & Eliasson, T. 1988. The Fjällbacka HDR Geothermal Energy Research Project: Reservoir characterisation and injection well stimulation. HDR Geothermal Energy Project, Dept. Geology, Chalmers Univ. Tech. / Univ. of Göteborg, Publ. Fj-9.

Wallroth, T. 1992. Hydromechanical breakdown of crystalline rock. Chalmers Tekn. Högskola / Göteborgs Univ., Geol. Instit. Publ. A71.

Other References

Banks, D. 1992. Optimal orientation of water supply boreholes in fractured aquifers. Groundwater, 30, 6, 895-900.

Carlsson, A. & Christiansson, R. 1987. Geology and tectonics at Forsmark, Sweden. Vattenfall, FUD-Rapport No. U(B) 1987/42, Statens Vattenfallsverk, Älvkarleby, Sweden, 91 pp.

Fairhurst, C. 1986. In-situ stress determination - an appraisal of its significance in rock mechanics. Proc. Int. Symp. on Rock Stress and Rock Stress Measurements, Stockholm 1-3 Sept. 1986, 3-17.

Huntoon, P.W. 1986. Incredible tale of Texasgulf well 7 and fracture permeability,Paradox Basin, Utah. Ground water, 24, 5, 643-653.

Lagerbäck, R. 1979. Neotectonic structures in North Sweden. Geol. Fören. i Stockholm Förhand., 100, 263-269.

Larsson, I. 1972. Groundwater in granite rocks and tectonic models. Nordic Hydrol., 3, 111-129.

Myrvang, A. 1979. Bergtrykksmålinger fra dagen i dype borehull - nye metoder *(Rock stress measurements from the surface in deep boreholes - new methods).* In "Fjellsprengningsteknikk, bergmekanikk, geoteknikk" 1979, Tapir forlag, Trondheim.

Odling, N.E. 1993. An investigation into the permeability of a 2-D natural fracture pattern. In Banks, S.B. & Banks, D. (eds.) Proc. XXIVth Congress Int. Assoc. Hydrogeol. "Hydrogeology of Hard Rocks", Ås, 28/6/93-2/7/93.

Olsson, T. 1979. Hydraulic properties and groundwater balance in a soil-rock aquifer system in the Juktan area, northern Sweden. Striae, Vol 12, Uppsala, 72 pp.

Rohr-Torp, E. 1987. Beskrivelse til hydrogeologisk kart Drøbak 1814 II *(Description to hydrogeological map Drøbak 1814 II).* Nor.geol.unders. Skrifter, 78, 19pp. with map.

Ruistuen, H. (pers. comm.) 1993. Arbeidsnotat: hydraulisk splitting, Hvaler 10-16 juni 1993 *[Working note: hydraulic fracturing, Hvaler 10-16 June 1993].* Telefax from SINTEF to NGU 22/10/93.

Selmer-Olsen, R. 1964. Alminnelig geologi og ingeniørgeologi *(General geology and engineering geology).* Tapir forlag, Trondheim, 409 pp.

Selmer-Olsen, R. 1981. Betraktninger over store vannlekkasjer i dyptliggende tunneller *(Considerations over large water leakages in deep tunnels).* Section 21 In Heltzen A.M., Nilsen, B. & Mowinckel A. (eds.) "Fjellsprengningsteknikk, bergmekanikk, geoteknikk, 1981", Tapir forlag, Trondheim.

SIFF 1987. Kvalitetsnormer for drikkevann *(Quality norms for drinking water).* Statens institutt for folkehelse (SIFF), report "Drikkevann G2".

Appendix 1 - Drilling logs, boreholes 1 - 3

Logged by H. Skarphagen

Borehole 1 - 24/9/92, vertical hole, drilling bit diameter at start = 77 mm.

2 m	Very small fracture
9.5 m	Dark cuttings but sound rock
c. 16 m	Light reddish rock, sound rock. The lighter rock is somewhat harder than the darker. Bone dry.
30.9 m	Small fracture, less red.
c. 37 m	Biotite lens/layer
42.4 m	Stop

Borehole 2 - 24/9/92, vertical hole.

