NGU Rapport 93.117

Groundwater in bedrock - Hvaler Project. Investigations at testsite Utengen.

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RAPPORT

Rapport nr. 93.117	ISSN 0800-3416	Gradering: Åpen

Tittel:

Groundwater in bedrock - Hvaler Project. Investigations at testsite Utengen.
Grunnvann i fast fjell - Hvaler prosjektet. Undersøkelser ved teststedet Utengen.

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Kartbladnavn (M=1:250.000) Oslo	Kartbladnr. og -navn (M=1:50.000) 1913-III Fredrikstad
Forekomstens navn og koordinater: Utengen, Kirkeøy, ^{6}1584 ^{65}5199	Sidetall: 29 Pris: 60,- Kartbilag:

Feltarbeid utført:	Rapportdato:	Prosjektnr.:	Ansvarlig:
1991-1993	31.12.93	63.2462.00	Tor Erik Finne

Sammendrag:

At testsite Utengen, Hvaler, extensive geophysical investigations have been carried out. Amongst the most promising methods was Georadar, indicating the presence of low-angle fractures at shallow depth in the granite bedock. A 3" borehole was drilled to 35 m to penetrate the most prominent such fracture, with success. The borehole had a short-term yield of some 470 l/hr, with a drawdown of less than 2 m, although there are indications that this is at the expense of limited aquifer storage, and that the long-term yield could be significantly smaller.

Ved teststedet Utengen, på Hvaler, ble det utført omfattende geofysiske undersøkelser. Blant de mest lovende metodene var Georadar, som indikerte flere sprekker med slakt fall i granittenes øverste 30 m. Et 3" borehull ble boret, og dette traff sprekkene som ventet. Borehullet hadde en korttids ytelse på ca.470 l/t (med < 2 m senkning). Det er imidlertid indikasjoner på at dette kan være betydelig overdrevet i langtidsperspektiv, på grunn av begrenset magasinstørrelse.

Emneord: Hydrogeologi	Grunnvannsbrønn	Sprekkesone
Grunnvann	Berggrunn	Grunnvannskvalitet
Borhullslogging	Geofysikk	Fagrapport

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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. 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
- establishment of six boreholes at a second testsite at Reffsgård
- investigation of methods to artificially enhance yields
- 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 (*Hvalerøyene*) 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.

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.

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).

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, 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. 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, ± epidote, related to cooling of granite; (2) haematite, chlorite, calcite ± quartz ± 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 Utengen

Early in the study, several localities on the northwestern peninsula of the island of Kirkeøy were selected as possible candiates for the establishment of permanent testsites. These were all subject to investigation by a variety of geophysical methods, including VLF, magnetometry, resistivity profiling and georadar.

Utengen (Fig. 1) was one of these sites. It was chosen because it lies on the intersection of several prominent and more minor lineaments, and also because the central part of the site is covered by thin Quaternary deposits, allowing the possibility of investigating the performance of bedrock geophysical methods through such a sediment cover. As with the other selected sites, the geophysical results from Utengen are reported by Lauritsen & Rønning (1992). One of the most interesting features of the Utengen site was the detection of relatively shallowly-dipping bedrock reflectors, interpreted to be fractures, by Georadar.

4 Geophysics

4.1 Introduction to geophysical methods in bedrock

During the eighties various geophysical methods for the mapping of fracture zones have been tested at the Geological Survey of Norway. These methods utilize, for example, acoustic wave velocity (refraction seismics), electrical resistivity (electrical and electromagnetic profiling), magnetic susceptibility (magnetic profiling) and dielectricity (ground penetrating radar). Some of the methods were used in the Hvaler project with great success.

Refraction seismics is a safe way to map fracture zones in bedrock. In addition to the location of fractures, this method gives information on thickness of overburden, thickness of fracture zones and degree of fracturing. The method is, however, unsuitable for the mapping of "thin fractures" and does not give information on fracture dip. Furthermore, the seismic method is time consuming, and cannot be interpreted during data acquisition.

Very Low Frequency Electromagnetic profiling (VLF-EM) is a quick and easy method for locating fractures, but cannot in practice constrain fracture dip, or be used to determine the thickness and depth of overburden. The military transmitters used are often unreliable and the method is heavily influenced by technical installations.

The problem with unreliable VLF transmitters might be solved by using the SLINGRAM method where a local transmitter is used. This is also a fast and easy method for location of fractures. In practice, the method cannot give information on fracture dip, thickness and depth of overburden. In addition, technical installations and severe topography may influence the data and cause false anomalies.

Resistivity profiling offers information on fracture location and thickness, but in practice not on fracture dip. The method is not seriously influenced by power lines and topography. The main inconvenience with this method is the strong influence of conductive overburden if present.

Magnetic profiling is an inexpensive method which can provide information on fracture location and thickness. The data may, however, be influenced by nearby technical installations and variations in soil thickness. For this method to be useful, it is necessary that the bedrock is magnetic.

Ground Penetrating Radar (GPR) is now used worldwide for the mapping of fractures in quarries and mines and for engineering purposes. This is the only method which can map shallow subhorizontal fractures. The method does not work well on steeply dipping zones and conductive overburden, such as marine clay, may shield all information from the bedrock below.

Geophysical well logging reveals an enormous amount of downhole information. At the Geological Survey of Norway we have concentrated on a simple data acquisition system, measuring formation resistivity with three different electrode configurations, fluid resistivity, temperature and self potential. The system can provide us with information on the location of fissures in bedrock and the sites of water (and hence potential pollution) inflow.

4.2 Application of geophysics at Testsite Utengen

The following methods were used within the Hvaler project:

* VLF-EM (NGU receivers, various transmitters)
* Magnetic profiling (Geometrics proton magnetometer)
* Resistivity profiling (ABEM Terrameter, gradient configuration)
* GPR profiling (Sensors & Software, pulse EKKO IV)
* Borehole logging (ABEM SAS LOG 200, resistivity, fluid resistivity, temperature and self potential)

The examples shown in Figs. 3 and 4 are from a profile at Utengen (Fig. 2). A rise in the VLF-Re curve (dipangle, Fig. 3a) from the start of the profile is caused by a power line at position 100. A steep dip in the curve from position 170 to 195 is interpreted to be caused by a conductive zone in the ground. Small variations in the VLF-Im curve (elipticity) indicate moderate conductivity.

The magnetic curve for the same profile (Fig. 3b) shows irregularities in the beginning caused by the power line. A local magnetic low from position 170 to 200 coincides with the VLF-anomaly. This is probably caused by a combination of fracturing in the bedrock and increased soil thickness. To distinguish between these two effects, we need to do some petrophysical work on rock samples and magnetic modelling.

The resistivity profile (Fig. 3c) has a low from position 165 to 200. This coincides with VLF and magnetic anomalies, but partly also with variations in soil thickness (Fig. 5). The apparent resistivity level between 200 and 210 seems to be caused by soil and to a certain degree fracturing. From this we can conclude that the extreme low level between 170 and 200 is mainly caused by bedrock fracturing.

A ground penetrating radar registration from the Utengen profile is presented in Fig. 4a. At both ends, bedrock is exposed and the more or less horizontal reflector at approximately 70 ns is interpreted as being caused by the overburden/bedrock interface. Consequently, a dipping reflector from position 210 (0 ns) down to position 165 (300 ns) must be an event within bedrock. In Fig. 4b, a processing technique called "trace difference" has been used to enhance dipping reflections. In this plot we clearly see reflections dipping in both directions.

An interpretation of GPR registrations is presented in Fig. 5. Several reflections with apparent dips of 20-30° are shown especially well in the central part of the profile where VLF, magnetometery and resistivity are anomalous.

