SKB

TECHNICAL REPORT

86-16

Site investigation
Equipment for geological, geophysical, Hydrogeological and hydrochemical characterization

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SITE INVESTIGATION

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A list of other reports published in this series during 1986 is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR-81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01) and 1985 (TR 85-20) is available through SKB.

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ABSTRACT

An extensive program for the development of equipment and instrumentation for investigations in geological formations is ongoing within the SKB research and development program. Instruments developed and used for geological, geophysical, hydrogeological and hydrochemical characterizations of a formation are presented.

Most of the investigations are performed within the site investigation program, which is briefly mentioned. In total about 60,000 m of cored 56 mm boreholes have been drilled and investigated at eight study sites. A summarized description of the main investigation methods is included.

Instruments for geophysical investigations contains equipment for ground measurements as well as for borehole logging. The Geophysical investigations including the borehole radar measurements, which has been very successful, are indirect methods for the geological and hydrogeological characterization of the rock formation.

Great effort has been laid on the development of hydrogeological instruments for hydraulic tests and groundwater head measurements. An umbilical hose system and a pipe string system for injection tests are used to determine the hydraulic conductivity. Groundwater head in one or several sections are monitored with GRUND and PIEZOMAC II respectively.

In order to obtain hydrochemical investigations with high quality, a complete system for sampling and analysis of ground water has been developed, including a mobile water laboratory.

A dilution probe have been constructed for the determination of undisturbed groundwater flow. The development of this instrument is still in progress.

1. INTRODUCTION

Since 1977 Swedish Nuclear Fuel and Waste Management Co., SKB, has been performing a research and development program for final disposal of spent nuclear fuel. The overall objective of this program is to acquire knowledge and data and to develop methods which are needed for safe disposal of radioactive waste. In integration with the development of methods for the characterization of deep geological formations, an extensive instrument developing program is underway. Measurement for the characterization of geological, geophysical, hydrogeological and hydrochemical conditions are performed in specific site investigations as well as for geoscientific research projects.

An extensive site investigation project for a nuclear waste repository in crystalline rock has been performed within the SKB research and investigation program. In total about 60,000 m of cored boreholes have been drilled and investigated down to a maximum depth of about 1,000 m at eight study sites. The main goal has been to study the repository design requirement of different types of geological formations. In the future the investigations will be focused on detailed requirements determining site selection.

In the beginning of the research and development program it was decided that the in-depth investigations should be performed in core-drilled boreholes of 56 mm diameter. That decision has reduced the drilling costs considerably. Another consequence of the decision was that all borehole instruments have to be designed to feed into such an extremely small diameter.

This report will describe the present state of the instruments used for site characterizations. After a short presentation of the site investigation program and the method used for the investigations, the different instruments for geological, geophysical, hydrogeological and hydrochemical investigations, employed at ground surface as well as from boreholes, are presented.

2. INVESTIGATION METHODS

As an introduction to the presentation of different instruments used for site characterization, the investigation methods used are briefly described in this chapter. Measurements for the characterization of geological , geophysical, hydrogeological and hydrochemical conditions are carried out at ground surface as well as from boreholes.

A great number of methods are included in the standard program for study site investigations which is presented in 2.1, while other methods are used in special applications and other research projects.

2.1 Standard program for site investigations

The SKB site investigation program has been in progress since 1977 in order to find suitable host rock for the construction of a repository. The investigations performed are defined in a standard program for site investigations (Ahlbom et al 1983). The investigation program is devided into four phases:

I Reconnaissance for selection of study site
II Investigations at ground surface
III Investigations at depth
IV Evaluation and modellings

The reconnaissance work starts with studies of maps, airphotos, literature etc, continues with field examination and selective geophysical ground measurements. Finally, a deep borehole is drilled, the core is mapped and geophysical and deep hydrogeological investigation is performed at some preliminary selected sites. The reconnaissance phase results in the selection of a few areas, study sites, for further investigations in accordance to the phases II-III of the standard program.

Surface investigations (phase II) at the study sites, with an approximate size of 5 km^2, include geological surveying with petrological and tectonic mapping and geophysical investigations performed using methods described in 2.2.1.

Investigations at depth (phase III) are performed from boreholes. Short boreholes are drilled in order to determine the properties of the rock and to define the geometry and character of fracture zones indicated at surface. A number of deep (500-1000 m) boreholes are drilled and the drill-core is mapped. In the boreholes extensive geophysical logging and hydrogeological measurements are performed by methods described in 2.3. The chemical composition of groundwater from selected borehole intervals is determined. Long-term registration of the groundwater table and piezometric head is carried out in some of the boreholes.

All data from the investigations is compiled and evaluated in order to get a descriptive model of the geology, tectonics, hydrogeology and geochemistry of the study site, Figure 2.1. This model serves as a base for the numerical modelling from which groundwater flow and direction at different points in the study site rock formation are calculated (Carlsson et al 1983). Results from a number of study sites are presented in SKBF/KBS, 1983.

Experience from earlier performed investigations, special conditions at some sites, development of new investigations and interpretation methods and instruments are reasons for succesive modification and supplementing of the investigation program.

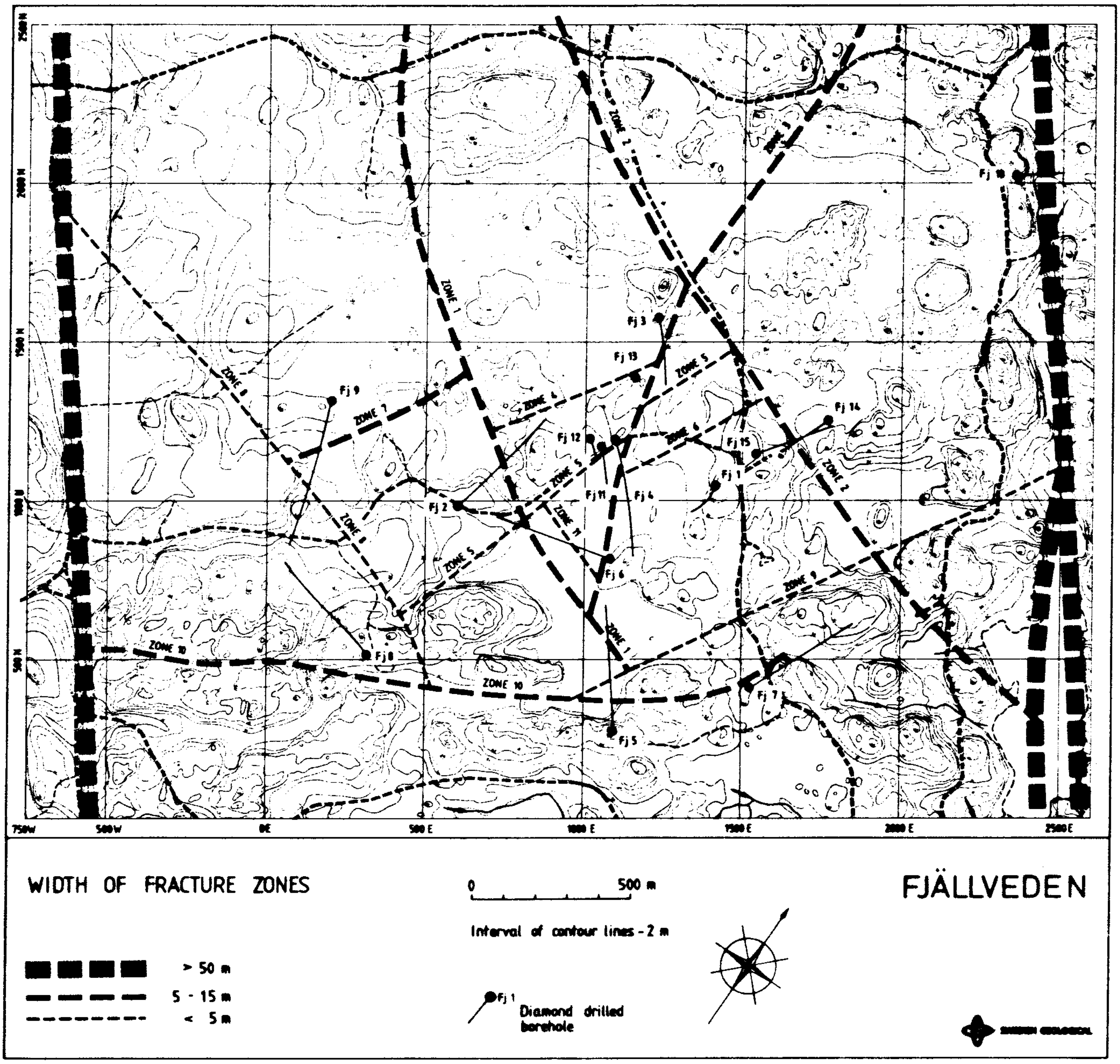


Figure 2.1 Interpretation from geological mapping, ground geophysics, core logging and borehole geophysics.

2.2 Surface investigations

2.2.1 Geophysics

Geophysical ground-surface measurements are performed in order to obtain information on the properties of the rock at the superficial part of the bedrock and in the soil covered areas. The measurements record various physical properties of the rock. The data is used to locate zones of fractures, boundaries and distribution of rock types and the presence of ore minerals.

The measurements are carried out both as dense ground-surface measurements over the study site and as individual profiles within a larger area. In the dense grid measurements the intervals between measuring points normally are 20 x 40 m. The results are reported in maps on a scale of 1:5000. The methods used are described briefly in the following text:

Magnetic measurements

These measurements indicate the presence of rock type boundaries, rock type extension, magnetic dykes and fracture zones. The method is performed in regional individual profiles and in detailed grid measurements at the study sites.

Horizontal Loop EM (slingram) measurements

These measurements indicate the presence of fracture zones and bedrock with high electric conductivity, e.g. graphitic gneiss or concentrations of sulphides. An estimation of the dip of a fracture zone can be made from the shape of the anomaly. The method is performed in regional individual profiles and in detailed grid measurements at the study site. The measurements may be conducted in ortoganal directions in order to better detect structures of different directions.

VLF measurements

The VLF measurements detect fracture zones at greater depths compared with the slingram method. A drawback is the sensitivity of the method to the direction of the VLF transmitter. Thus fracture zones perpendicular to the direction of the transmitter are not detected. This drawback can to a large extent be overcomed by using two transmitter stations of different directions. The method is performed in regional individual profiles and in detailed grid measurements at the study sites.

Gravimetric measurements

These measurements are used to locate contacts between rock types with different densities. Depth estimations of limited rock bodies with sufficient density contrasts can be made. In combination with magnetic measurements it is sometimes possible to locate faults in the bedrock. The method has so far only been used in the reconnaissance work concerning gabbros.

Seismic refraction measurements

These measurements give the thickness of the overburden and indicate fracture zones if they are wide enough. This method is specially useful at sites with an abundance of electric conductive clays. In such areas electric and electromagnetic measurements give limited information. The method is performed in individual profiles in the study sites.

Electrical resistivity measurements

Areas with high fracture frequency as well as fracture zones are indicated by electrical resistivity measurements. Bedrock with high electrical conductivity, e.g. graphite and sulphide ore minerals, is also indicated. This method is used when other electrical methods are disturbed by powerlines, etc.

Induced polarization measurements

These measurements reveal the occurrence of sulphide minerals in disseminated form that are difficult to detect by other geophysical methods. This method is used in connection with the electrical resistivity measurements and is therefore not used as a matter of routine in site investigations programs.

Petrophysical investigation

100-200 samples, from the drill core and ground surface of different rock types are taken for petrophysical measurements at each site. The samples are measured with respect to density, porosity, susceptibility, magnetic remanence, IP-effect and resistivity.

2.3 Depth investigations

The purpose of the depth investigations is to study the distribution and characteristics of rock mass and fracture zones at depth. This is done in a number of core boreholes down to and below the intended repository depth. These boreholes permit sampling and testing of the rock and the fracture zones as well as the groundwater chemistry at repository depth.

2.3.1 Geology

The cores are mapped using a microcomputor-based core logging system. The system is used for registration, storage and presentation of information. In addition, a detailed description of rock types, structures and other important factors is made by hand. All mapping of cores is performed in the field concurrently with drilling.

The core mapping covers the following:

* rock type
* occurrence and character of fractures, fracture zones and

crushed zones

* orientation of fractures relative to the core axis
* core losses
* fracture mineralogy
* sampling of rock types and fracture minerals for chemical and petrographical analysis
* photographic documentation

All geological information from sruface mapping, core logging etc are evaluated in order to characterize the rock formation of the study site, (Olkiewicz and Stejskal, 1986).

2.3.2 Geophysics

The geophysical borehole measurements provide information on the resistivity of the rock, the presence and the character of the fractures, the groundwater flow along the borehole and the presence of electrically conductive and radioactive minerals. The curvature of each borehole is also determined by geophysical borehole measurements.

The measurements yield data on the bedrock adjacent to the borehole and provide support for the description of the geological structure of the investigated site and its hydrogeological conditions (Sehlstedt et al 1986).

Several electrical methods are used in the borehole logging program. Fractures, fracture zones and conducting minerals are indicated by single point resistance, lateral and normal resistivity. Concentrations of conducting minerals such as sulphides or graphite as well as water movements are indicated by Spontaneous Potential (SP). The same minerals will influence the Induced Polarization (IP) method, but it is more sensitive to disseminated mineral occurrences. Changes in borehole water salinity will be indicated by borehole fluid resistivity, indicating water movements in the borehole.

Some radiometric methods are also available. Variations in natural gamma radiation often indicates rock type changes. The density of the surrounding bedrock will be described by gammma-gamma measurements, while the hydrogen content is measured by neutron-neutron.

Two acoustic methods, sonic and tube wave, are used. To indicate single fractures, fracture zones and density changes the sonic (acoustics) is measured. Water filled fractures or fracture zones are indicated by the tube wave method.

To get information of the magnetite content of the bedrock magnetic susceptibility is measured.

The curvature of the borehole is determined by a borehole deviation log, while the diameter of the borehole is measured by a caliper log.

The temperature of the borehole water is measured by a temperature log. Water movements in the borehole are indicated by this log.

2.3.3 Radar

A new borehole radar system has been developed as a part of the Crosshole program of the International Stripa Project (Olsson et al 1985:a). The radar uses very short pulses, which are transmitted and received by dipole antennas inserted into the borehole. The distance to a reflecting object, e.g. fracture zone, is determined by measuring the difference in arrival time between direct and reflected pulses. Thus, it is possible to determine the geometry (point or plane) of the reflector, the distance to it and the crossing angle to the borehole. If measuring in several boreholes, not too far from each other, it is possible to determine the orientation of a fracture zone. Reflections of fracture zones have been observed up to 150 m from the borehole.