	Light grey cuttings
c.15 m	Reddish yellow cuttings
c.16 m	Greyish white cuttings again
16.5 m	Small fracture
17 m	Small fracture
21.6 m	Somewhat larger fracture
23.2 m	Small fracture
27.5 m	Borehole a little damp following a break in drilling
32.4 m	Very small fracture
39.6 m	Fracture with a little water, fracture rather clayey.
42.4 m	Stop

Borehole 3 - 24/9/93, vertical hole, new drillbit

1 m	Small fracture, reddish cuttings
8.3 m	Large fracture - c. 10 cm. Brown water, extremely high drilling rate down to 10 m. (Sample of porous bedrock)
	Water "dries up" gradually, and by 17 m the borehole is almost dry.
25 m	Some deviation from vertical around this depth
35 - 39 m	Cuttings and drilling fluid (air) disappeared !
42.4 m	Stop

Appendix 2 - Drilling logs boreholes A-C

Logged by T.Klemetsrud

Borehole A

3 - 3.5 m	Rather altered/fractured rock
6 - 6.5 m	Rather altered/fractured rock with a little water
35 - 37 m	Rather altered/fractured rock
54.5 - 54.7 m	Fracture
62 - 63.5 m	Rather altered/fractured rock

Total depth : 73 m

Borehole B

11 - 14 m	Rather altered/fractured rock with a little water
24 - 25.5 m	Rather altered/fractured rock
32.5 - 33 m	Rather altered/fractured rock

Total depth : 70 m

Borehole C

4.5 m	A little water
11 - 12.5 m	A little altered/fractured rock
20.5 - 21.5 m	Rather altered/fractured rock
56.5 - 57 m	Rather altered/fractured rock

Total depth : 70 m

Appendix 3

Documentation of test pumping results

Q_a = inflow from aquifer

Calculated using diameter of 3" boreholes = 7,7 cm; diameter of 5½" boreholes = 14,0 cm

Reffsgård Hull 1		Time after pump switchoff		Water level (m bgl)	Q_a (l/hr)	Average time (Hours)	Average water level (m bgl)
Date	Time	Days	Hours				
17-aug-93	03:24:00 pm			-11,79			
17-aug-93	03:34:00 pm	Pump on, placed at 40 m.					
17-aug-93	04:34:00 pm	Sample taken					
17-aug-93	04:46:40 pm	Pump sucks air, switched off, removed from hole.					
17-aug-93	04:49:46 pm	0,0022	0,052	-36,1			
17-aug-93	04:50:16 pm	0,0025	0,060	-35,8	167,6	0,056	35,95
17-aug-93	04:50:38 pm	0,0028	0,066	-35,6	152,4	0,063	35,7
17-aug-93	04:50:59 pm	0,0030	0,072	-35,4	159,7	0,069	35,5
17-aug-93	04:51:22 pm	0,0033	0,078	-35,2	145,8	0,075	35,3
17-aug-93	04:51:43 pm	0,0035	0,084	-35	159,7	0,081	35,1
17-aug-93	04:52:41 pm	0,0042	0,100	-34,5	144,5	0,092	34,75
17-aug-93	04:53:41 pm	0,0049	0,117	-34	139,7	0,109	34,25
17-aug-93	04:54:37 pm	0,0055	0,133	-33,5	149,7	0,125	33,75
17-aug-93	04:55:38 pm	0,0062	0,149	-33	137,4	0,141	33,25
17-aug-93	04:56:41 pm	0,0070	0,167	-32,5	133,0	0,158	32,75
17-aug-93	04:57:47 pm	0,0077	0,185	-32	127,0	0,176	32,25
17-aug-93	04:58:49 pm	0,0084	0,203	-31,5	135,2	0,194	31,75
17-aug-93	04:59:57 pm	0,0092	0,221	-31	123,3	0,212	31,25
17-aug-93	05:02:13 pm	0,0108	0,259	-30	123,3	0,240	30,5
17-aug-93	05:04:40 pm	0,0125	0,300	-29	114,0	0,280	29,5
17-aug-93	05:07:16 pm	0,0143	0,343	-28	107,5	0,322	28,5
17-aug-93	05:10:00 pm	0,0162	0,389	-27	102,2	0,366	27,5
17-aug-93	05:12:55 pm	0,0182	0,438	-26	95,8	0,413	26,5
17-aug-93	05:16:03 pm	0,0204	0,490	-25	89,2	0,464	25,5
17-aug-93	05:19:26 pm	0,0228	0,546	-24	82,6	0,518	24,5
17-aug-93	05:23:05 pm	0,0253	0,607	-23	76,5	0,577	23,5
17-aug-93	05:27:08 pm	0,0281	0,674	-22	69,0	0,641	22,5
17-aug-93	05:31:36 pm	0,0312	0,749	-21	62,6	0,712	21,5
17-aug-93	05:36:30 pm	0,0346	0,831	-20	57,0	0,790	20,5
17-aug-93	05:42:13 pm	0,0386	0,926	-19	48,9	0,878	19,5
17-aug-93	05:48:48 pm	0,0431	1,036	-18	42,4	0,981	18,5
17-aug-93	05:56:47 pm	0,0487	1,169	-17	35,0	1,102	17,5
18-aug-93	09:27:00 am	0,6947	16,672	-11,93	1,5	8,920	14,465