5 Drilling

Because of the interesting results of the geophysical investigations, it was felt desirable to confirm these by drilling. A single, 35 m deep, 3" diameter top-hammer drilling was performed at position 160 with a dip of 59° towards the center of the profile (i.e. towards NW, parallel with the profile; Figs. 1,2). A simple borehole log is shown in Appendix 1. The main water-bearing fracture appeared to be at 9.3 m depth, although there may have been additional contributing fractures below this level.

Utengen borehole - borehole details	
Depth (along borehole axis)	35 m
Diameter	77 mm
Fall / Direction	59° / NW
Rest Water Level (13/8/93)	0.97 m below ground level

Table 1: Details of Utengen borehole

6 Geophysical logging

Geophysical logging of the borehole (Fig. 6) shows resistivity lows at 7, 9-10 and 25-27 meters depth. The first two of these correspond with reflections obtained from GPR profiling. The deepest reflector had to be migrated to match the resistivity log. A weak resistivity anomaly at 15 meters corresponds with a very weak reflector.

The SP log indicates porous structures at 5-7.5 meter and 25-33 meters which coincide with resistivity anomalies. Fluid resistivity and temperature logs are anomalous at 7 and 9 meters indicating water inflow at those levels, the largest anomaly in the fluid resistivity log being at c. 9 m. There was no indication of water inflow at 26 metres during the data acquisition period. All this information corresponds with registrations during drilling.

Date : 13/8/93		
Rest water level = 0,97 m below ground level (BGL)		
Pump (GRUNDFOS MP-1; 2" diam.) placed at 30 m bgl.		
Start pumping at 14:32 pm. Pumping rate = 470 - 480 l/hr.		
Time	Water level (m bgl)	Temp. of water (°C)
14:42	1,50	9.1
14:57	1,91	
15:15	2,20	9.4
15:22 Pump stopped - ran out of fuel. Recovery commences.		
15:23:10	2,00	
15:24:36	1,92	
15:25:26	1,88	
15:26:32	1,84	
15:28:50	1,77	
13:30:02	1,74	
15:32:11	1,69	
15:38:24	1,59	
15:46:15	1,49	
15:52:13	1,44	

Table 2: Short-term testing of Utengen borehole, 13/8/93. Bgl = below ground level.

7 Test-pumping

The borehole was test-pumped in August 1993, using techniques described by Banks (1993). The weather in the preceeding weeks had been exceptionally wet, although during test-pumping itself, the weather was fine. Details of the pumping test are summarised in table 2, and processed in Appendix 2.

During pumping, the water was slightly turbid due to drilling cuttings. It was also possible to detect a slight H_2S smell and taste during pumping. In the nearby ditch, the water temperature was above 10°C. The slight increase in temperature during pumping could therefore either be due to progressive intrusion of surface water or shallow groundwater from Quaternary deposits, or to "artificial" upwarming from the pump-motors.

It will be noted from Figs. 7 & 9 that the drawdown and recovery are not symmetrical. The aquifer releases relatively large amounts (around 470 l/hr) of water (Q_A) during drawdown, but very little (less than 15 l/hr) under recovery. This implies that, during pumping, one is emptying an aquifer storage system. Although this may have a relatively high transmissivity connection to the borehole (high Q_A) during drawdown, it is only replenished very slowly from e.g. more widespead fracture systems or overlying Quaternary deposits, and thus the recovery of water level is slow. The pumping test can therefore not be adequately analysed by simple traditional techniques (infinite homogeneous aquifer assumption is violated) or by Banks's (1993) method, which assumes that transmissivity of fractures connecting with the borehole is the limiting factor for borehole yield, rather than aquifer storage. Nevertheless, a simple Jacob analysis (Fig. 11) has been attempted (Kruseman & de Ridder, 1989), yielding transmissivity values of 2.2 m^2/d from drawdown data and 3.4 m^2/d from recovery. The recovery data clearly do not form a satisfactory straight line, however, indicating that the Jacob analysis is (as expected) not valid, and little importance should be attached to these values. It would be expected that the borehole does not have a high sustainable yield. The yields of 470 l/hr measured during short term testing are derived at the expense of emptying aquifer storage.

8 Chemistry

Water samples were taken at 14:57 pm during pumping. These consisted of:

1 x 500 ml flask (unfiltered) for laboratory alkalinity, pH and conductivity determination.
1 x 100 ml flask (filtered, 0,45μm Millipore) for cation analysis by ICP methods and anion analysis by ion chromatograph.

Unfortunately, during transport to NGU, the samples were inadvertently placed near the vehicle ventilation system and subjected to upwarming. Analyses were performed at NGU. The samples for cation analysis were analysed twice, once without acidification (analysis U1 F) and a second time after addition of Ultrapure nitric acid to the flask to remobilise any precipitated or adsorbed cations/metals (analysis U1 F+S). Analysis results reveal no substantial differences between the two analyses.

The results (Table 3) indicate a typical granitic groundwater, with relatively high Si (6.1 - 6.4 ppm). The water displays problems typical of granitic groundwater on Hvaler, namely high Na, F, Cl, Fe, Al. The significant excess of Na over Cl indicates a high degree of water-rock interaction, and therefore that the borehole is drawing upon true granitic groundwater, rather than "short-circuited" Quaternary groundwater or surface water.

Locality: Utengen - Hvaler		Table 3.			
Sampled by: David Banks		**Dato:** 13. August 1993			
Analyzed by: NGU Trondheim					
Parameter	Utengen U1 (F+S)	Utengen U1 (F)	Utengen U1 (U)	**SIFF(G)**	**SIFF(A)**
pH			8,39	7,5 - 8,5	6,5 - 9,0
Alkalinity (mmol/l)			3,88	0,6 - 1,0	
Conductivity (µS/cm)			784		
Silicon ppm	6.1	6.4			
Aluminium ppm	0.11	0.11			
Iron ppm	0.39	0.39		< 0.1	< 0.2
Magnesium ppm	2.7	2.5		< 10	< 20
Calcium ppm	4.6	4.2		15 - 25	
Sodium ppm	181	173		< 20	
Potassium ppm	3.4	3.5			
Manganese ppb	37	32		< 50	< 100
Copper ppb	< 2	< 2		< 100	< 300
Zinc ppb	< 5	< 5		< 300	
Lead ppb	< 50	< 50		< 5	< 20
Cadmium ppb	< 10	< 10		< 1	< 5
Barium ppb	6.3	5.3		< 1000	
Strontium ppb	43	40			
Chromium ppb	< 10	< 10			
Titanium ppb	< 10	< 10			
Boron ppb	220	220			
Beryllium ppb	< 2	< 2			
Lithium ppb	< 2	< 2			
Fluoride ppb		4300		< 1500	
Chloride ppm		95		< 100	< 200
Nitrite ppb		< 2500		< 16	< 164
Nitrate ppb		< 50		< 11000	< 44000
Phosphate ppb		< 200			
Sulphate ppm		21		< 100	
Bromide ppb		260			

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

9 Conclusions

At the Utengen testsite, several geophysical methods have been employed to yield a model of fracturing which is in good agreement with fractures actually penetrated during drilling, and confirmed by borehole geophysical logging. Georadar was particularly successful at detecting low-angle fractures, although the most prominent fractures shown by Georadar are not necessarily the most prominent in terms of transmissivity.