2.3.4 Hydrogeology

The hydrogeological investigations in the deep boreholes within the study site are aimed primarily at determining the hydraulic conductivity of the fracture zones and the rock mass in between. Furthermore, the investigations also determine the groundwater head in different sections of the boreholes. From the measurements it is also possible to calculate the frequency of the hydraulically conductive fractures.

Hydraulic conductivity

The hydraulic conductivity of the bedrock is determined by water injection tests and interference tests. The water injection tests are performed in sections of the boreholes sealed off by packers. The length of the sections is normally 20 m. Measurements in shorter sections, 2-10 m, are also made in order to provide information on special sections such as water-bearing fracture zones and for determination of the frequency of hydraulically conductive fractures. The water injection tests are performed in all deep core boreholes. A compilation of the results from hydraulic injection tests in boreholes within a study site is shown in Figure 2.2 (Gentzschein 1986).

The purpose of the interference tests is to provide values of hydraulic conductivity in large fracture zones and in volumes of the rock mass. Hydraulic conductivity is determined from recordings of pressure changes in the boreholes when water is injected into or pumped out from a nearby borehole.

Determination of groundwater head

The groundwater head in the bedrock within a site is measured by means of the following methods:

* In all available boreholes, ground water table monitors are installed. The groundwater level above a packer at 10-15 m depth is continuously monitored.

* Recording of the groundwater head at different levels in boreholes sealed off by packers (piezometry).

* Calculation of groundwater head from the water injection and fall-off phases of the hydraulic tests.

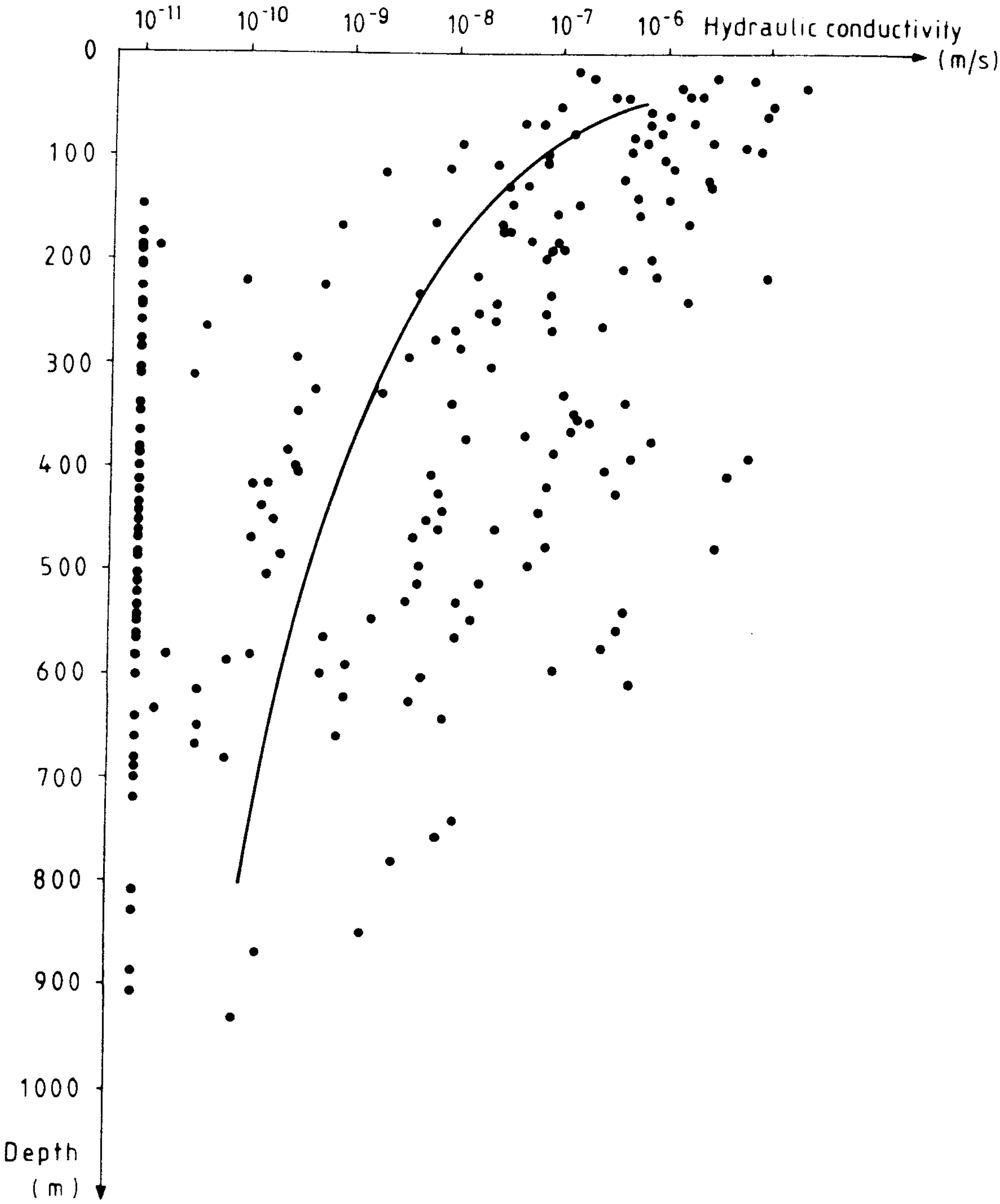


Figure 2.2 Hydraulic conductivity for the rock mass in a study site (20/25 m-sections). Indicated is also the depth-dependence of the hydraulic conductivity obtained from regression analysis.

2.3.5 Hydrochemistry

The purpose of the hydrochemical investigations is to document the chemical-physical composition of the groundwater within the rock formation. The data is utilized for calculations concerning the corrosion of cannisters, buffer stability and leaching of the spent fuel.

Based on the results of core mapping and hydraulic measurements, at least two core boreholes are selected for water sampling. Water is collected in each borehole from 3-4 different levels sealed off by packers. Before the sampling, the boreholes are cleaned by gas-lift pumping.

Water samples are taken after different time of continous pumping, table 2.1 and Laurent, 1986. Samples are also taken from the circulating water used for drilling.

Table 2.1 Results of analyses in the field laboratory.

Sample no	Na	K	Ca	Mg	Mn	Fe_{tot}	Fe^{2+}	HCO_3	Cl	F	SO_4	S(-II)	SiO_2
1028	29	1.2	29	2.4	0.25	0.78	0.73	182	3.6	0.54	1.8	0.11	8.6
1029	29	1.4	27	2.8	0.25	0.73	0.72	182	3.5	0.51	1.9	0.13	8.7
1030	29	1.4	27	2.6	0.19	0.70	0.69	181	4.1	0.61	2.1	0.18	8.4
1031	29	1.4	26	2.9	0.24	0.65	0.65	-	3.7	0.61	2.2	0.17	13.7
1032	29	1.4	27	3.0	0.22	0.65	0.65	183	3.7	0.59	2.1	0.13	7.4
1033	29	1.4	27	3.0	0.24	0.58	0.58	183	3.7	0.58	2.0	0.24	8.1
1045	290	-	40	0.30	-	<0.005	<0.005	18	555	7.3	0.40	0.59	5.1
1046	295	-	40	0.20	-	<0.005	<0.005	17	523	6.5	0.50	0.59	5.1
1047	297	-	40	0.40	-	-	-	17	417	7.4	0.35	0.56	5.1
1048	303	-	41	0.40	-	<0.005	<0.005	16	575	7.3	0.60	0.55	5.1
1049	295	-	38	0.40	-	0.008	0.006	17	543	7.7	0.25	0.45	4.9
1050	-	-	42	0.30	-	0.007	0.005	16	525	7.5	0.33	0.53	5.1
1051	323	-	42	0.20	-	0.009	<0.005	17	567	7.4	0.28	0.63	5.1

3. EQUIPMENT FOR CORE LOGGING

A microcomputer-based core logging system has been developed. The system is used for registration, storage and presentation of the information from fracture and rocktype mapping of drill cores.

Equipment

The system is based on the microcomputer Luxor ABC 800 and consists of keybord, monitor and floppy disk unit (ABC 832), Epson MX 100 matrix printer and a HP plotter 7575 A, Figure 3.1. The computer has a 64 kByte RAM-memory and data is stored on a 5 1/4" diskette, double-sided with a storage capacity of 0.5 MByte.

Figure 3.1 Equipment for core logging

Software

The software of the system is based on a general database system named Basregister 800. The database is made by PDATA.

The software is built up according to the menu technique. This means that handling and user training is comparatively simple. The operator is guided by text menus and different functions in the system can be selected by choosing among the various alternatives.

The information is stored in five registers:

Register	Name	Max. no of items	Comments
1	Format	10	Contains print-out format
2	Rocktype mineral code	100	To be modified/ extended by the operator as necessary
3	Borehole information	1	Storage of general data on boreholes
4	Core log	4500	Storage of all observations in connection with fracture and rocktype mapping
5	Comments	1000	Storage of comments in connection with mapping.

Since the system is connected to a matrix printer and a plotter, the operator is free to plot stored fracture and rocktype information.

The printout from the matrix printer is divided into one rocktype profile and one fracture mapping profile, Figure 3.2. These profiles are plotted side by side. The charting resolution is 5 cm, i.e the observations are rounded off to 5 cm intervals. Each page of the print-out will display 7 m of the borehole. The average printing time is approx. 100 m/h. A diskette has the capacity to store information from approx. 1000 m of drill core.

Data programs for statistical summaries of stored borehole data have been developed by which fracture frequency, etc may be presented.

Up to June 1986 the system has been tested on c. 24 000 m of drillcore. Even to staff not accustomed to computers the system can be easily learned and after c. 2-3 days, they can handle the functions required in order to achieve the same mapping speed as in manual mapping. The equipment has endured the mapping environment satisfactorily, especially after placing the floppy disk unit and monitor into a dust proof, ventilated transport box.

As in the case of manual procedure, computer mapping is handled by two persons, one of them measuring and making observations, while the other person handles the registration.

Upon completed mapping, all information on the borehole is transferred to the central computer for storing in the data base. Data is then available for search in the data base and for more sophisticated processing.

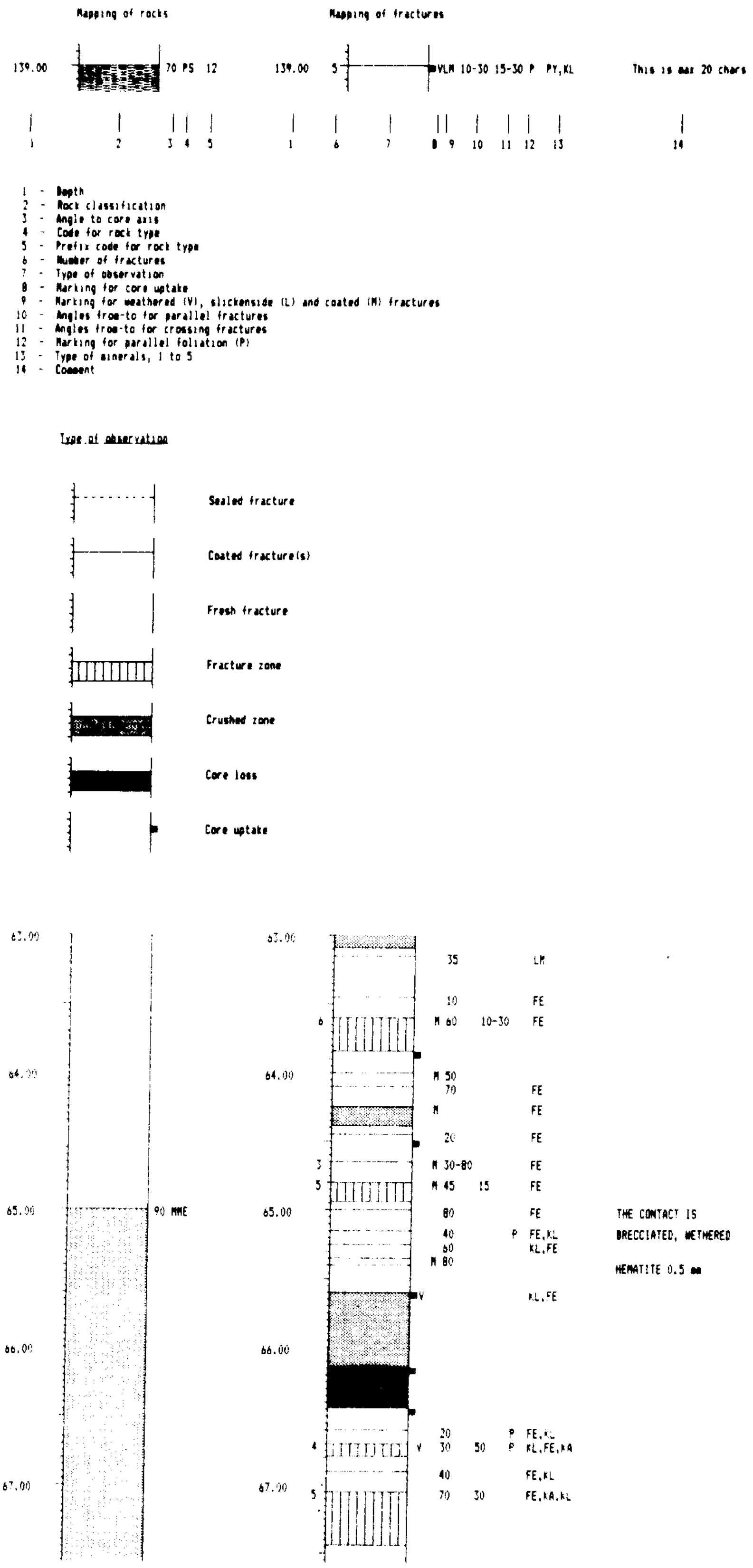


Figure 3.2 An example of a print-out of mapped core sections and description of symbols used.

4. EQUIPMENT FOR GEOPHYSICAL INVESTIGATIONS

The main geophysical equipments used for ground and borehole measurements in site characterization have been developed and designed by Swedish Geological Company (SGAB). Supplementary equipment has been purchased from other manufacturers. The following text contains a brief description of the instruments used.