Reffsgård Hole 2		Time after pump stop		Water level (m bgl)	Qa (l/hr)	Average time (hrs)	Average water level (m bgl)
Date	Time	Days	Hours				
13-aug-93	04:30:00 pm			-8,74			
14-aug-93	09:15:00 am			-8,72			
14-aug-93	10:02:00 am			-8,72			
14-aug-93	10:12:24 am	Pump start, pump at 30 m					
14-aug-93	10:54:00 am	Pump sucks air, cuts out					
14-aug-93	11:40:00 am	Pump on again, water sample taken					
14-aug-93	11:48:00 am	Pump cuts out without drawing air. Pump removed from hole.					
14-aug-93	11:51:51 am	0,0027	0,064	-26,61			
14-aug-93	11:52:23 am	0,0030	0,073	-26,6	5,24	0,069	26,605
14-aug-93	11:53:55 am	0,0041	0,099	-26,55	9,11	0,086	26,575
14-aug-93	11:55:19 am	0,0051	0,122	-26,5	9,98	0,110	26,525
14-aug-93	11:58:24 am	0,0072	0,173	-26,4	9,06	0,148	26,45
14-aug-93	12:01:28 pm	0,0094	0,224	-26,3	9,11	0,199	26,35
14-aug-93	01:36:25 pm	0,0753	1,807	-19,98	18,60	1,016	23,14
14-aug-93	01:37:49 pm	0,0763	1,830	-19,9	15,97	1,819	19,94
14-aug-93	01:39:48 pm	0,0776	1,863	-19,8	14,09	1,847	19,85
14-aug-93	01:47:43 pm	0,0831	1,995	-19,4	14,12	1,929	19,6
14-aug-93	01:56:06 pm	0,0890	2,135	-19	13,33	2,065	19,2
14-aug-93	02:06:55 pm	0,0965	2,315	-18,5	12,92	2,225	18,75
14-aug-93	02:27:50 pm	0,1110	2,664	-17,6	12,02	2,490	18,05
14-aug-93	02:46:23 pm	0,1239	2,973	-16,92	10,24	2,818	17,26
14-aug-93	03:15:19 pm	0,1440	3,455	-15,95	9,37	3,214	16,435
14-aug-93	03:19:50 pm	0,1471	3,531	-15,8	9,28	3,493	15,875
14-aug-93	03:57:15 pm	0,1731	4,154	-14,53	9,48	3,842	15,165
14-aug-93	04:22:26 pm	0,1906	4,574	-13,8	8,10	4,364	14,165
14-aug-93	05:25:53 pm	0,2346	5,631	-12,14	7,31	5,103	12,97
14-aug-93	06:11:11 pm	0,2661	6,386	-11,1	6,41	6,009	11,62
14-aug-93	09:11:25 pm	0,3913	9,390	-8,38	4,22	7,888	9,74
15-aug-93	10:00:10 am	0,9251	22,203	-7,555	0,30	15,797	7,9675
15-aug-93	10:12:40 am	0,9338	22,411	-7,555	0,00	22,307	7,555
15-aug-93	06:37:00 pm	1,2840	30,817	-7,22	0,19	26,614	7,3875
16-aug-93	09:25:00 am	1,9007	45,617	-6,9	0,10	38,217	7,06
16-aug-93	06:23:00 pm	2,2743	54,583	-7	-0,05	50,100	6,95
17-aug-93	09:31:00 am	2,9049	69,717	-7,1	-0,03	62,150	7,05
18-aug-93	10:21:40 am	3,9400	94,561	-6,19	0,17	82,139	6,645
18-aug-93	02:35:00 pm	4,1160	98,783	-6,13	0,07	96,672	6,16
18-aug-93	06:22:00 pm	4,2736	102,567	-6,07	0,07	100,675	6,1
19-aug-93	09:43:00 am	4,9132	117,917	-5,94	0,04	110,242	6,005