A 3" borehole drilled to 35 m appeared to yield up to 470 l/hr groundwater during short-term testing, with a drawdown of less than 2 m. Closer inspection of recovery data reveals, however, that this yield is apparently derived from aquifer storage which is only slowly replenished by new recharge. Traditional methods of test-pumping analysis could not be successfully applied to the borehole.

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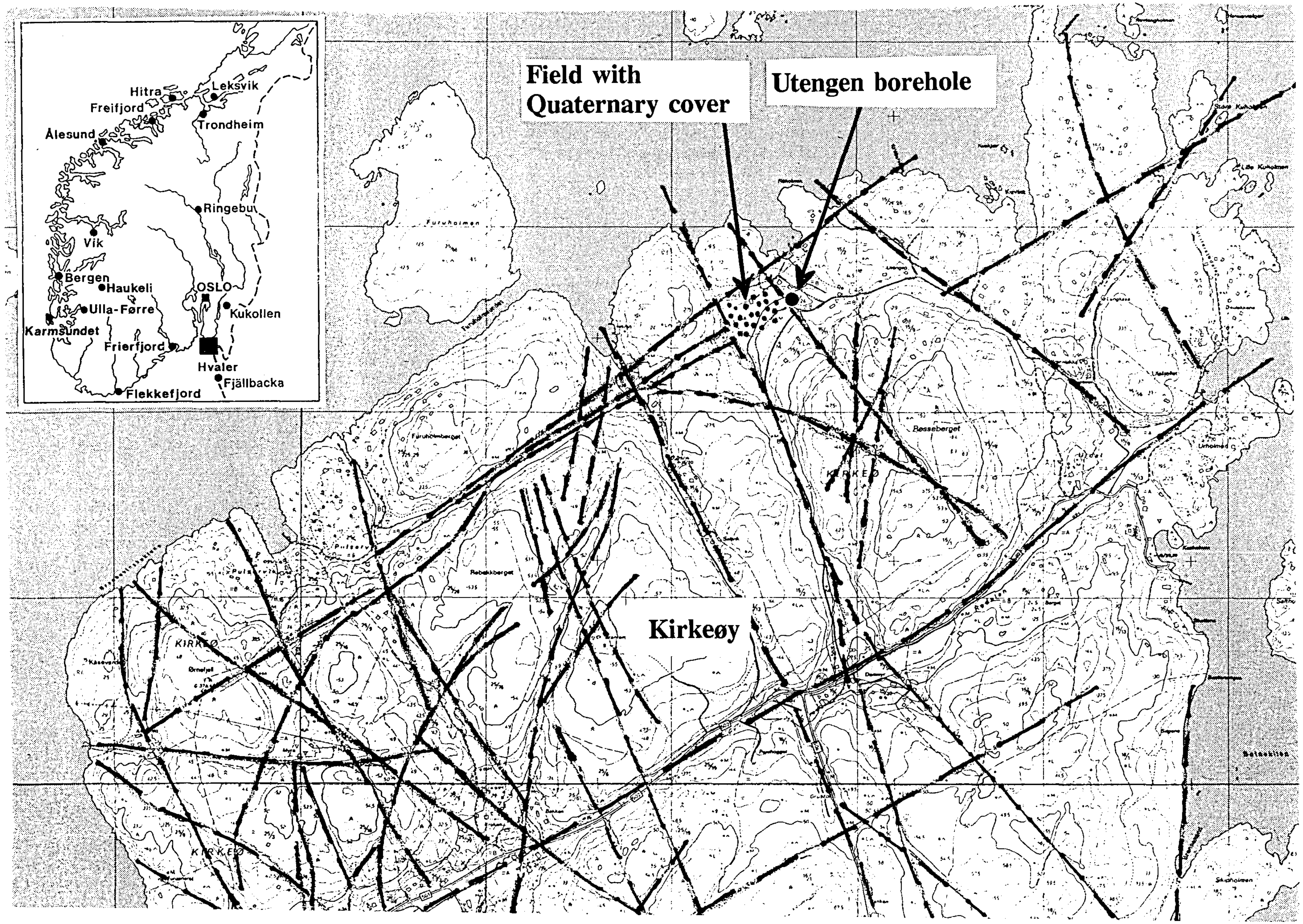


Fig. 1. Location of Testsite Utengen, showing mapped fracture zones

PROFILE AND DRILLHOLE LOCATION

at Utengen

LEGEND:

120 240 Profile (with positions)

Drillhole

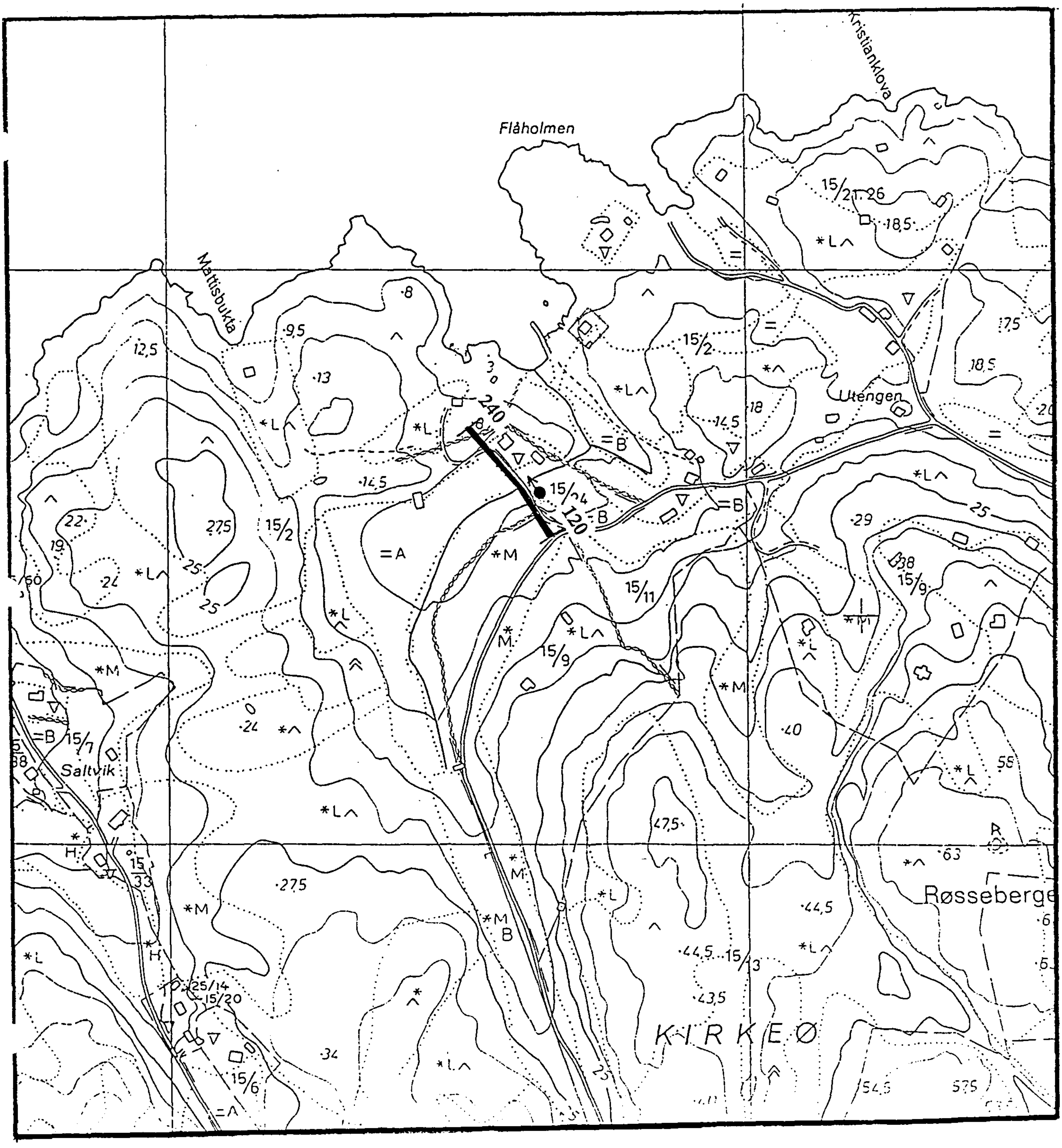
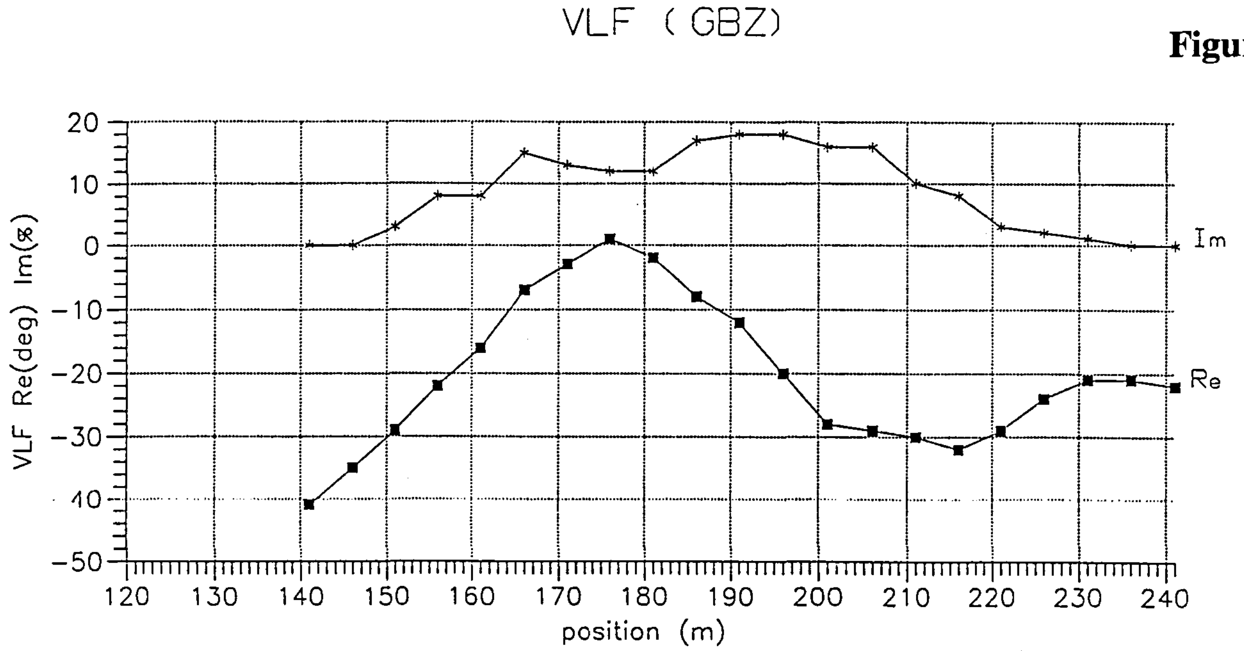