4.1 Equipment for ground measurements

The instruments normally used for ground geophysical measurments on the study sites are the following:

Method	Instrument	Manufacturer
Magnetometer	GSM-8 Proton	GEM-Systems Canada
Resistivity	RIPT-400	SGAB Sweden
	RIPS-2	SGAB Sweden
IP	RIPT-400	SGAB Sweden
	RIPS-2	SGAB Sweden
Slingram	18 kHz 60 m.	SGAB Sweden
VLF	EM-16	Geonics Canada
Gravimetry	P 420 T	Sodin Ltd. Canada
	Model G	La Coste & Romberg Inc. USA
Seismic	Terraloc - 24	ABEM Sweden
Field computer	Geomac II	SGAB Sweden

Figure 4.1 Field measurements with Proton magnetometer GSM-8 and field computer Geomac II.

4.1.1 Magnetic methods

The magnetometer is used for measuring local variations in magnetic field intensity. The instrument used is a proton precession magnetometer GSM-8. The measurement values are expressed in the unit nanoTesla. The measurement accuracy of the instrument is 1 nT in the interval 20,000 - 100,000 nT. The maximum permissible gradient of the magnetic field with retained measurement accuracy is 5,000 nT per meter. The magnetometer is power supplied by internal rechargeable NiCd-batteries. The measurement sensor is mounted on a backpack frame, Figure 4.1. Measurement height above the ground is approximately 2.0 m and the total weight including backpack and sensor is approximately 5 kg.

The field magnetometer is connected to a Geomac II field computer described below, and the data obtained from the magnetometer is stored digitally directly in the computer. In addition to measured data, other necessary information is stored in the computer, such as survey area, survey crew, date, time of measurement, and the coordinate of the measured point in the grid system.

Within each study site a fixed base station is used for checking the daily variations in the earth-magnetic field. A measurement value is recorded automatically every 15 seconds and stored in the field computer Geomac II.

Specifications for GSM-8 magnetometer:

Resolution:	1 nT
Accuracy:	+/- 1 nT
Range:	20,000 - 100,000 nT
Gradient tolerance:	5,000 nT per metre
Visual output:	5 digits 1 cm high LCD display.
Digital output:	Multiplied precession frequency and gating pulse.
Power source:	Internal 12 V 0.75 Ah NiCd rechargeable battery. 3,000 readings from fully charged battery.
Operating temperature:	-40 to +55 degree C.

Field computer GEOMAC II

Geomac II is an interactive microprocessor-based field computer adapted to both digital and analogue signals. Ten different instructions are preprogrammed including storage search and optional alphanumeric comments to individual measurements. Data can be transferred from the field computer to other personal computers or by telephone network directly to the main office computer for further processing.

Specifications for GEOMAC II Field Computer:

Primary memory size:	65 kByte
Secondary memory size:	384 kByte Internal "RAM-disk"
Display:	2 x 16 character alphanumeric LCD-display.
Operating system:	CP/M 2.2 compatible GOS.
High level language:	Microsoft Basic and Turbo Pascal
Interface:	RS-232C serial channel and 20 bits digital I/O ; 2 x 16 bit counter / timer.
Battery:	0.6 Ah Rechargeable NiCd battery 0.75 Ah for memory back-up.
Operating time:	Continuous operation 30 hours.
Data retention solid state disks:	approximately 7 years.
Weight:	0.95 kg.
Operating temperature:	-25 to +70 degree C.

4.1.2 Electrical methods

The resistivity and IP (Induced Polarisation) measurements are performed simultaneously. The equipment consists of the transmitter RIPT-400 with 400 W output power, and the receiver RIPS-2 with two current electrodes and two non-polarizing potential electrodes ($Cu-CuSO_4$) and cables (Figure 4.2).

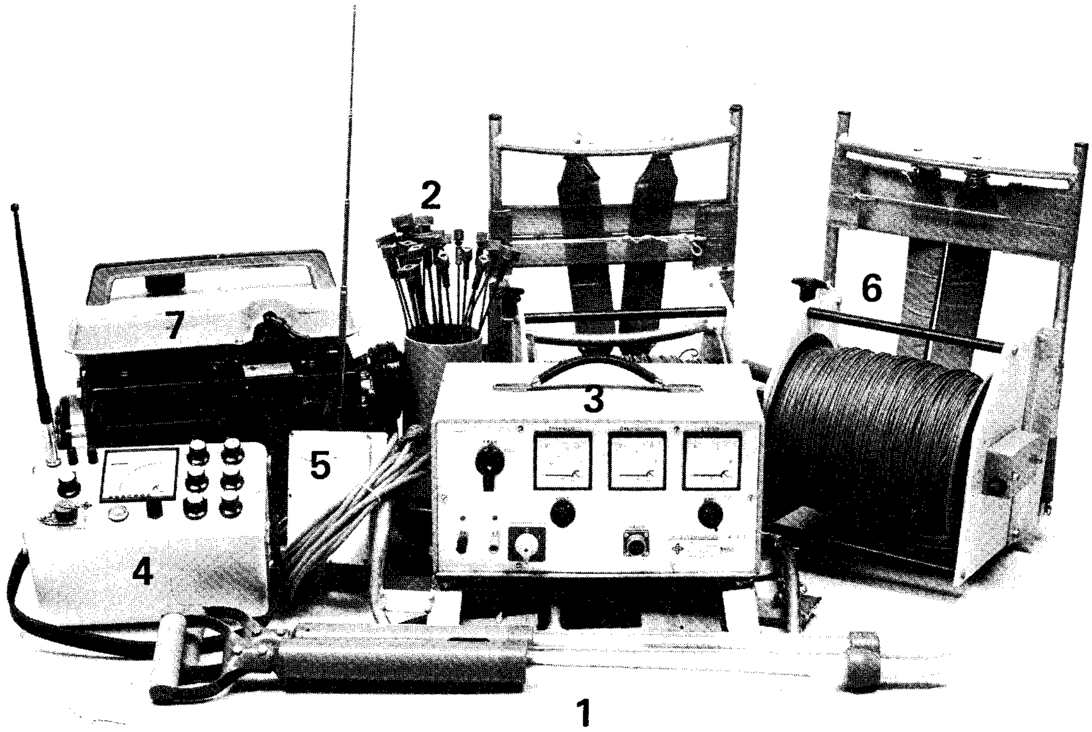


Figure 4.2 Combined Resistivity and Induced Polarization measuring equipment. 1. Potential electrodes, 2. Current electrodes, 3. Transmitter RIPT 400, 4. IP RIPS-2, 5. Radio, 6. Signal cable, 7. Generator.

The measurement system is a DC-time domain system, designed for gradient measurement, and generally a modified Schlumberger configuration is used. The transmitter is equipped with a radio transmitter for synchronization of the reciever. The current is emitted in the form of a continuous square wave. The influence of natural currents in the ground (self-potential effect) are automatically corrected by the receiver. The relative accuracy of the measurement is 1-2 % depending on the magnitude of the measured value. The power supply of the transmitter is a motor generator of 220 V 50 Hz AC.

The receiver is operated using a rechargeable NiCd battery with continuous operating time of 10 hours.

Specifications for IP Transmitter RIPT-400:

Output power:	400 W
Output voltage:	80 - 280 V
Output current:	0.35 - 1,5 A
Current stability:	Better than 0.05 %
Reference system:	External radio
Weight:	15.5 kg
Power requirements:	Generator 220 V +/-15 % 50 Hz 1 kVA.
Operating temperature:	-20 to +55 degree C.
Current waveform:	Square wave. period time 3.92 s

Specifications for IP Reciever RIPS-2:

Input Impedance:	20 Mohm //47 pF
Powerline rejection 50 & 60 Hz	60 dB
Timing reference:	Selectable radio or wire visual LED control
Weight:	5.0 kg
Power supply:	Rechargeable NiCd battery
Operating temperature	-10 to +55 degree C

RP

Range:	4mV - 1 V
Resolution:	40 microvolts
Accuracy:	1.5 % of full scale

SP

Range:	100 mV - 400 mV
Resolution:	1 mV
Accuracy:	1.5 % of full scale
Buckout:	Fully automatic
Polarity:	Automatic polarity indicator

IP

Range:	1 mV - 400 mV
Resolution:	10 microvolts
Accuracy:	1.5 % of full scale

4.1.3 Electromagnetic methods

Two different types of electromagnetic methods are employed in the project: the Slingram (Horisontal Loop EM) and the VLF (Very Low Frequency).

Slingram (Horizontal loop EM)

The Slingram system consists of a transmitter and a receiver, interconnected with a 40, 60 or 100 m long reference cable (Figure 4.3). The transmitter emits an electromagnetic field with a frequency of 18 kHz. This field induces a secondary field in the ground.

Figure 4.3 Slingram (Horizontal Loop EM) Field Measurement.

The resulting field measured by the receiver will deviate from the primary field in intensity, phase and direction. Deviations indicate the presence of electric conductors in the ground, such as fracture zones.

The receiver measures the real and the imaginary component of the anomalous field in percent of the primary field (in-phase and quadrature referred to the primary field.) The result is read directly on an analog meter.

Specifications for the Slingram 18 kHz:

Parameters measured:	Real and Imaginary component (In-phase and quadrature)
Operating frequency:	18 kHz
Coil separation:	40, 60 or 100 m
Temperature range:	-30 to +60 degree C

Transmitter unit:	
Power supply:	Rechargeable NiCd accumulators 15 V 4 Ah.
Operating time:	10 hours continuous use.
Weight:	7 kg

Receiver unit:	
Sensitivity ranges:	+/- 10 % res. +/- 0.1 % +/- 100 % res. +/- 1 %
Power supply:	Rechargeable NiCd accumulators +/- 18 V 0.225 Ah.
Operating time:	6 hours coninuous use.
Weight:	6 kg.

VLF instrument

The VLF method measures the magnetic field strength of distant military transmitters operating in the frequency range 15-25 kHz. The instrument EM-16 consists of a receiver with two coils perpendicular to each other (Figure 4.4). The coils are oriented in a certain position in relation to the VLF transmitter and the quotient between the field strength of the coils is measured. This is in principle, a measurment of the vertical component of the magnetic field, induced in subsurface conductors, relative to the primary field.

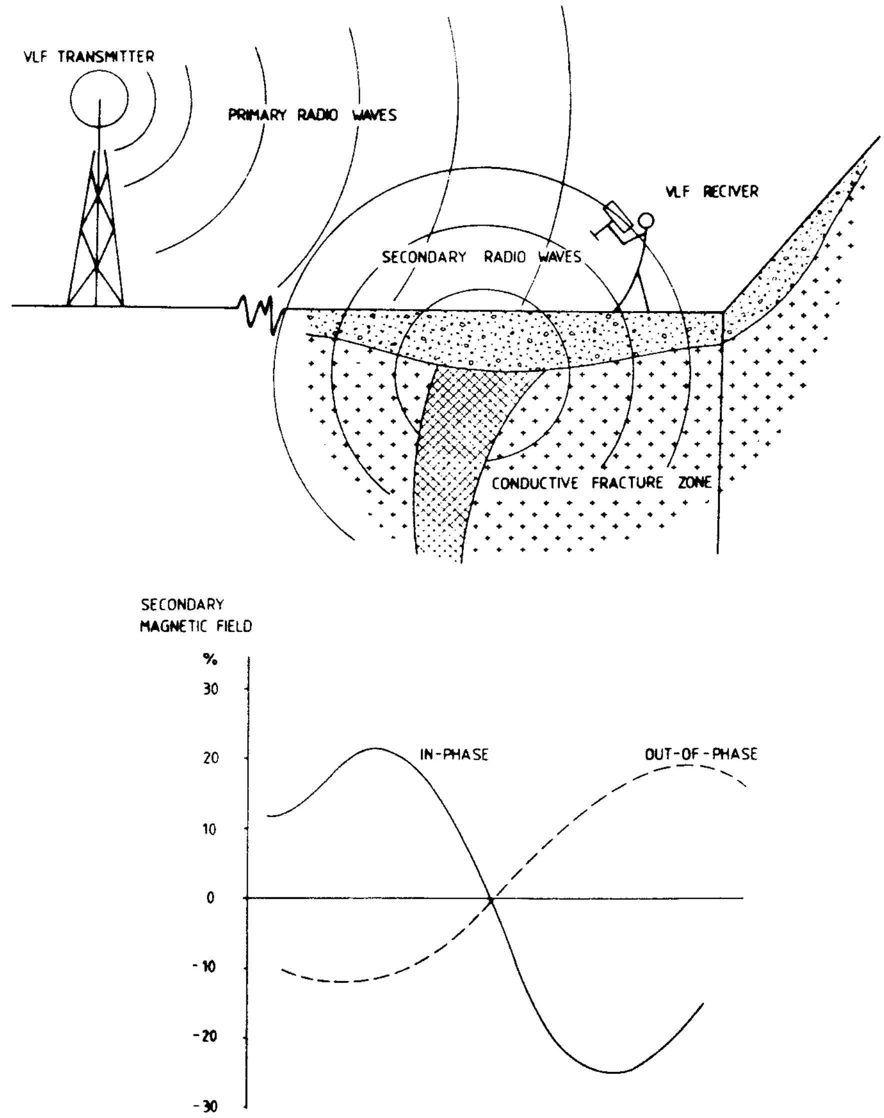


Figure 4.4 The principle of VLF measurements with the expected anomaly of a fracture zone.

Specifications for the VLF Instrument EM-16:

Operating frequency:	15 - 25 kHz
Measured quantity:	In-phase and quad-phase components of vertical magnetic field.
Sensitivity:	In-phase +/- 150 % Quad-phase +/- 40 %
Resolution:	+/- 1 %
Power supply:	6 ´AA´ cells
Weight:	1.6 kg

4.1.4 Gravimetric method

Gravimeters are used in order to obtain the lateral variations of gravitational acceleration. In the reconnaissance phase the results are used to locate and delineate rock masses which possess high or low specific density e.g. mafic rock types. In the site investigations the measurements are preferably performed in a grid system. The gravimeter measurements are then used to delineate large fracture zones and to calculate the bulk porosity of large fracture zones. Sodin P 420 T and La Coste & Romberg mod G Gravity meters are used in field measurements.

4.1.5 Seismic method

The seismic instrument (Terraloc-24) is a portable 24-channel equipment. The measurements are generally employed along profiles with a distance between the geophones of 5 m. The system is a digital equipment which has a data memory of 126 kBytes. Data can be stacked (averaged) from several measurements at the same location to get better signal to noise ratio. The A/D conversion is done by a 8-bit converter and the memory-cells are 16 bits wide, so it is possible to do 255 stackings before saturation occurs in the stack memory.
The instrument has an built-in CRT display and a digital tape recorder.