Reffsgård Hole 3		Time after pump stop		Water level (m bgl)	Qa (l/hr)	Average time (hrs)	Average water level (m bgl)
Date	Time	Days	Hours				
14-aug-93	09:15:00 am			-4,05			
14-aug-93	09:32:00 am	Pump start, pump at 40 m					
14-aug-93	09:36:00 am			-10			
14-aug-93	09:41:30 am			-14,8			
14-aug-93	10:02:00 am	Pump stop, pump removed from hole					
14-aug-93	10:06:55 am	0,0034	0,08	-24,9			
14-aug-93	10:10:58 am	0,0062	0,15	-24,85	3,45	0,12	24,875
14-aug-93	10:15:34 am	0,0094	0,23	-24,8	3,04	0,19	24,825
14-aug-93	10:29:53 am	0,0194	0,46	-24,7	1,95	0,35	24,750
14-aug-93	10:46:40 am	0,0310	0,74	-24,6	1,66	0,60	24,650
14-aug-93	11:38:50 am	0,0672	1,61	-24,35	1,34	1,18	24,475
14-aug-93	01:42:37 pm	0,1532	3,68	-23,86	1,11	2,65	24,105
14-aug-93	02:30:30 pm	0,1865	4,48	-23,71	0,88	4,08	23,785
14-aug-93	03:17:45 pm	0,2193	5,26	-23,57	0,83	4,87	23,640
14-aug-93	04:24:30 pm	0,2656	6,38	-23,38	0,80	5,82	23,475
14-aug-93	05:27:30 pm	0,3094	7,43	-23,2	0,80	6,90	23,290
14-aug-93	06:10:00 pm	0,3389	8,13	-23,09	0,72	7,78	23,145
14-aug-93	09:13:10 pm	0,4661	11,19	-22,63	0,70	9,66	22,860
15-aug-93	10:01:30 am	0,9997	23,99	-20,925	0,62	17,59	21,778
15-aug-93	06:39:00 pm	1,3590	32,62	-19,8	0,61	28,30	20,363
16-aug-93	09:25:00 am	1,9743	47,38	-18,14	0,52	40,00	18,970
16-aug-93	06:25:00 pm	2,3493	56,38	-17,28	0,44	51,88	17,710
17-aug-93	09:25:00 am	2,9743	71,38	-15,73	0,48	63,88	16,505
17-aug-93	01:17:00 pm	3,1354	75,25	-15,39	0,41	73,32	15,560
18-aug-93	10:20:00 am	4,0125	96,30	-13,615	0,39	85,78	14,503
18-aug-93	02:37:00 pm	4,1910	100,58	-13,24	0,41	98,44	13,428
18-aug-93	06:20:20 pm	4,3461	104,31	-12,905	0,42	102,44	13,073
19-aug-93	09:42:00 am	4,9861	119,67	-11,59	0,40	111,99	12,248