Figure 3a



Geophysical Profiles from Utengen

MAG.

Figure 3b

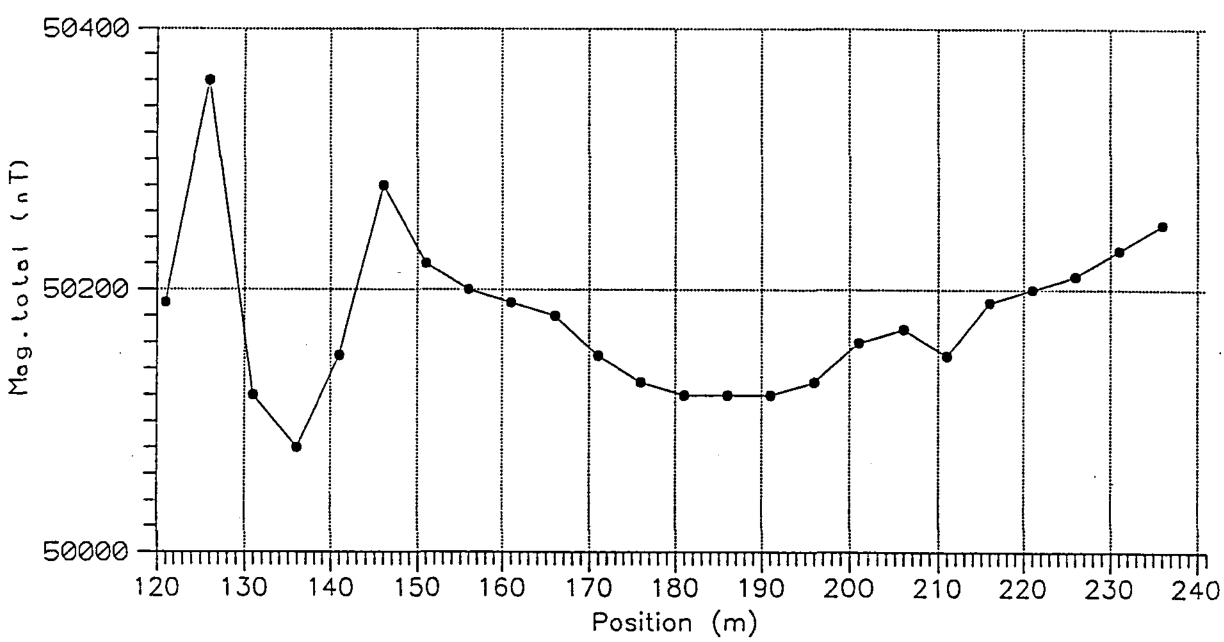
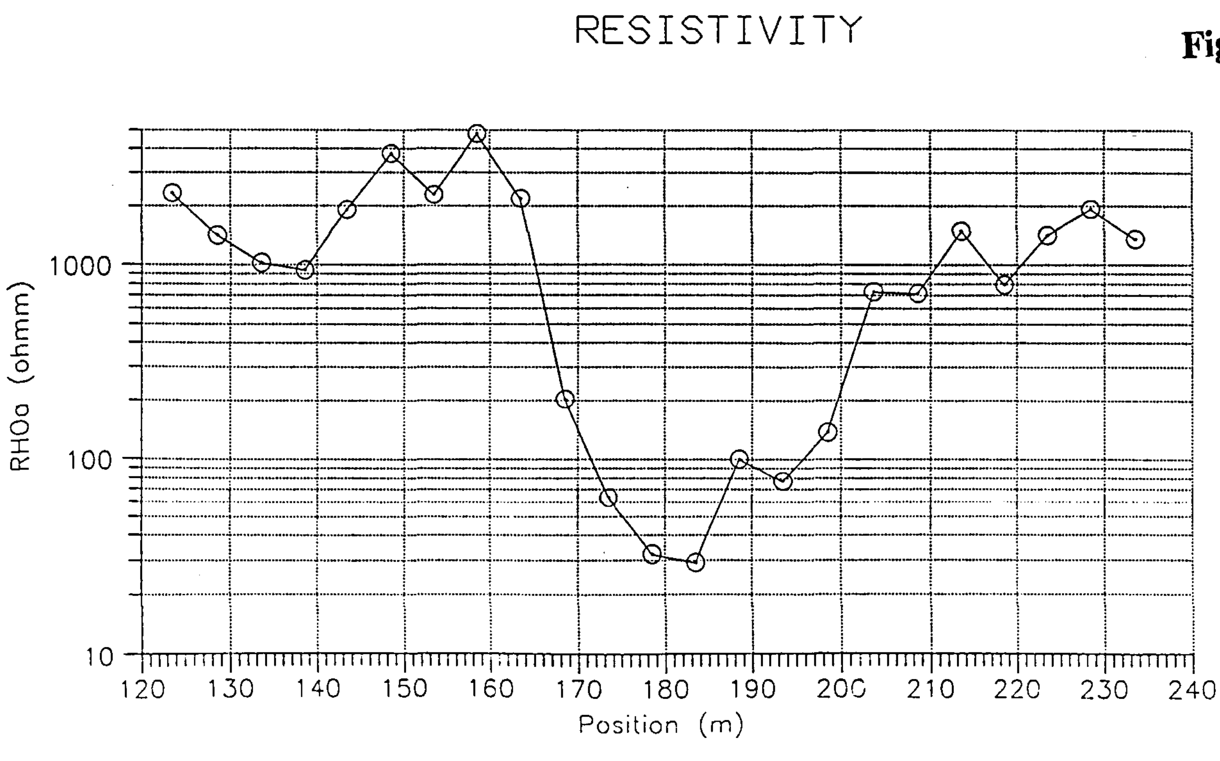