The seismic wave is generated by using explosives. A separate high voltage shotbox (Nitro Nobel C115 VA) is used for firing. The travel times of the seismic wave between the shotpoint and the geophones are registered in the solid state memory of the instrument. The travel times can be read with an accuracy better than 1 millisecond. This microprocessor controlled instrument can be used for signal processing in order to improve data quality (Figure 4.5).

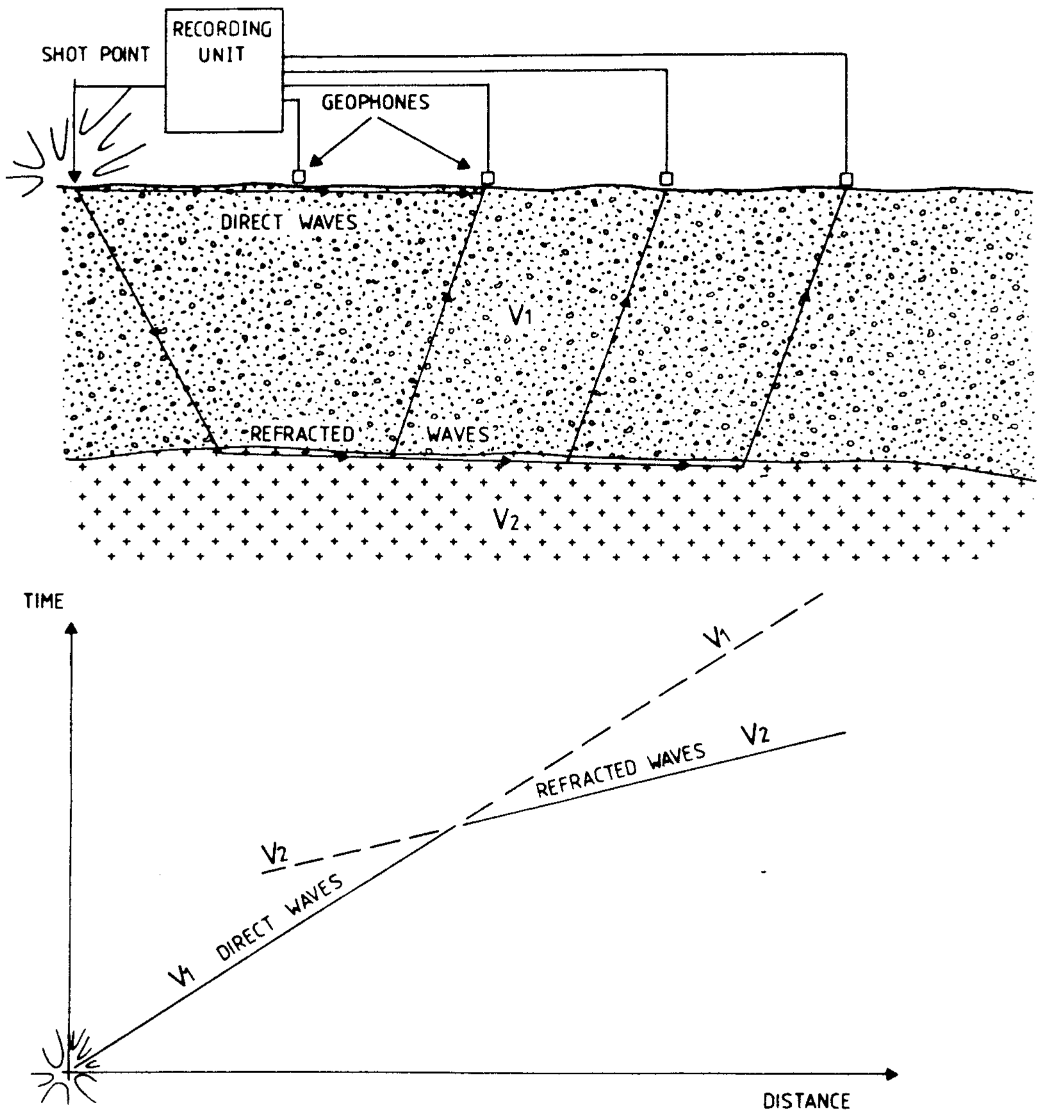


Figure 4.5 The principle of a refraction seismic profile.

Specifications for Terraloc-24 seismic system:

Number of channels:	24
Time resolution:	better than 1 msec.
Time delay:	0 - 9.999 sec.
Amplitude gain control:	6 - 126 dB
Filters:	Low and High selectable frequencies
Output:	GPIB and RS-232C.
Record initiation:	Mechanical, solid state, geophone or radio.
Timing:	Crystal based.
Power supply:	Built-in rechargeable or external car battery.
Weight:	20 kg excluding batteries
Operating time:	7 hours with external batt.
Operating temperature:	-10 to +40 degrees C.

4.1.6 Data processing and presentation

Data from the GEOMAC II is transferred to a portable desktop computer, either a HP 85 or an IBM XT/AT, and stored on magnetic media. At this level it is possible to take out raw data plots in the field and also to inspect data alphanumerically.

The tapes or floppy disks are sent to a main computer (Prime 750). The flow of data is indicated in Figure 4.6.

Before data is in a form familiar to the geophysicist, different corrections and calculations need to be applied. The data is corrected for offset and instrumental drift during the day. For the magnetic measurements the diurnal variations are recorded by the base station. This is essential in an high resolution survey in order to obtain an overall accuracy in the order of 5 nT.

In order to enhance certain features in the data set, different space-domain filters may be used. Directional, derivative and crispening filters are a few examples. Other types may be phase-conversion for slingram data of Hjelt filters for VLF. Also see under Image processing system.

Profile and color maps

Profile maps are produced with a Calcomp pen plotter. These maps are mainly used as work copies during production. Color maps of a maximum size of 85 cm by 55 cm (4250 by 2750 pixels) are produced with an Applicon plotter.

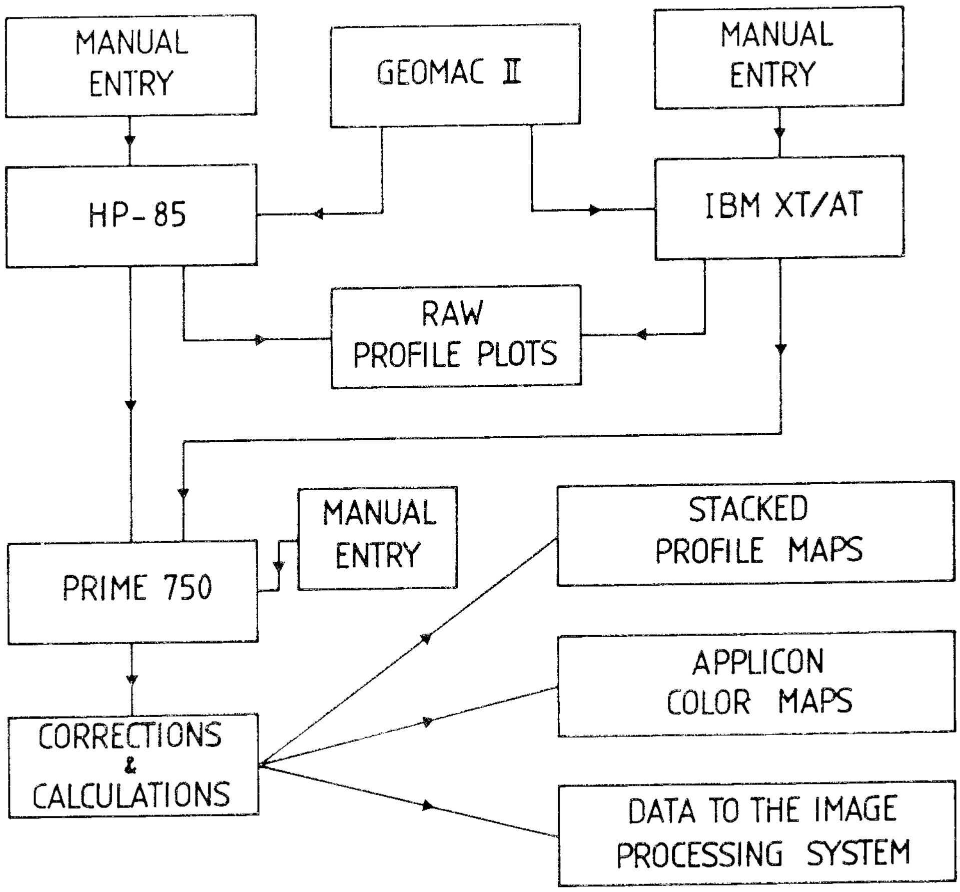


Figure 4.6 Data flow for processing and presentation of ground geophysical investigations.

Maps may be interpolated by different methods or the measured value may be outputed simply as a colored square. Isolines can be generated at will. An example of an Applicon color map is given in Figure 4.7.

Image processing system

An image processor named EBBA made by the Swedish Space Co is also used in the process of interpreting geophysical data. It has the capacity of three image planes and one graph plane, all eight bits deep. Maximum size is 512 by 152 pixels. In this system subtle features may be enhanced in an interactive manner. The system is equipped with a program package for extracting information from digital data. Principal Component analysis may be used if multivariate data is available.

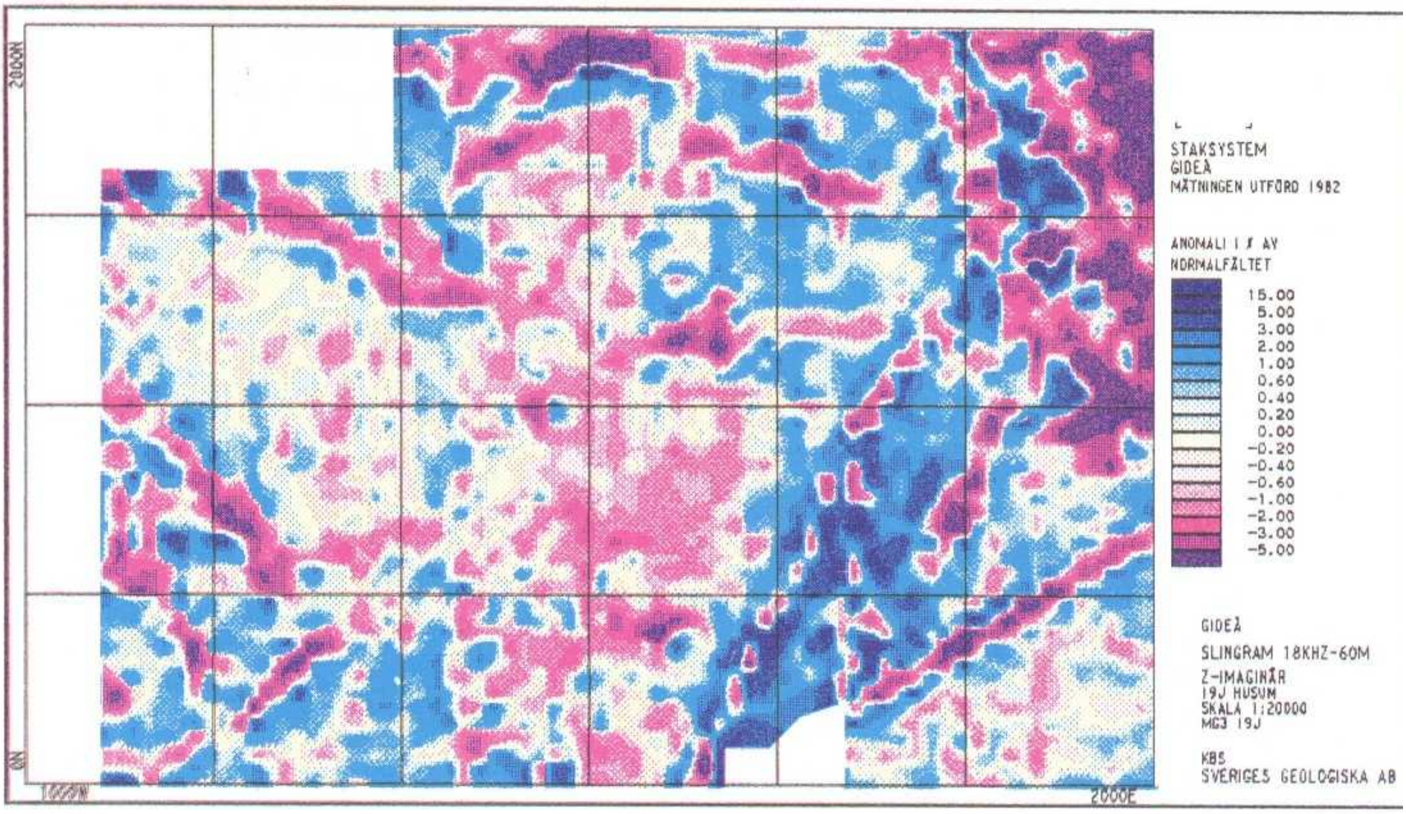


Figure 4.7 Slingram measurements presented with an Applicon color map.

4.2 Equipment for borehole measurements

For site investigations the following geophysical borehole methods are available;

Method	Manufactured by	O.D. (mm)	Chapter
Borehole deviation	SGAB	42	4.2.2
	Industri AB Reflex	54	4.2.2
Caliper	Mount Soupris Co	42	4.2.2
Spontaneous potential	SGAB	42	4.2.3
Single point resistance	SGAB	54	4.2.3
Resistivity	SGAB	42	4.2.3
Induced polarization	SGAB	42	4.2.3
Magnetic susceptibility	Geoinstruments OY	42, 54	4.2.4
Temperature	SGAB	42	4.2.5
Fluid resistivity	SGAB	42	4.2.5
Natural gamma ray	SGAB	42	4.2.6
Gamma-gamma (density)	Mount Soupris Co	52	4.2.6
Neutron-neutron (porosity)	Comprobe Co	54	4.2.6
Sonic	Simplec Co	52	4.2.7
Tubewave	Mark Products	51	4.2.7

For each geophysical method except the Fotobor and the tubewave, the specific logging probe is connected to the same surface equipment. Furthermore, some probes are constructed for simultaneous logging with other probes. Each method except the deviations methods, the induced polarization and the tubewave is measured continuously along the borehole.

All logging methods described in this chapter can be used in core-drilled boreholes of SKB standard diameter 56 mm. For larger diameters such as 76 mm core-drilled, 115 or 165 mm percussion-drilled boreholes, the majority of the methods are available. All probes described in the text are pressure rated to 10 MPa, i.e. 1000 meters depth when using water as borehole fluid.

The main surface equipment and the different logging methods are described in detail in the following text. Some of the equipment and the operation principle of the system is shown in figures 4.8 and 4.9.