Reffsgård Hole A		Time after pump stop		Water level (m bgl)	Qa (l/hr)	Average time (hrs)	Average water level (m bgl)
Date	Time	Days	Hours				
13-aug-93	05:00:00 pm			-17,24			
14-aug-93	04:04:00 pm	Pump on at c. 45 m					
14-aug-93	04:36:50 pm	Pump stop, removed from hole					
14-aug-93	04:51:53 pm	0,0105	0,25	-45,02			
14-aug-93	04:53:38 pm	0,0117	0,28	-45	10,56	0,27	45,010
14-aug-93	05:07:08 pm	0,0210	0,51	-44,95	3,42	0,39	44,975
14-aug-93	06:01:00 pm	0,0584	1,40	-44,1	14,57	0,95	44,525
14-aug-93	06:05:09 pm	0,0613	1,47	-44,05	11,13	1,44	44,075
14-aug-93	09:18:10 pm	0,1954	4,69	-42,1	9,33	3,08	43,075
14-aug-93	09:22:44 pm	0,1985	4,77	-42,05	10,11	4,73	42,075
15-aug-93	10:00:00 am	0,7244	17,39	-36,75	6,46	11,08	39,400
15-aug-93	06:44:00 pm	1,0883	26,12	-34,6	3,79	21,75	35,675
16-aug-93	09:25:00 am	1,7001	40,80	-31,33	3,43	33,46	32,965
16-aug-93	06:28:00 pm	2,0772	49,85	-29,88	2,47	45,33	30,605
17-aug-93	09:28:00 am	2,7022	64,85	-27,52	2,42	57,35	28,700
17-aug-93	01:28:00 pm	2,8689	68,85	-27,12	1,54	66,85	27,320
18-aug-93	10:25:00 am	3,7418	89,80	-25,345	1,30	79,33	26,233
18-aug-93	02:40:00 pm	3,9189	94,05	-25,065	1,01	91,93	25,205
18-aug-93	06:25:00 pm	4,0751	97,80	-24,85	0,88	95,93	24,958
19-aug-93	09:40:00 am	4,7105	113,05	-24,02	0,84	105,43	24,435

Reffsgård Hole B		Time after pump stop		Water level (m bgl)	Qa (l/hr)	Average time (hrs)	Average water level (m bgl)
Date	Time	Days	Hours				
13-aug-93	04:45:00 pm			-10,26			
18-aug-93	10:28:30 am			-10,7			
18-aug-93	11:47:30 am	Pump started at 50 m deep					
18-aug-93	12:28:40 pm	Pump draws air, stops and is removed from hole					
18-aug-93	12:39:00 pm	0,0072	0,17	-49,62			
18-aug-93	02:25:00 pm	0,0808	1,94	-49,575	0,39	1,06	49,598
18-aug-93	06:16:00 pm	0,2412	5,79	-49,545	0,12	3,86	49,560
19-aug-93	09:29:00 am	0,8752	21,01	-49,325	0,22	13,40	49,435

Reffsgård Hole C							
13-aug-93	04:50:00 pm			-8,86			
18-aug-93	10:04:00 am			-9,31			
18-aug-93	10:17:30 am	Pump started at 50 m deep					
18-aug-93	10:57:40 am	Pumpestopp					
18-aug-93	11:06:55 am	0,0064	0,15	-49,44			
18-aug-93	11:42:50 am	0,0314	0,75	-49,425	0,39	0,45	49,433
18-aug-93	12:15:30 pm	0,0541	1,30	-49,41	0,42	1,03	49,418
18-aug-93	02:44:00 pm	0,1572	3,77	-49,365	0,28	2,53	49,388
18-aug-93	06:29:15 pm	0,3136	7,53	-49,315	0,21	5,65	49,340
19-aug-93	09:34:00 am	0,9419	22,61	-49,05	0,27	15,07	49,183