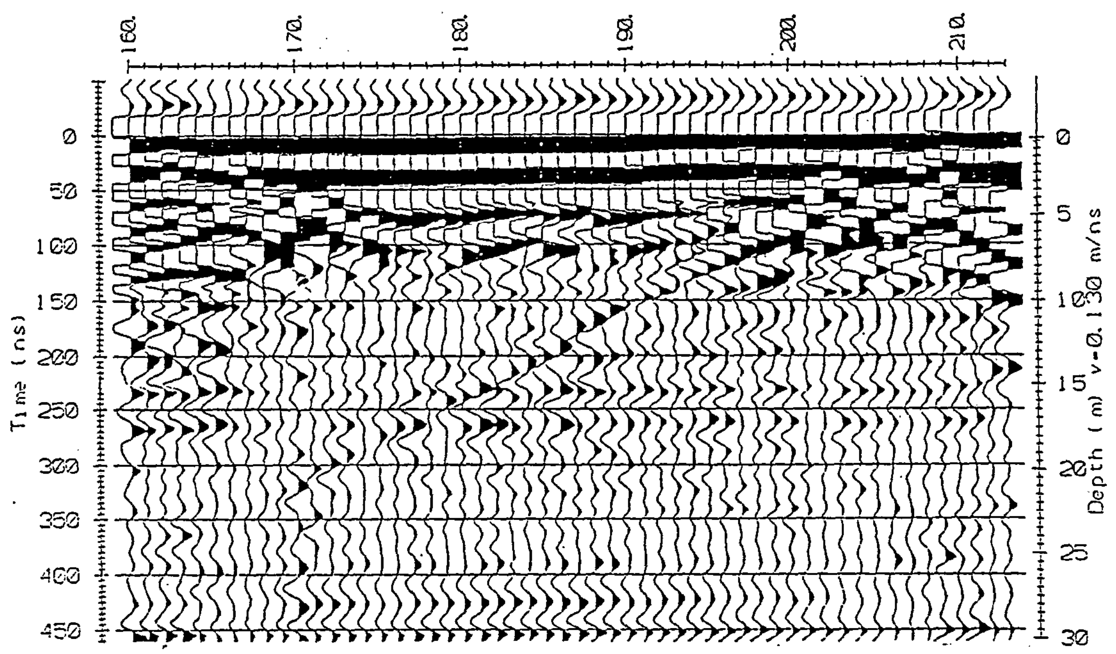
Figure 3c



Georadar Profiles from Utengen

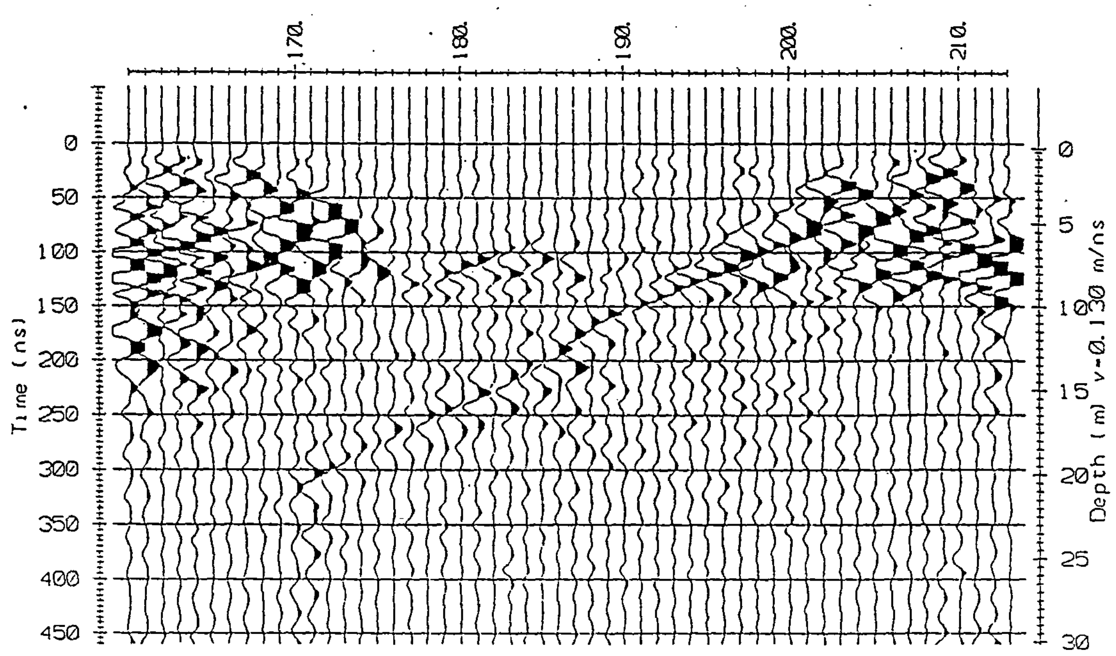
GPR RECORD

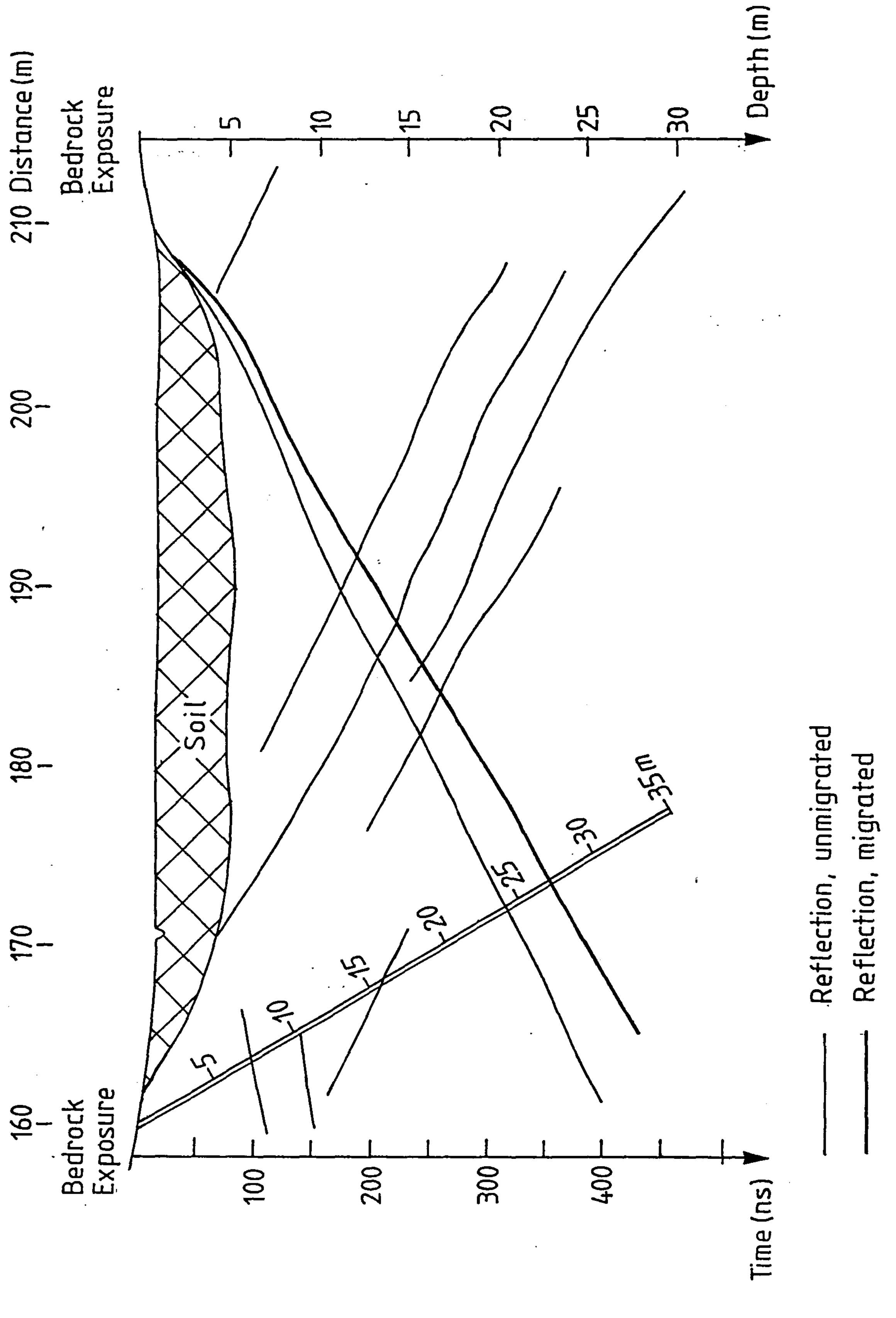
Figure 4a



GPR RECORD (Trace Diff.)