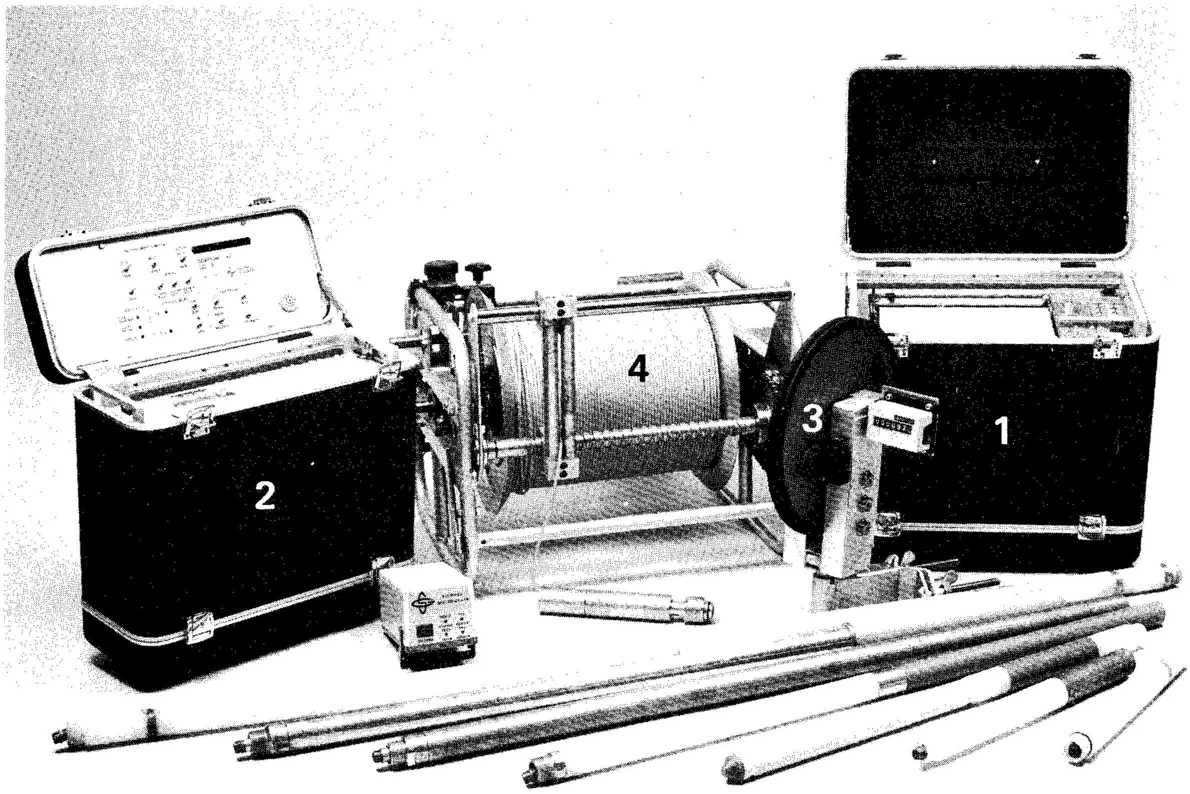


Figure 4.8 Boremac Digital borehole logging equipment. 1. Analog recorder, 2. Digital recorder, 3. Measuring weel, 4. Winch, 5. Probes.

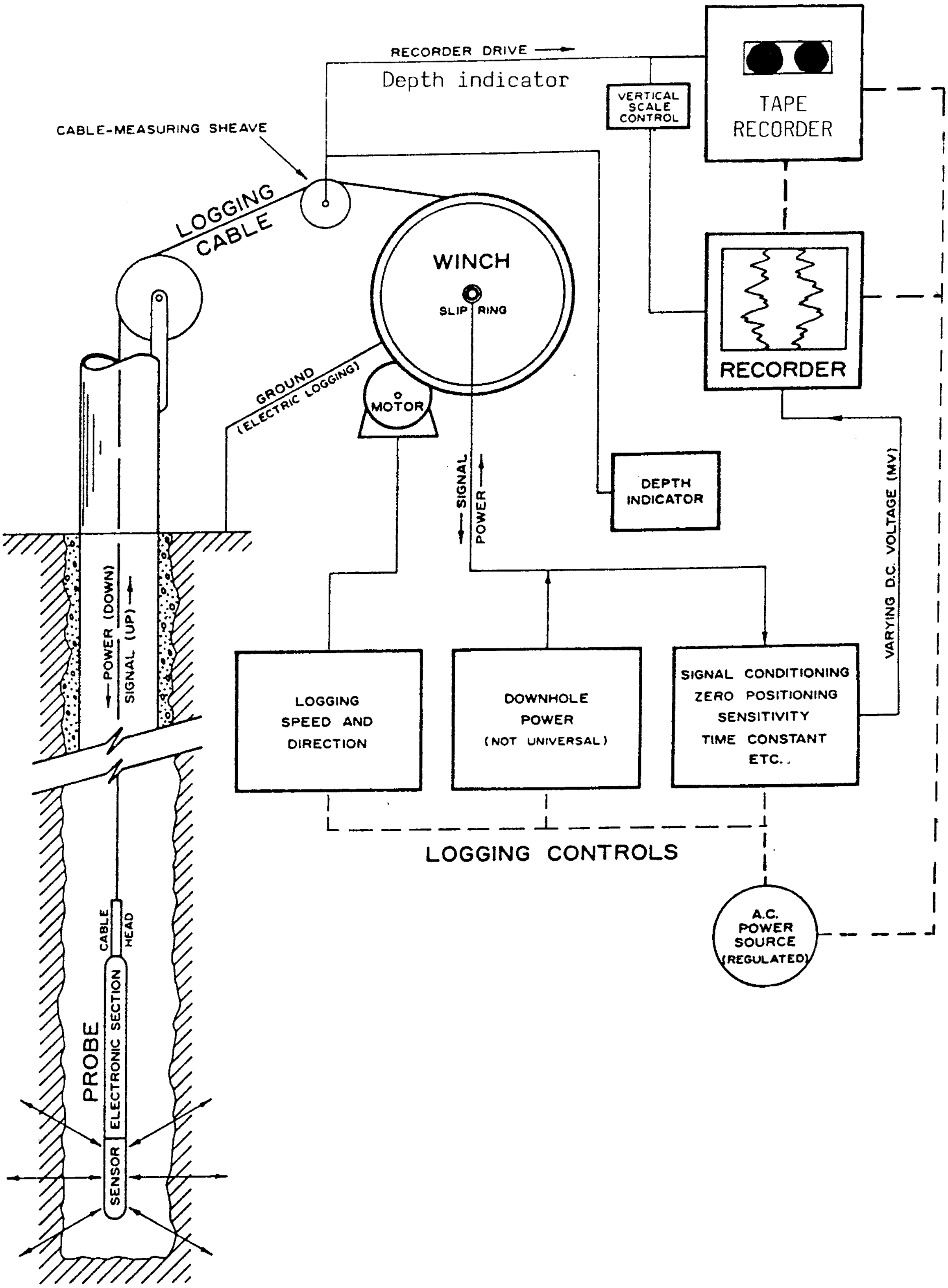


Figure 4.9 Operation principle for the geophysical borehole system.

4.2.1 Surface equipment

The available logging system is a lightweight, portable, one-man operated multilogger with good versatility. The surface equipment consists of the following parts:

* Boremac A2 analog recorder
* Cassette type digital recorder
* Measuring wheel with digital counter
* Winch with cable
* Power supply

Boremac A2 analog recorder, main unit:

Dimensions:	500 x 500 x 350 mm
Weight:	22 kg including built-in rechargeable batteries
Recording width:	250 mm
Depth scales:	1:100 or 1:1000
Operating time:	10 hours
Operating temperature:	$-20^{o}C$ - $+50^{o}C$

Cassette type digital recorder:

Dimensions:	480 x 507 x 207 mm
Weight:	15 kg
Power supply:	External 110 V/50 Hz and 220 V/50 Hz
Input:	2 channel analog +/- 10 V
Output:	16 character alpha numeric display
Format:	ISO/ECMA 34
Data storage capacity:	180 KByte/cassette
Operating temperature:	$-30^{o}C$ - $+50^{o}C$

Measuring wheel:

Weight:	8.7 kg
Dimensions:	500 x 450 mm
Depth indicator:	7 digit bidirectional, resettable mechanical odometer geared to the measuring wheel
Measuring length:	0 - 10000 m
Resolution:	0.1 m
Accuracy:	+/- 1%

Winch with cable:

Winch weight:	Including electrical motor 34 kg
Dimensions:	480 x 670 x 580 mm
Cable capacity:	Up to 1500 m, 5 mm cable
Cable type:	Five conductor polyuretane cable with kevlar fibres as carrying elements Cable braking strength: 280 kg
Cable head:	Brass. Connection to probe is made with a Cannon contact
Cable resistance:	4 conductors 88 ohm/1000 m 1 conductor 129 ohm/1000 m
Slip ring assembly:	Sealed high quality Silver-Graphite rings

4.2.2 Borehole deviation and diameter measurements

Borehole deviation measurements are performed in order to determine the orientation and location in three dimensions of the entire borehole. Two different methods are used: the Boremac and the Fotobor. Both methods are performed by point measurements in the borehole, normally with 10 meter spacing.

Boremac D2

Boremac D2 borehole unit has a pressure-proof outer barrel with O.D. 42 mm. The probe will fit into 46 mm boreholes and by using oversize collars the probe can be used to measure boreholes up to 150 mm diameter.

The probe contains a resistance wire on a loaded wheel for determining the inclination (+/- 90 deg.) of the borehole. The probe is connected to the surface unit via an electric cable.

The orientation of the borehole in the horizontal plane is measured by a compass needle whose direction relative to magnetic north (0 - 359 deg.) is measured electrically. The accuracy of the inclination is 0.1 degree and in the horizontal plane 1 degree assuming the hole is inclined more than 1 degree. The accuracy determining the location of the borehole is in practice estimated to 1 meter per 100 meters of boreholes length.

Fotobor

The Fotobor probe contains an automatic minicamera, light source, bubble ring and reflector ring. It is lowered down in the borehole using a standard drill rod string, and is not electrically connected to the surface. The probe rods form a sealed self-contained probe with an outside diameter of 45 mm.

The probe bends to conform to the deviation of the hole being surveyed, and photographs are taken at regular intervals to record bends. The first exposure is made with the camera lens at the borehole mouth and related to the known initial deviation of the hole. After the measurements are completed the film has to be taken to the base for processing and interpretation.

The major drawback with the method is when the initial collar dip is vertical; the methods just does not work. It is also relatively time-consuming to interpret. The major advantage is that the measurements are not influenced by magnetic disturbances.

The accuracy and resolution are in most cases on the same order as for the Boremac.

Caliper

The borehole diameter is measured continuously along the borehole by means of a one-arm or three-arm caliper connected to the main surface unit.

The three-arm caliper probe measures the borehole diameter using three motor-actuated spring loaded arms. The caliper can be closed and opened by remote control, and operates borehole diameters from 46 mm to approximately 500 mm.

The one-arm caliper tool is an integrated part of the gamma-gamma density probe where the caliper arm presses the probe against the borehole wall.

Calibration of the different caliper tools is done manually by putting the probe into jigs of known diameters. At the site calibration is done when running the tool in the casing.

4.2.3 Electrical methods

Electrical methods available for borehole measurements are spontaneous potential (SP), single point resistance, normal and lateral resistivity and induced polarization (IP). While the SP measures naturally potentials that occur in the earth, the resistivity methods measure potentials generated by an external electrical field. Finally, IP is a recording of the induced polarization occurring after the shutting of the external field. The different methods are described below and the electrode configurations are shown in Figure 4.10. The O.D. of the probes is manufactured according to the borehole specifications but is generally 42 mm when logging SKB standard boreholes.

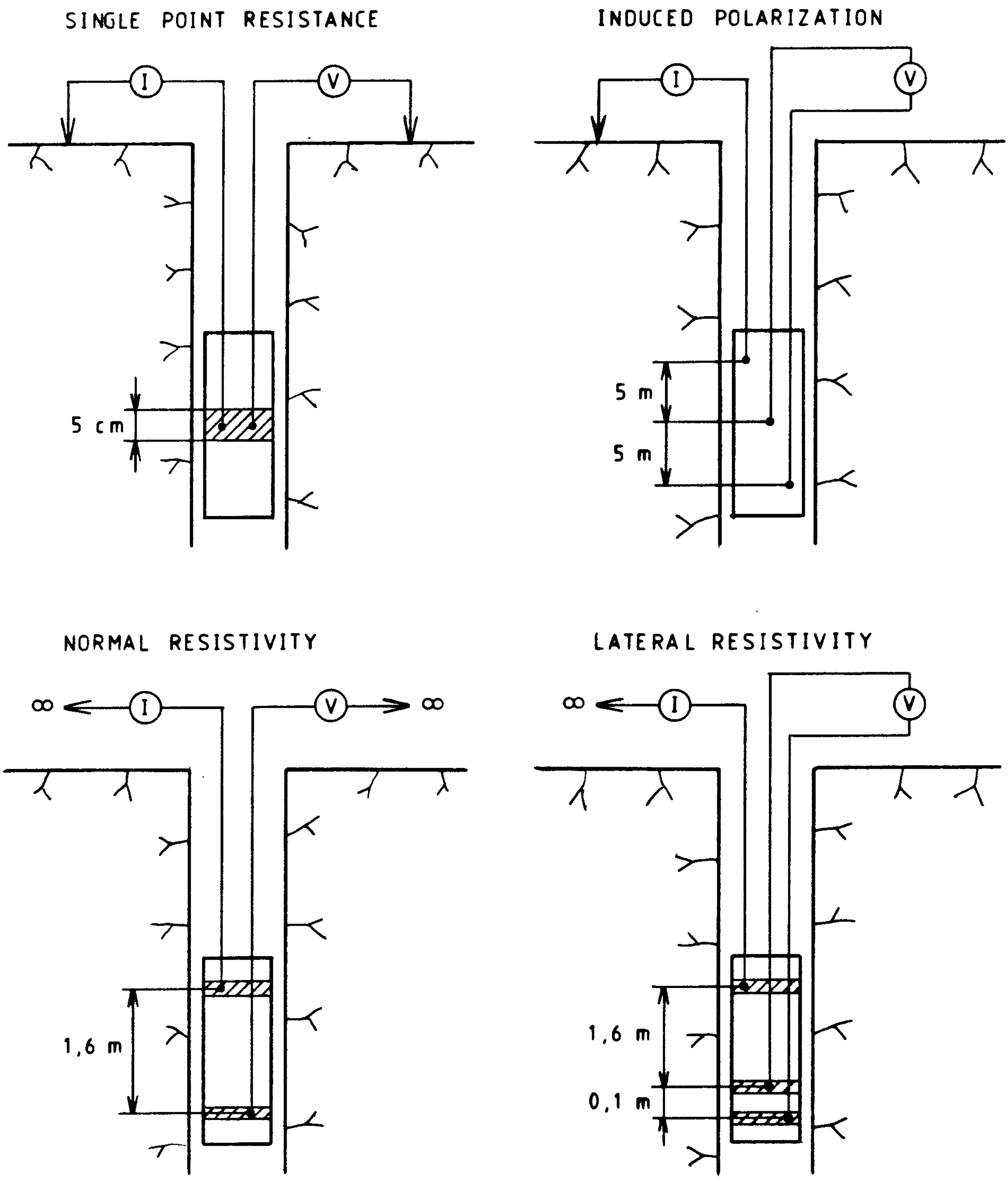


Figure 4.10 Electrode configurations used for the electrical logs.