Appendix 4: Documentation of Analytical Results - see Chapter 9

Oppdragsnr. 151/93

Nr.	Prøvemrk.	Ledn.evne µS/cm	pH	Alkalitet mmol/l
1.	R1a	338	7.34	2.48 *
2.	R1b	332	7.53	2.47 *
3.	P1a	545	7.76	4.83
4.	P1b	654	7.74	4.97
5.	P2	290	7.29	2.14
6.	P4	995	6.91	1.50
7.	U1	784	8.39	3.88
8.	TL2	223	6.53	0.71
9.	TL3	251	7.28	1.41 *
10.	RB	335	7.25	1.84

*)= Prøvemrk. R1a, R1b og TL3 inneholder det endel uløste fragmenter, og da blir den oppgitte alkalitet noe usikker.

Side 2
Dato 19.11.93

Oppdragsnummer : 151/93

Prøve nr	F^-	Cl^-	NO_2^-	Br^-	NO_3^-	PO_4^{3-}	SO_4^{2-}
1	3.80ppm	16.4ppm	<1.00ppm	<100 ppb	762 ppb	<200 ppb	14.5ppm
2	3.35ppm	14.8ppm	<1.00ppm	<100 ppb	332 ppb	<200 ppb	16.8ppm
3	2.52ppm	28.0ppm	<1.00ppm	<100 ppb	<50.0ppb	<200 ppb	4.85ppm
4	2.15ppm	53.4ppm	<1.00ppm	157 ppb	<50.0ppb	<200 ppb	7.94ppm
5	1.67ppm	19.6ppm	<1.00ppm	<100 ppb	<50.0ppb	<200 ppb	7.72ppm
6	2.07ppm	206 ppm	<5.00ppm	516 ppb	<50.0ppb	<200 ppb	31.6ppm
7	4.30ppm	95.0ppm	<2.50ppm	255 ppb	<50.0ppb	<200 ppb	21.0ppm
8	1.79ppm	15.6ppm	<1.00ppm	<100 ppb	81.3ppb	<200 ppb	31.6ppm
9	3.40ppm	15.6ppm	<1.00ppm	<100 ppb	228 ppb	<200 ppb	15.3ppm
10	187 ppb	27.9ppm	<1.00ppm	<100 ppb	5.13ppm	<200 ppb	15.1ppm

Løpenr.	Prøve mrk.
1	R1a
2	R1b
3	P1a
4	P1b
5	P2 filt.
6	P4 filt.
7	U1 filt.
8	TL2
9	TL3
10	RB filt.