Figure 4b





Interpretation of Georadar Profiles at Utengen

SN = short normal, LN = long normal, LL = lateral log

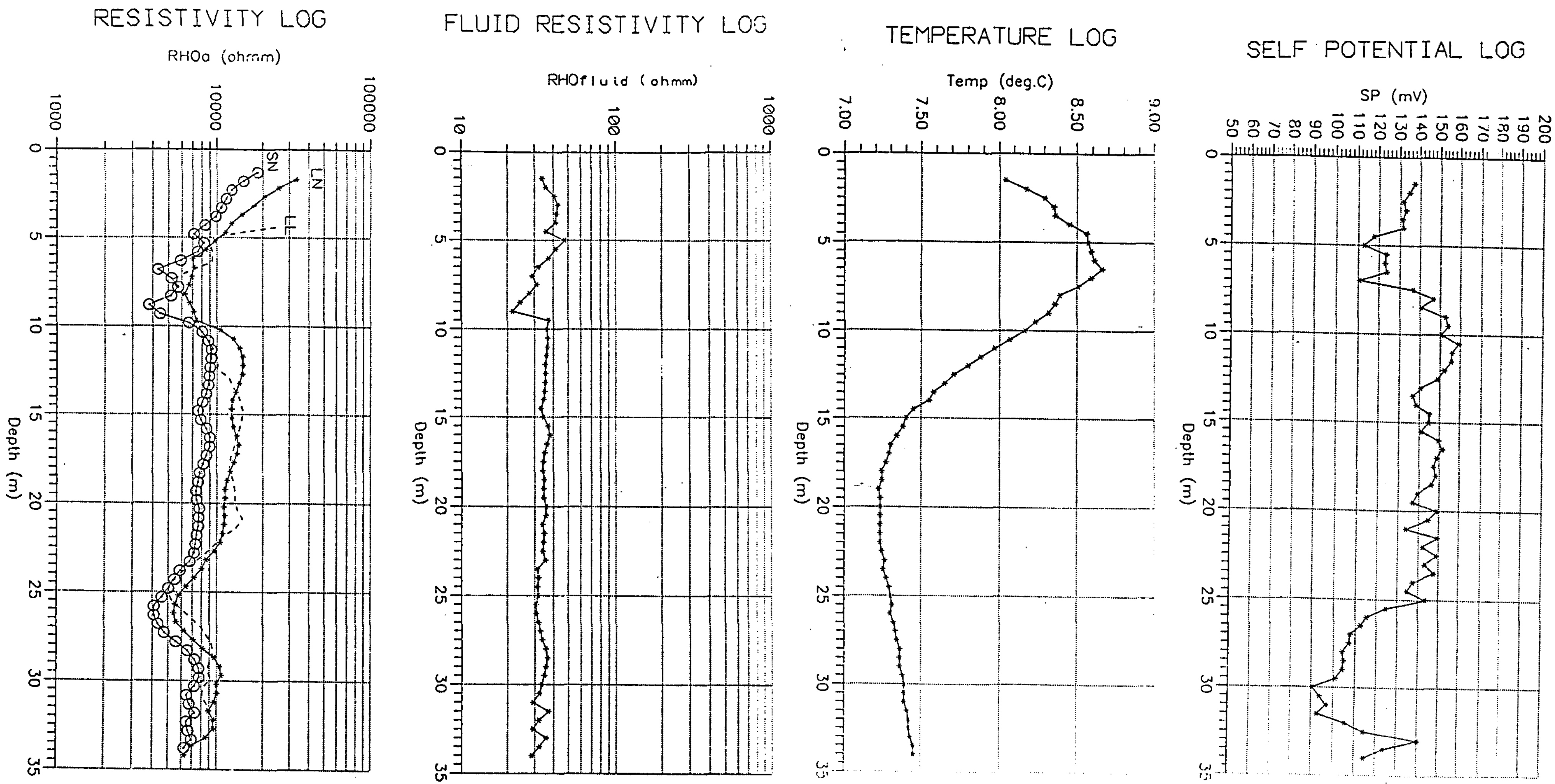


Figure 6 **Borehole logs from 3" borehole at Utengen**

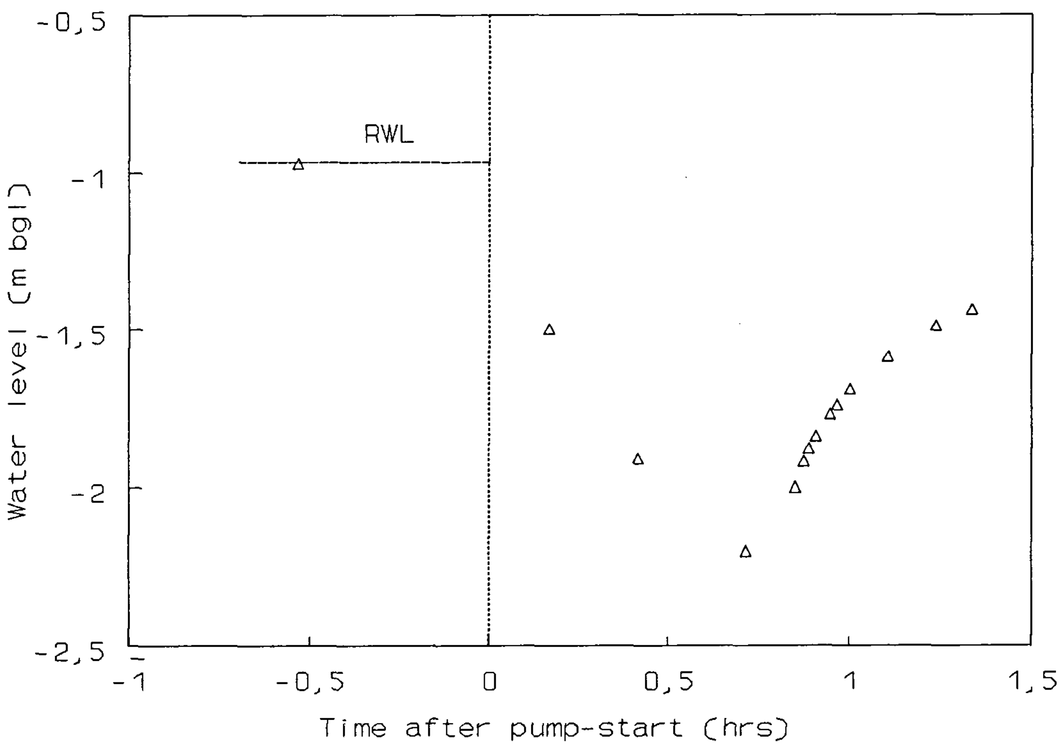


Figure 7. Water level vs. time plot for test pumping of Utengen borehole, 13/8/93.