Spontaneous potential, SP

The spontaneous, natural or self potential is generated by a number of different causes, mainly of chemical origin, but also due to flow of groundwater.

The natural voltage between two nonpolarizable electrodes, one in the hole and one on the ground surface, is recorded.

Single point resistance

The single point resistance method consists of a two electrode system with one of the electrodes in the borehole and one at the surface. The small electrode (length 5 cm) in the borehole is surrounded by an insulator slightly less than the diameter of the borehole to reduce the effect of the conductive fluid. The resistance may be measured at any of four different frequencies; 3, 11, 33 or 110 Hz.

The results are calibrated, and if necessary also corrected for borehole size, and expressed in ohm.

Normal and lateral resistivity

The resistivity of the bedrock is determined by means of a four electrode system. Two different configurations are used: normal configuration and lateral configuration.

In the normal configuration one current and one potential electrode are in the hole, the distance between the two is normally 1.6 meters. The other two electrodes are placed at the surface approximately 50 meters from the borehole in the opposite direction.

In the lateral configuration, one current and two potential electrodes are in the hole. The other current electrode is placed on the surface. The distance between the current electrode in the hole and the nearest potential electrode is normally 1.6 meters, and the distance between the potential electrodes 0.1 meter. The same probe is used for both configurations, though at separate runs.

Calibration of the resistivity systems is done at the site by connecting a variable resistor to the system, thus calibrating the response to a known resistance. The results are expressed in ohmmeters.

Induced polarization, IP

Several different electrode configurations on the probe employed for IP-measurements can be used. Normally a three-electrode array is used in the borehole with one-current electrode positioned on the ground. The separation between the electrodes is normally one or five meters, and nonpolarizing copper-copper-sulphate electrodes are used as potential electrodes. A square wave current with a frequency of 0.25 Hz is transmitted by a regulated power supply.

The induced polarization is measured at discrete points. Normally the interval between the recordings is 5 to 100 meters.

The induced polarization is expressed in percent of the voltage transmitted and indicates the presence of electrically conductive mineralizations such as sulphides and graphite. It can also be used to find aquiferous zones.

4.2.4 Magnetic susceptibility

Magnetic susceptibility gives information about the content of magnetic minerals in the rock. Since each rock type has a characteristic magnetite content, magnetic susceptibility measurements are very useful in order to classify crystalline rock formations.

Two similar susceptibility probes are available: one for borehole diameters above 46 mm and one for borehole diameters above 56 mm. The measurements are based on electromagnetic induction in two coils in the probe; an alteration of the susceptibility in the rock surrounding the borehole gives rise to a measurable change in the inductance in the coils.

The instrument has three measuring ranges, viz 0 - 2 x E-2, 0 - 2 x E-1 and 0 - 2 SI units, and the resolution 5 x E-5 SI. Calibration is done in calibration pads with known magnetic susceptibility.

The resistivity of the surrounding rock attenuates the amplitude of the signal. Information regarding this attenuation effect is also transmitted to the surface. However, it is only sensitive to very low resistivities, i.e. 0.0001 to 1 ohmmeter.

4.2.5 Temperature and fluid resistivity

The temperature and resistivity of the borehole fluid are measured simultaneously using the same probe. The best accuracy and resolution are achieved when measuring discrete points, but it is also possible to measure continuously. The O.D. of the probe is 42 mm.

Temperature

The temperature is measured by a thermistor. When measuring discrete points the absolute accuracy is 0.06 degrees C and the relative accuracy 0.004 degrees C. Then measuring continuously these values are $0.1^{o}C$ and $0.05^{o}C$, respectively.
Calibration is done both in the laboratory and at the site using a very accurate quartz thermometer.

The results are expressed in degrees Celsius or, after calculation, in degrees C/km (temperature gradient). From these parameters information is obtained on water flow in the hole.

Fluid resistivity

The resistivity of borehole fluid is measured by a five-electrode system. The electrodes are positioned in a plastic tube open at both ends. The insulation from the formation is necessary to eliminate the effect of conducting minerals and fractures present in the formation. Calibration is done in the laboratory where the probe is lowered into a tank filled with a water solution having variable salinity concentrations.

The results are expressed in ohmmeters and can, after correlation with the temperature, be used to determine the salinity of the drillhole fluid. The results are also used for corrections of the data obtained from the electric measurements.

4.2.6 Radioactivity methods

The radioactivity methods described below are the natural gamma ray method, measuring natural gamma radiation, gamma-gamma and neutron-neutron methods, measuring the attenuation of emitted gamma rays and neutrons, respectively, in the formation surrounding the borehole.

Natural gamma rays

The natural gamma radiation of the bedrock will give information about the total radioactivity of the rock, i.e. the summation of the potassium, uranium and thorium content. Variation in the concentrations of these elements will normally correspond to mineralogical changes in the rock.

The probe, with an O.D. of 42 mm, contains a scintillation detector. The active part is a 1.5" or 4" (Litholog) crystal of NaI(Tl), which is connected to a photomultiplier which transforms the light pulses created in the crystal to electrical signals proportional to the incoming gamma rays. The lower cut-off limit in gamma ray energy is 300 KeV.

Calibration is done both at a calibration camp in three constructed calibration models, and using a well-known radioactive source activity. After calibration and correction for borehole size the results are presented in microRoentgen/hour.

Gamma-gamma (density)

The gamma-gamma probe measures rock density and is used for lithology determinations and to determine variations in rock porosity and fractures. The equipment is manufactured by Mount Soupris Co, Colorado, USA. The surface electronics have been modified and the ratemeter moduls have been replaced by ratemeters manufactured by Nuclear Data Co, USA.

The probe (O.D. 52 mm) contains a radioactive 300 mCi Cs-137 source, which emits gamma rays at a constant energy level of 0.66 MeV, and a single Geiger-Muller tube detector. The one-arm caliper presses the measuring side of the probe against the borehole wall.

There are three modes of gamma ray interaction with matter that can affect the tool response: Compton scattering, the photoelectric effect and pair production. In this case the Compton scattering will have the main influence.

The relation between the reduction of gamma ray flux to electron density is known. Furthermore most of the elements in the formations encountered have a ratio of the numbers of electrons per atom to the atomic mass number that is very close to 0.5. Hence, a proportional relation between the intensity of gamma rays present at the detector and the formation bulk density is established.

Calibration is done at the calibration camp using models with known density, in a water tank and on an aluminium block. The results can be presented in counts per second or in density units such as g/cc.

Neutron-neutron

The neutron-neutron method records the hydrogen content in the formation. As the pore species are generally filled with water, the tool response will reflect porosity. However, in crystalline rock with very low porosity the method is greatly affected by mafic minerals such as iron and manganese. In combination with the gamma-gamma method these high density minerals can be detected.

The probe, O.D. 54 mm, contains a radioactive 5 Ci Am(Be)-241 source, which emits high energy neutrons into the formation. Two detectors (He-3) are positioned at a distance of 0.26 and 0.52 m from the source, respectively, and the instrument measures the amount of thermal neutrons present at the detectors.

The pulses from the two detectors are divided by a geometrical factor at the surface to compensate for geometrical spreading. The pulses from the closest spaced detectors are divided by 8 and the other by 4. The surface unit separates pulses from the two detectors and transforms the pulses into a DC-voltage proportional to the neutron counts.

The neutron-neutron probe is calibrated in calibration models with known porosity values and controlled water content in the pore spaces. When measuring in crystalline rock with low porosity values, the instrument is used to perform relative measurements since absolute calibration is impossible today in these ranges.

The results are often presented as the ratio of the counts at the front detector to the rear detector. It is also possible to present the results on counts/s or in porosity units, i.e. hydrogen index.

4.2.7 Acoustic methods

Acoustic borehole methods available are sonic and tube wave. While the sonic tool is connected to the main surface unit, the tube wave measurements are performed with a separate, complete system including cable and surface unit.

Sonic

The sonic velocity probe records the time for a compressional elastic wave to travel a defined length in the formation surrounding the borehole. This time depends on the elastic properties of the rock.

The probe, O.D. 52 mm, uses an acoustic transmitter of the magnetostrictive type to generate an elastic wave. The frequency of the transmitter is in the order of 20 000 Hz and is sent in short pulses with a firing rate of 15 Hz. The distance between the transmitter and the nearest receiver is three feet, and the interval between the receivers is generally one or two feet. The two receivers mounted above the transmitter trigger register the incoming wave when the amplitude exceeds a preset amplitude treshold.

The probe is designed in such a way that the direct wave through the probe will propagate more slowly than the wave propagating through the rock formation.

The measurements with the sonic velocity tool are dependent on the probe geometry and very accurate timing, and no field calibration is therefore generally needed. Nevertheless it is advisable to check the instrument in the casing.

The time difference for the elastic wave to travel between the receivers is computed and presented as microseconds per foot or microseconds per meter. Data can also be presented in s/ft, m/s or km/s.

Tube wave

The tube wave method is a seismic method, where tube waves (low frequency Stonely waves) propagating up and down the borehole along the interface between the borehole wall and the borehole fluid are registered.

A twelve-channel hydrophone array lowered stepwise into the borehole is set to identify permeable fractures and fracture zones intersecting the borehole. For each array position a small dynamite charge is detonated in a shallow borehole at an offset distance of 20 - 40 meters from the well head. When the compressional wave energy from the surface explosive source impinges onto a fracture, the water contained in the fracture is squeezed out into the borehole, thus generating a tube wave which travels up and down the hole.

The hydrophones have built-in preamplifiers and a frequency resonance between 2 and 1000 Hz. The diameter of the hydrophones is 51 mm, and the interval between them is 1.06 m, giving an array length of 11.66 m. The crystal cable is connected to a 24-conductor steel cord cable, 780 m in length. Another 290 m cable is also connected, giving a total cable length of 1070 m.

Data are digitally recorded on a 24-channel signal enhancement seismograph. A built-in electronic printer provides a permanent paper record if desired. The memory size is 1024 8-bit words for each channel, and the sample interval is selectable in five steps from 0.125 ms up to 4 ms giving a record length from 125 ms up to 4 s.

The data recorded on the seismograph is then transferred to a computer for permanent storage and future analysis. The records are plotted on a Calcomp plotter to form a continuous record suite displaying seismic traces along the hole at selectable intervals according to the scale.

The tube wave method gives information about the main water-bearing fractures along the borehole. For example, the tube wave results can be used for the selection of sections for detailed hydraulic tests, or for the selection of sampling points for hydrochemical studies. In Figure 4.11 the principle of the tube wave measurement is shown.

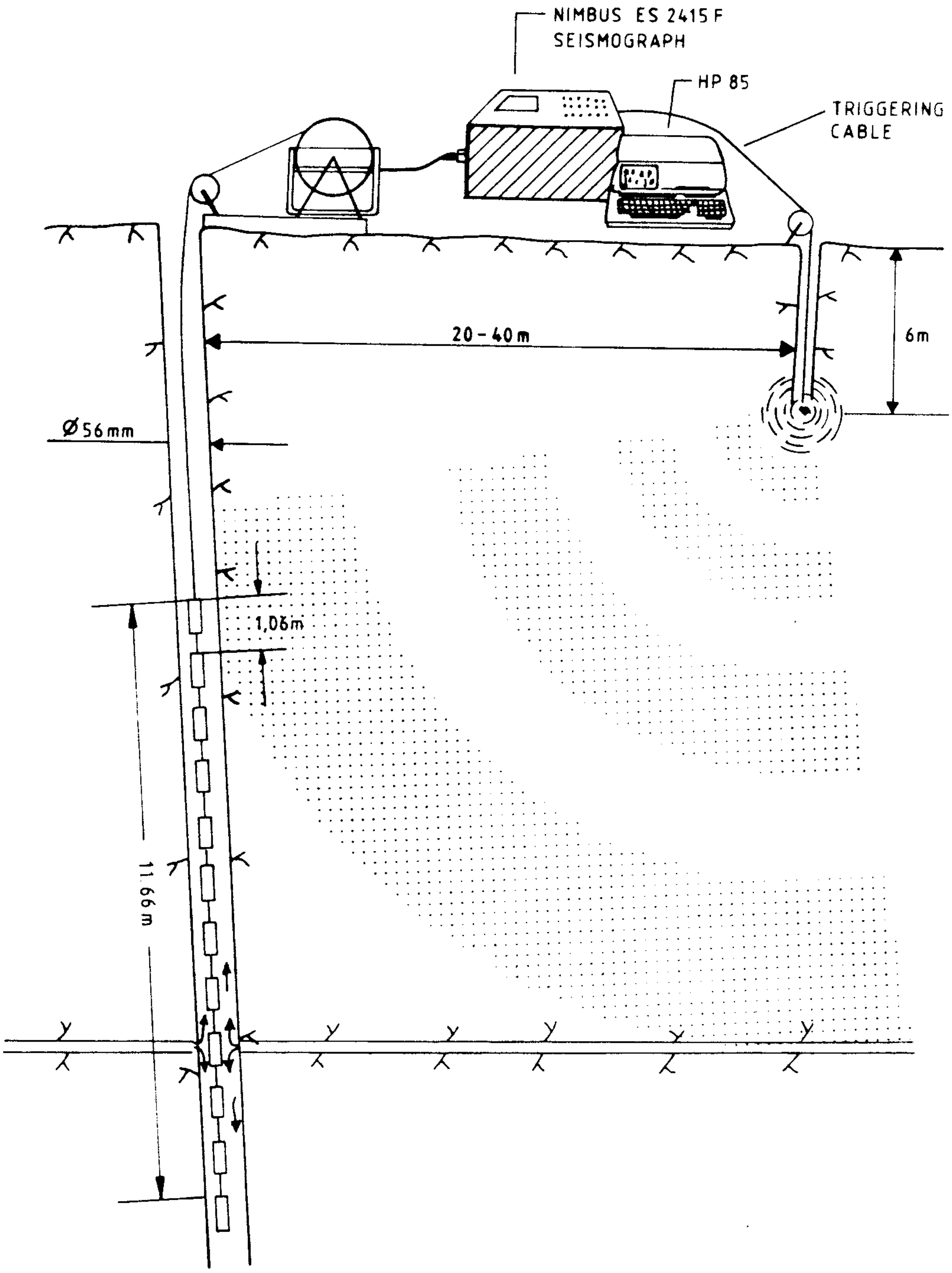


Figure 4.11 Principle of the tube-wave method.