Side 2 15.SEP 1993

Prosjektnr: 63.2462.00 Oppdragsnr: 151/93

	R1A	R1B	P1A	P1B	P2 F	P2 F+S	P2	P4 F	P4 F+S	P4
Si	127.2 ppm	34.34 ppm	19.96 ppm	15.98 ppm	7.55 ppm	7.19 ppm	10.24 ppm	8.85 ppm	7.96 ppm	11.00 ppm
Al	57.38 ppm	12.58 ppm	5.97 ppm	4.27 ppm	425.6 ppb	348.1 ppb	2.09 ppm	1.93 ppm	1.63 ppm	3.26 ppm
Fe	40.55 ppm	9.69 ppm	5.43 ppm	4.06 ppm	5.25 ppm	4.91 ppm	5.39 ppm	3.19 ppm	2.88 ppm	3.52 ppm
Ti	2.06 ppm	454.1 ppb	313.5 ppb	221.7 ppb	12.0 ppb	<10.0 ppb	74.7 ppb	82.5 ppb	59.5 ppb	138.8 ppb
Mg	9.45 ppm	2.46 ppm	2.19 ppm	2.24 ppm	3.06 ppm	3.39 ppm	3.31 ppm	7.10 ppm	7.57 ppm	7.15 ppm
Ca	4.74 ppm	2.51 ppm	3.95 ppm	13.60 ppm	10.75 ppm	12.19 ppm	10.63 ppm	20.93 ppm	22.69 ppm	19.98 ppm
Na	81.10 ppm	80.41 ppm	136.9 ppm	148.6 ppm	52.09 ppm	57.27 ppm	50.93 ppm	180.0 ppm	192.4 ppm	172.4 ppm
K	21.02 ppm	5.09 ppm	3.29 ppm	2.27 ppm	3.79 ppm	4.08 ppm	3.96 ppm	3.19 ppm	3.44 ppm	3.33 ppm
Mn	390.3 ppb	97.7 ppb	107.7 ppb	109.9 ppb	212.6 ppb	236.0 ppb	212.2 ppb	172.2 ppb	182.9 ppb	167.7 ppb
P	650.2 ppb	178.5 ppb	110.6 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb	<100.0 ppb
Cu	57.9 ppb	20.1 ppb	17.7 ppb	12.2 ppb	< 2.0 ppb	5.3 ppb	7.7 ppb	< 2.0 ppb	2.1 ppb	4.0 ppb
Zn	197.9 ppb	46.2 ppb	64.6 ppb	30.9 ppb	5.1 ppb	6.4 ppb	8.5 ppb	9.9 ppb	11.4 ppb	13.2 ppb
Pb	51.4 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb
Ni	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb	<40.0 ppb
Co	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
V	101.4 ppb	28.8 ppb	18.7 ppb	15.1 ppb	< 5.0 ppb	< 5.0 ppb	9.4 ppb	< 5.0 ppb	5.2 ppb	6.9 ppb
Mo	<10.0 ppb	<10.0 ppb	16.0 ppb	13.7 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
Cd	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
Cr	54.4 ppb	11.8 ppb	10.6 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	65.8 ppb	58.0 ppb	42.7 ppb
Ba	357.0 ppb	84.9 ppb	59.2 ppb	59.9 ppb	15.4 ppb	16.3 ppb	25.1 ppb	46.1 ppb	47.3 ppb	54.2 ppb
Sr	59.9 ppb	24.8 ppb	49.5 ppb	178.1 ppb	56.8 ppb	64.1 ppb	56.3 ppb	247.9 ppb	269.2 ppb	234.3 ppb
Zr	215.0 ppb	57.2 ppb	17.9 ppb	13.0 ppb	< 5.0 ppb	44.6 ppb	8.8 ppb	< 5.0 ppb	18.4 ppb	6.8 ppb
Ag	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
B	86.2 ppb	69.1 ppb	123.9 ppb	120.2 ppb	44.9 ppb	35.5 ppb	35.4 ppb	101.4 ppb	101.4 ppb	97.6 ppb
Be	17.0 ppb	4.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb
Li	30.9 ppb	5.3 ppb	3.7 ppb	3.7 ppb	< 2.0 ppb	< 2.0 ppb	2.1 ppb	4.3 ppb	3.2 ppb	5.3 ppb
Sc	17.9 ppb	4.0 ppb	2.1 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb
Ce	546.5 ppb	127.0 ppb	111.2 ppb	76.7 ppb	<50.0 ppb	<50.0 ppb	61.6 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb
La	278.1 ppb	69.8 ppb	58.8 ppb	35.5 ppb	<10.0 ppb	<10.0 ppb	22.8 ppb	13.4 ppb	13.1 ppb	20.7 ppb
Y	458.6 ppb	131.9 ppb	42.1 ppb	28.5 ppb	8.8 ppb	9.4 ppb	16.8 ppb	9.9 ppb	9.4 ppb	12.0 ppb