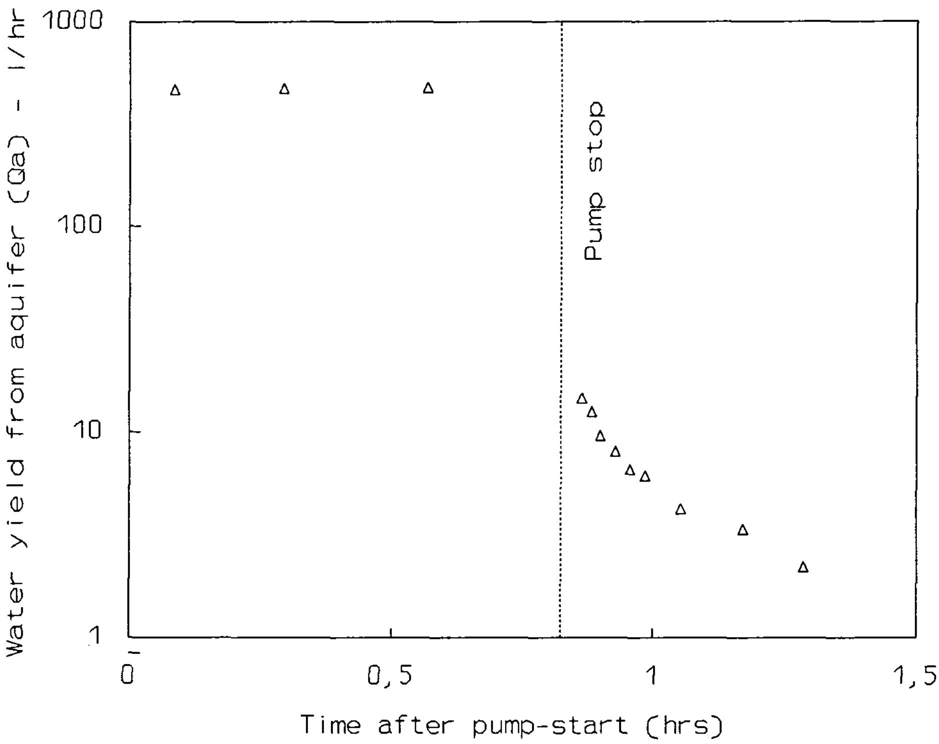


Figure 8. Plot of inflow from aquifer (Q_a) vs. time for pumping test at Utengen, 13/8/93.

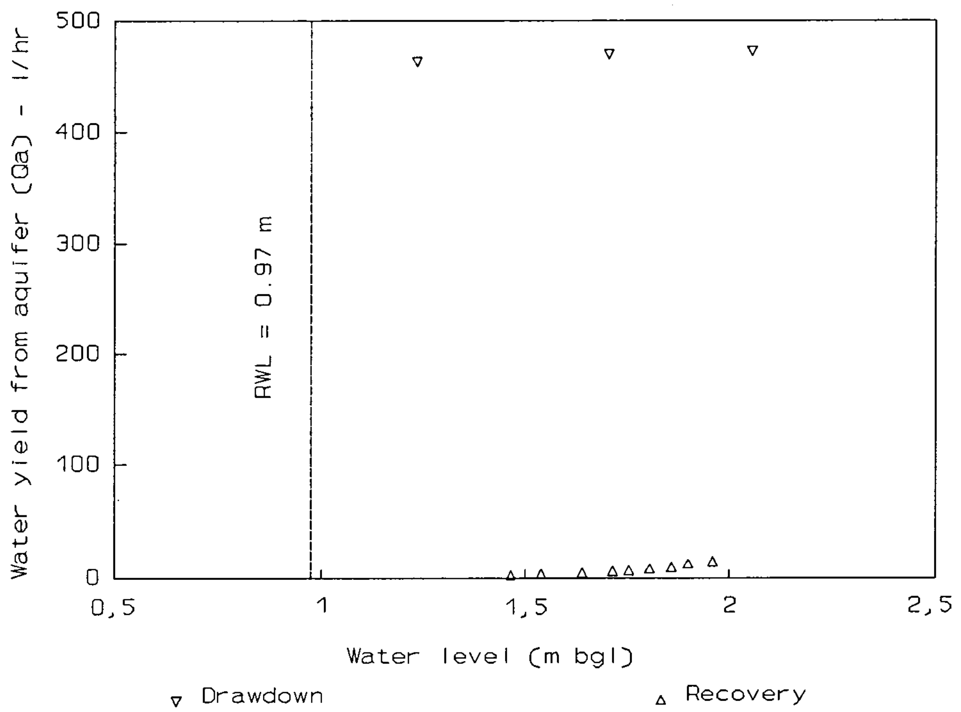


Figure 9. Plot of Q_a (inflow from aquifer) vs. water level (m below ground level). Utengen pumping test, 13/8/93.