4.2.8 Data processing and presentation

Data recorded during the continuous measurements is stored on a digital cassette tape, format ISO/ECMA 34. When returning to the base, data is then easily transferred to a main computer (Prime or IBM AT).

Data recorded at discrete points is annotated in the field and typed into the computer when returning to the base.

Raw data is seldom plotted out according to depth directly. The steps to be taken before presentation of the results are generally: Calibration, correction and calculation.

Calibration

At first, raw data has to be transferred (calibrated) to units well known to a geophysicist and a geologist. The natural gamma ray is recorded in counts and has to be calibrated into units such as microRoentgen/h. The calibration routines are described in more detail in the text describing each specific method.

Method	Measuring values	Calibrated values
Resistivity	Volt, Ampere	Ohmmeter
Gamma ray	Counts	microR/h
Gamma-gamma	Counts	Density
IP	Volt, Apmere	Ohmmeter, IP%

Furthermore, results from the temperature/fluid resistivity measurement and the Boremac, for example, which seem to give an absolute reading, have to be adjusted according to calibration curves made in advance at the laboratory.

Corrections

A number of different corrections can be applied if required. Some examples are given below.

Method	Correction for:
Resistivity	Temperature, fluid resistivity and borehole diameter variations.
Gamma ray	Borehole diameter variations
Gamma-gamma	Borehole diameter variations
IP	As resistivity above plus borehole deviation

Calculations

Some calculations are made during calibration, for example the calculation of resistivity from electrode configuration, voltage and current intensity and the calculation of the borehole deviation from the measured declination and inclination values. It is also possible to

* calculate the temperature gradient from the temperature and borehole deviation results

* calculate the salinity from the temperature and fluid resistivity results

* produce histograms

* produce crossplots

All data is stored on special tapes to be kept by the customer for future analyses.

Finally, the results are presented according to depth on a plot in the COMPLOT system, where the methods, units, and scales can be chosen by the operator. Furthermore, auxiliary data such as corelog or the results from hydraulic tests can be presented at the same plot. Figure 4.12 shows an example of some results presented in the COMPLOT system.

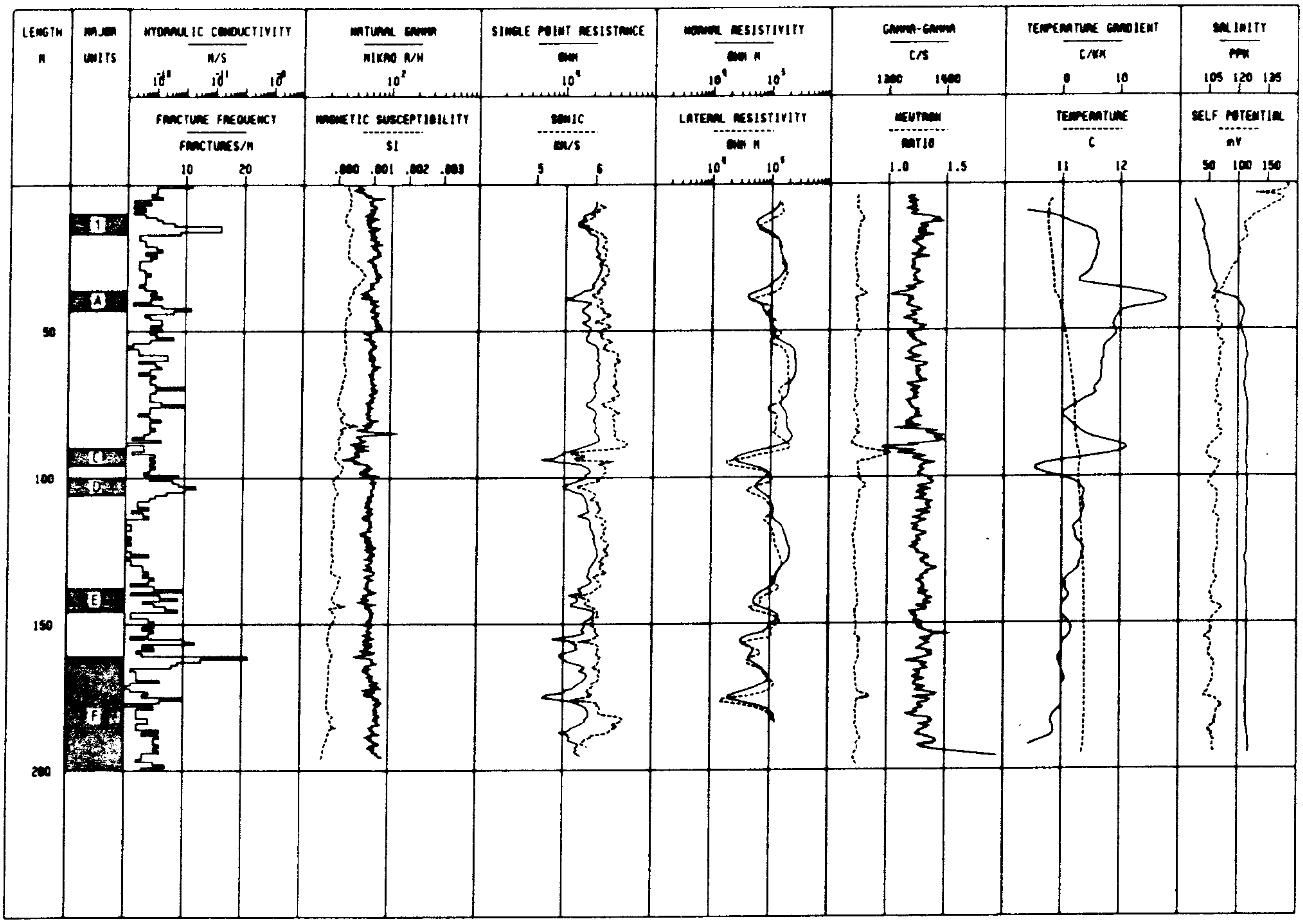


Figure 4.12 COMPLOT presenting results from different borehole measurements in the same diagram.

5. BOREHOLE RADAR EQUIPMENT

5.1 General

In the radar technique, electromagnetic waves are transmitted through the rock in order to obtain information on structures, such as fracture zones, in the rock mass. It is the wave aspect of the electromagnetic field that gives the radar its high resolution, which is on the order of meters. In combination with investigation ranges of 100-150 m this makes the radar a unique instrument for the mapping of structures in the rock.

The borehole radar system, RAMAC, utilized by SKB has been developed by a group at the Swedish Geological Co. Pioneering work on borehole radar had previously been made by Boliden Mineral AB and the know-how gained was kindly made available to the project group at Swedish Geological Co. The initial development of the system was funded as a part of the Crosshole Program of the International Stripa Project, which is an autonomous OECD/NEA project supported by organizations from 9 different countries (Canada, Finland, France, Japan, Switzerland, Sweden, Spain, United Kingdom, and United States). Continued development has been funded by SKB to construct a system adapted for field work on a production basis and for use in 56 mm boreholes. This system is now in routine use.

The radar system can be classified as a short pulse system, which means that the length of the pulse transmitted into the rock will be approximately one wavelength. The system works in principle in the following manner. A short current pulse is fed to the transmitter antenna, which generates a radar pulse that propagates through the rock. The pulse is made as short as possible to obtain high resolution. The pulse is received by the same type of antenna, amplified, and registered as a function of time. The receiver may be located in the same borehole as the transmitter or in any other borehole. From the full wave record of the signal the distance (travel time) to a reflector, the strength of the reflex, and the attenuation and delay of the direct wave between transmitter and receiver may be deduced.

The radar system consists of six different parts:

* a microcomputer with two 5 1/4-inch floppy disc units for control of measurement, data storage, data presentation and signal analysis.

* a Winchester hard disc unit with 20 MByte data storage capacity.

* a control unit for timing control, storage and stacking of a single radar measurement.

* a borehole transmitter for sending out short radar pulses.

* a borehole receiver for detection and digitization of radar pulses.

* a fiber optical borehole cable and cable winch.

The system parts are shown in Figures 5.1 and 5.2 and the technical specifications of the system are given in Table 5.1.

Table 5.1. Technical specifications for the RAMAC borehole radar system.

General	
Frequency range	20-80 MHz
Total dynamic range	150 dB
Sampling time accuracy	1 ns
Maximum optical fiber length	1000 m
Maximum operating pressure	100 Bar
Outer diameter of transmitter/receiver	48 mm
Transmitter	
Peak power	500 W
Operating time	10 h
Length	4.8 m
Weight	16 kg
Receiver	
Bandwidth	10-200 MHz
A/D converter	16 bit
Least significant bit at antenna terminals	1 µV
Data transmission rate	1.2 MBaud
Operating time	10 h
Length	5.4 m
Weight	18 kg
Control unit	
Microprocessor	RCA 1806
Clock frequency	5 MHz
Pulse repetition frequency	43.1 kHz
Sampling frequency	30-500 MHz
No of samples	256-4096
No of stacks	1-32767
Time window	0-11 µs

The system has been designed in such a way that it may be used for both single-hole and crosshole measurements. The system has been made flexible in order to provide possibilities for changing the transmitted frequency, the sampling frequency, and the length and position of the sampled time interval.

The measurement procedure is relatively simple. After initialization of a data disc and selection of the variable parameters, the borehole probes are put into the hole and the measurement is started. When the measurement of a trace is completed the computer unit gives an audio signal to indicate

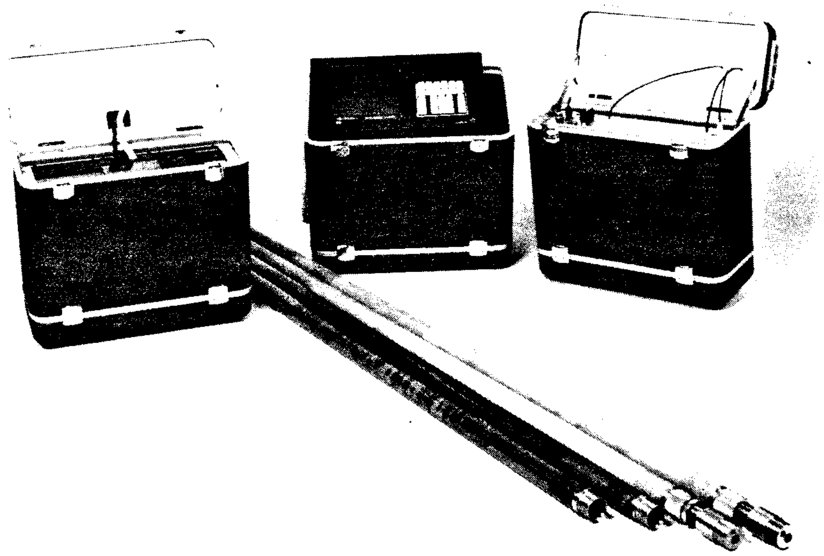


Figure 5.1 The RAMAC borehole radar system units from left to right: Winchester unit, transmitter and receiver probes with batteries, computer unit and control unit.

that it is time for the operator to move the probes to the next measuring position. In horizontal holes the probes are pushed into the boreholes by glass fiber rods with a length of 2 meters. In vertical holes the probes are lowered down the borehole with the cable winch. Measurements are normally carried out with a separation of measurement points of 1 m. The measurement at each position takes about 20-40 s depending on the number of samples and stacks. This corresponds to about 100 m of measured borehole per hour in one meter steps.

In a single hole reflection measurement the transmitter and receiver are lowered into the same hole and the distance between them is kept constant. The result is displayed in the form of a diagram where the position of the probes is shown

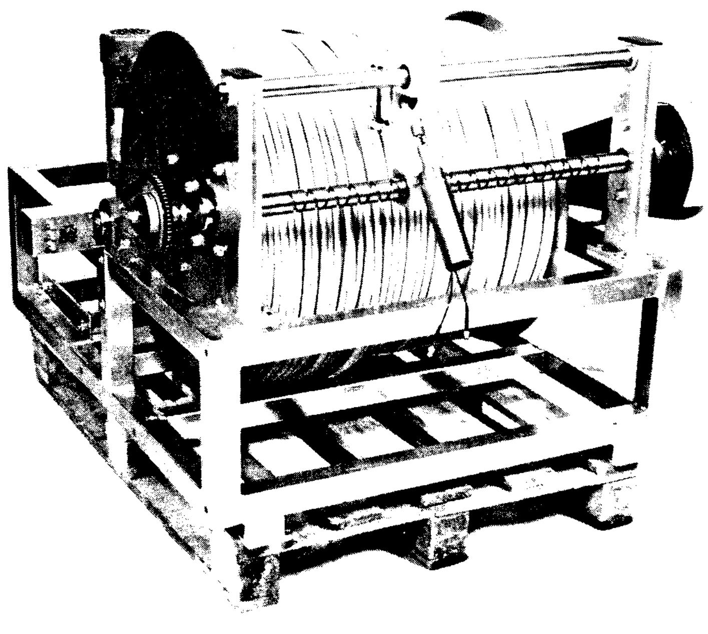


Figure 5.2 Cable winch with 1 000 m of optical fiber cable.

along one axis and the distance from the hole to a reflecting object along the other axis (Figure 5.3). The amplitude of the received signal is shown in a grey scale. The distance to a reflecting object is determined by measuring the difference in arrival time between the direct wave and the reflected pulse. As the radar is pushed step by step into the borehole the time difference will vary in a characteristic manner typical of the geometry of the reflector. The two basic patterns are point reflectors and plane reflectors as shown in Figure 5.3. A result from a reflection measurement is the borehole F2 at Stripa as shown in Figure 5.4. Additional results and methods of interpretation have been presented in papers by Olsson et al, 1985a, and Olsson et al, 1985b.