Side 3

Prosjektnr: 63.2462.00 Oppdragsnr: 151/93

	U1 F	U1 F+S	U1	TL2	TL3	RB F	RB F+S
Si	6.35 ppm	6.12 ppm	6.50 ppm	35.95 ppm	78.70 ppm	4.48 ppm	4.30 ppm
Al	109.7 ppb	111.7 ppb	147.6 ppb	16.66 ppm	38.38 ppm	50.2 ppb	41.8 ppb
Fe	394.3 ppb	392.7 ppb	522.5 ppb	9.91 ppm	23.30 ppm	54.9 ppb	58.2 ppb
Ti	<10.0 ppb	<10.0 ppb	<10.0 ppb	613.1 ppb	1.42 ppm	<10.0 ppb	<10.0 ppb
Mg	2.50 ppm	2.68 ppm	2.53 ppm	4.91 ppm	5.71 ppm	3.10 ppm	3.14 ppm
Ca	4.21 ppm	4.59 ppm	4.29 ppm	6.30 ppm	3.13 ppm	47.97 ppm	48.47 ppm
Na	172.6 ppm	181.3 ppm	175.1 ppm	36.28 ppm	55.34 ppm	14.63 ppm	14.66 ppm
K	3.47 ppm	3.38 ppm	3.13 ppm	8.39 ppm	14.26 ppm	2.49 ppm	2.70 ppm
Mn	31.8 ppb	36.5 ppb	31.7 ppb	395.7 ppb	324.1 ppb	16.5 ppb	14.5 ppb
P	<100.0 ppb	<100.0 ppb	<100.0 ppb	133.4 ppb	406.4 ppb	<100.0 ppb	<100.0 ppb
Cu	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	29.9 ppb	52.8 ppb	8.2 ppb	10.6 ppb
Zn	< 5.0 ppb	< 5.0 ppb	< 5.0 ppb	55.8 ppb	217.3 ppb	15.4 ppb	19.3 ppb
Pb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb	<50.0 ppb
Ni	<40.0 ppb	<40.0 ppb	<40.0 ppb	355.1 ppb	259.1 ppb	<40.0 ppb	<40.0 ppb
Co	<10.0 ppb	<10.0 ppb	<10.0 ppb	14.3 ppb	10.3 ppb	<10.0 ppb	<10.0 ppb
V	< 5.0 ppb	< 5.0 ppb	< 5.0 ppb	33.1 ppb	52.2 ppb	< 5.0 ppb	< 5.0 ppb
Mo	<10.0 ppb	<10.0 ppb	<10.0 ppb	144.0 ppb	150.3 ppb	<10.0 ppb	<10.0 ppb
Cd	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
Cr	<10.0 ppb	<10.0 ppb	10.6 ppb	39.5 ppb	107.9 ppb	<10.0 ppb	<10.0 ppb
Ba	5.3 ppb	6.3 ppb	5.6 ppb	166.4 ppb	271.5 ppb	13.5 ppb	13.2 ppb
Sr	40.2 ppb	43.4 ppb	41.0 ppb	56.2 ppb	33.2 ppb	229.1 ppb	230.7 ppb
Zr	< 5.0 ppb	55.3 ppb	< 5.0 ppb	32.2 ppb	82.6 ppb	< 5.0 ppb	< 5.0 ppb
Ag	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb	<10.0 ppb
B	221.9 ppb	220.1 ppb	212.5 ppb	31.4 ppb	38.2 ppb	<20.0 ppb	24.5 ppb
Be	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	6.1 ppb	< 2.0 ppb	< 2.0 ppb
Li	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	19.2 ppb	41.6 ppb	< 2.0 ppb	< 2.0 ppb
Sc	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	4.0 ppb	9.1 ppb	< 2.0 ppb	< 2.0 ppb
Ce	<50.0 ppb	<50.0 ppb	<50.0 ppb	84.1 ppb	238.1 ppb	<50.0 ppb	<50.0 ppb
La	<10.0 ppb	<10.0 ppb	<10.0 ppb	31.7 ppb	109.7 ppb	<10.0 ppb	<10.0 ppb
Y	< 2.0 ppb	< 2.0 ppb	< 2.0 ppb	17.1 ppb	69.5 ppb	< 2.0 ppb	< 2.0 ppb

N.B.

F = filtered in field
S = acidified in flask in lab.

U1 = sample from Utengen borehole (see report 93.117)
P1a,b = samples from test pumping of Pulservik borehole 1 15/8/93 at 1615 hrs & 1714 hrs respectively.
P2 = sample from Pulservik borehole 2 (see report 93.120)
P4 = sample from Pulservik borehole 4 (see report 93.120)