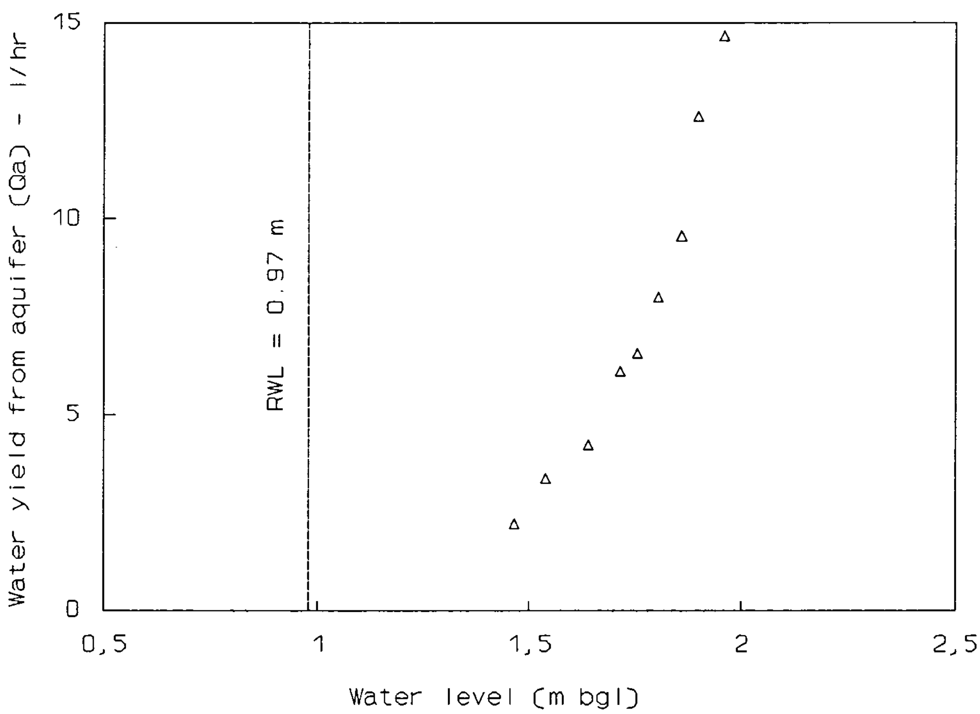


Figure 10. Expanded plot of Q_a vs. water level for recovery from pumping test at Utengen 13/8/93.

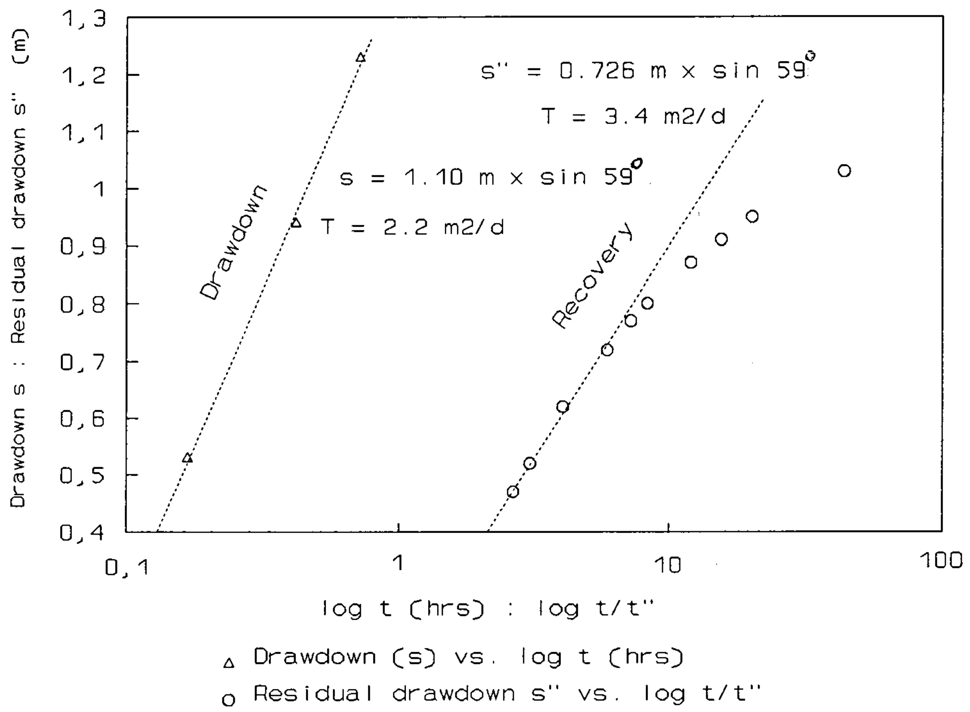


Figure 11. Attempted Jacob analysis of drawdown and recovery during Utengen pumping test, 13/8/93.

Appendix 1: Drilling log - Utengen borehole

Logged by Helge Skarphagen

Date: 24/9/92. Air flush top-hammer drilling.

Drillbit diameter = 78 mm before drilling, 77 mm on completion. Deviation from vertical = 31° (Fall = 59°).

Depth	Comment
4 m	Sample of cuttings
7.5 m	Small fracture
9.3 m	Fracture with large quantities of water
18 m	Darker rock. Sample of cuttings.
21.6 m	Dark rock
31.5 m	Appeared to be much loose material when adding drilling rods. Uncertain where this is derived from.
c. 32 m	Darker cuttings.
35 m	Stop.

The hole was then jetted clean, without the water becoming clear (much drilling cuttings). The groundwater quantity from the borehole was so large that it was impossible to discern any increase in capacity during drilling below 9.3 m. For the same reason, it was also difficult to observe changes in cuttings properties. Good penetration rate during the entire drilling.

Utengen		Time after pumpstart		Water level	Q_a	Ave. time after pump start (hrs)	Average water level (m)	Q_{tot}	Q_b
Date	Time	Days	Hrs	(m bgl)	(l/hr)			(l/hr)	(l/hr)
13-aug-93	02:00:00 pm	-0,0222	-0,533	-0,97					
13-aug-93	02:32:00 pm	Pump start							
13-aug-93	02:42:00 pm	0,0069	0,167	-1,5	462,1	0,08	-1,235	476	-13,9
13-aug-93	02:57:00 pm	0,0174	0,417	-1,91	468,8	0,29	-1,705	476	-7,2
13-aug-93	03:15:00 pm	0,0299	0,717	-2,2	471,8	0,57	-2,055	476	-4,2
13-aug-93	03:22:00 pm	Pump stopped. Pump remains in hole during recovery.							
13-aug-93	03:23:10 pm	0,0355	0,853	-2					
13-aug-93	03:24:36 pm	0,0365	0,877	-1,92	14,6	0,86	-1,96		
13-aug-93	03:25:26 pm	0,0371	0,891	-1,88	12,6	0,88	-1,9		
13-aug-93	03:26:32 pm	0,0379	0,909	-1,84	9,5	0,90	-1,86		
13-aug-93	03:28:50 pm	0,0395	0,947	-1,77	8,0	0,93	-1,805		
13-aug-93	03:30:02 pm	0,0403	0,967	-1,74	6,6	0,96	-1,755		
13-aug-93	03:32:11 pm	0,0418	1,003	-1,69	6,1	0,99	-1,715		
13-aug-93	03:38:24 pm	0,0461	1,107	-1,59	4,2	1,05	-1,64		
13-aug-93	03:46:15 pm	0,0516	1,238	-1,49	3,3	1,17	-1,54		
13-aug-93	03:52:13 pm	0,0557	1,337	-1,44	2,2	1,29	-1,465		

Calculations performed using a borehole diameter of 7,7 cm, and a pump-hose diameter of 1,9 cm.

Cross section = 0,00437 m^2

Q_a = inflow from aquifer, Q_b = contribution from borehole storage, Q_{tot} = total pump rate

Appendix 2: Raw test-pumping data from Utengen, 13/8/93

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

Appendix 3: Chemical analyses from Utengen borehole

Taken during test-pumping at 1500 hrs, 13/8/93.

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

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.

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

Oppdragsnummer : 151/93 Side 2

Dato 19.11.93

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

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)
R1a,b = samples from Reffsgård borehole 1 (see report 93.118)
TL2 = samples from Reffsgård borehole 2 (see report 93.118)
TL3 = samples from Reffsgård borehole 3 (see report 93.118)
RB = samples from Reffsgård dug well (see report 93.118)

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

Appendix 4: Map of the Iddefjord Granite area, showing the Hvaler islands and Hvaler tunnel.

The rocks surrounding the Iddefjord Granite are Precambrian gneisses.