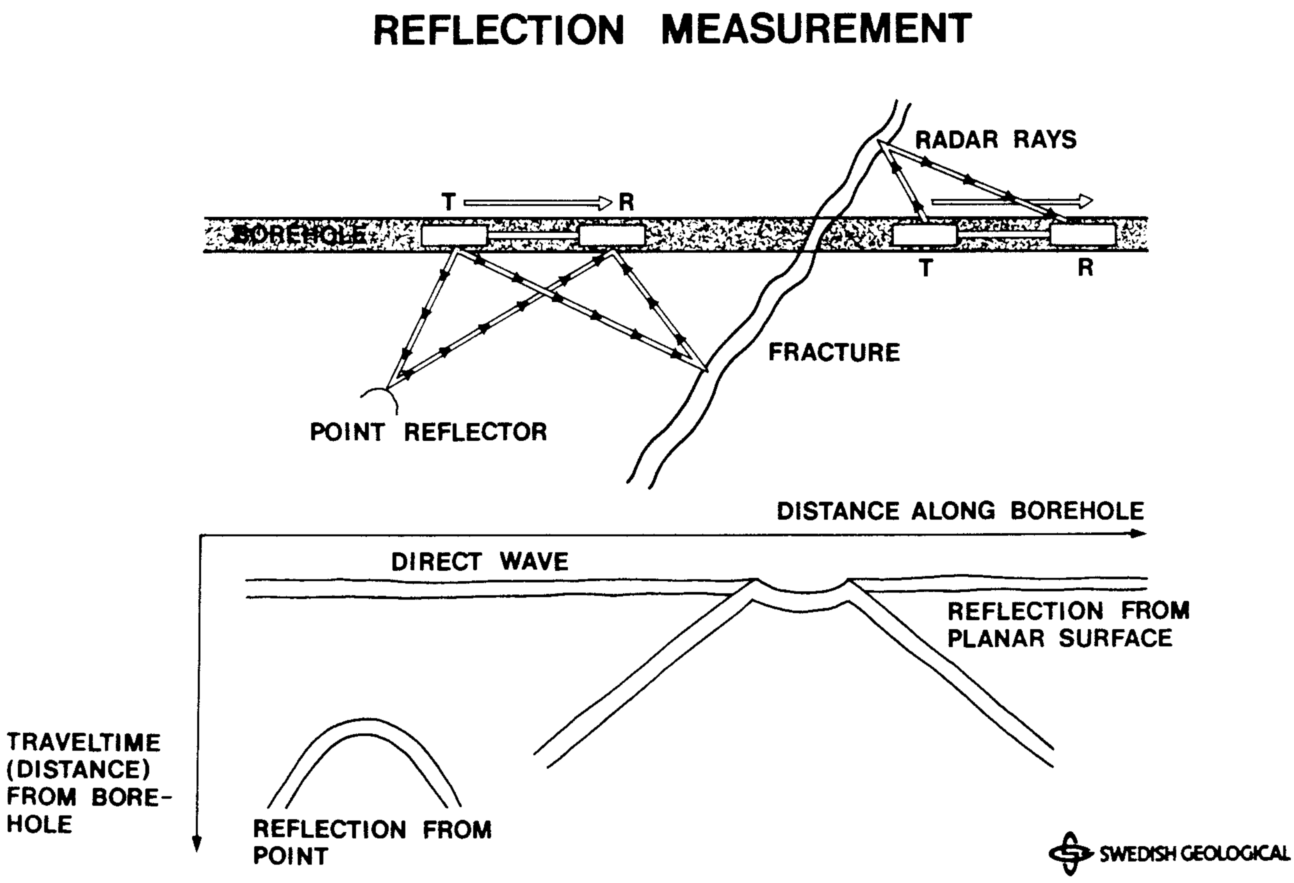


Figure 5.3 Principle of the borehole reflection radar and the patterns generated by plane and point reflectors.

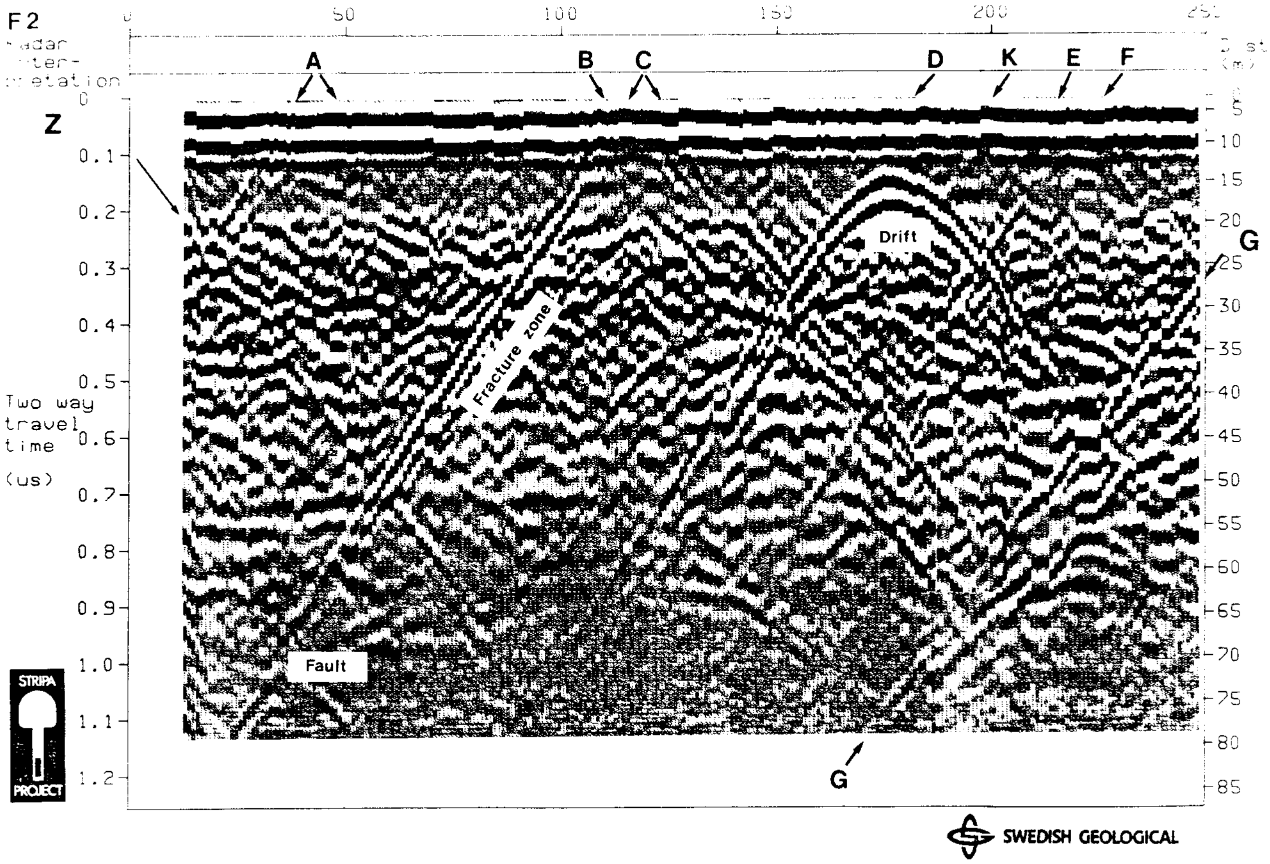


Figure 5.4 Radar reflectogram from the borehole F2 at Stripa measured with a center frequency of 25 MHz.

5.2 Radar system units

5.2.1 Microcomputer

The borehole radar system is controlled by the microcomputer unit and its associated software. The radar system software includes the following facilities:

* selection of parameters controlling the measurement, e.g signal position, sampling frequency, number of samples and number of stacks.

* control of measurement.

* display of radar results on screen or on matrix printer.

* signal processing including Fourier transformation, correlation, deconvolution and/or bandpass filtering.

* display of the signal or spectrum of single traces.

The processing software is described in some more detail in section 5.3.

The microcomputer is a standard desktop computer system named ABC806 and has been mounted into a special field box. This makes the system rugged and easy to transport. The system includes two 5 1/4-inch floppy disc units, and optionally a 20 MByte Winchester unit, where the measured data is stored.

5.2.2 Control unit

The control unit is designed to perform a limited number of well - defined tasks, viz.

* determination of sampling frequency and position of transmitted pulse in relation to the registered time window (signal position).

* generation of trig pulses to transmitter and receiver.

* storage of digital data from the receiver.

* stacking of a single trace.

* transmission of data to external microcomputer.

The control unit is built up around the microprocessor RCA 1806, which is an 8-bit CMOS-processor with 16-bit registers. A block diagram of the control unit and the transmitter and receiver probes are shown in Figure 5.5.

The sampling of the received signal is in principle made as in a sampling oscilloscope, i.e. for each pulse sent by the transmitter only one sample of the received electric signal is taken at a specific time instant. When the next pulse is sent out, a new sample is taken which is displaced slightly in time. Thus after a number of samples a replica of the entire signal is recorded as a function of time (Olsson and Sandberg, 1984). The trig pulses to the borehole probes are generated by comparing voltages which increase with time at different rates. The sampling frequency is determined by the rise time of the ´slow ramp´ voltage in relation to the ´fast ramp´. The setting of the rise time is controlled by the microprocessor.

The 16-bit serial data from the borehole receiver are decoded by a DMA-interface (Direct Memory Access) to achieve a high data transfer rate. With the 32 kByte memory it is possible to store a maximum of 4096 samples per trace. The 16-bit data is stacked by adding into a 32-bit word, which gives a maximum of 32767 stacks.

When a measurement of a single trace, including stacking, has been completed the data is transferred to the computer unit through an RS232 interface.

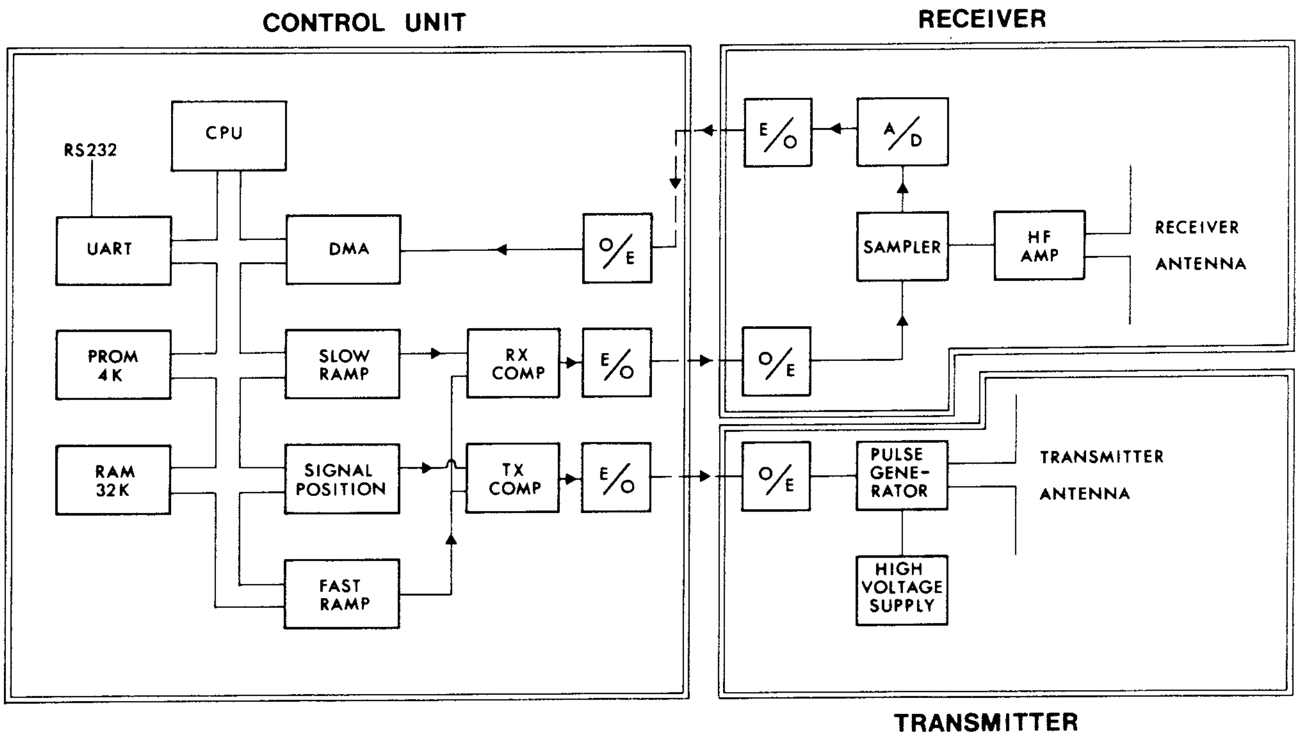


Figure 5.5 Block diagram of the borehole radar system.

5.2.3 Transmitter

The transmitter consists of a high voltage generator (DC/DC converter) which charges a transmission line. When a trig pulse is received on the optical fiber connected to the transmitter, the transmission line will be discharged through a transistor working in the avalanche mode. The duration of the current pulse fed to the antennas is proportional to the length of the transmission line, e.g. a 1-m long transmission line will give a pulse width of 10 ns.

The choise of a fiber optic link between the probes and the control unit makes it necessary to use a rechargeable battery pack for power.

5.2.4 Receiver

A high frequency amplifier increases the amplitude of the antenna signal before it is sampled by a track and hold circuit. The amplifier is designed to cover the frequency range 10 - 200 MHz. The sampled signal is digitized by an A/D converter with a resolution of 16 bits. The digital data is converted to serial form and sent through the optical fiber to the control unit at the surface.

The power to the receiver is supplied by means of a rechargeable battery pack.

5.2.5 Antennas

The current pulse generated by the transmitter is converted into radiated energy by the antenna. In an analog fashion the receiver antenna converts the energy of the electromagnetic wave into a voltage which is amplified and converted into a digital signal in the receiver.

In order to get high resolution in the radial direction it is necessary to transmit a pulse with a limited time duration.

Thus, in the construction of a short pulse radar system it is essential to have a large bandwidth. The bandwidth of the dipole antennas is increased by introducing a resistive load increasing with the distance from the feeding point.

Antennas have been designed for the following center frequencies: 25, 45, and 60 MHz.

5.2.6 Fiber optic borehole cable and winch

The borehole probes communicate with the control unit by optical fibers. This will eliminate any disturbing reflections due to wave propagation along the borehole which would be the case if electrically conductive cables had been used. Two fiber links are used to transmit timing information for the sampling process; one to the transmitter and one to the receiver. One fiber link is used to transmit the digital data from the receiver to the control unit.

Two special fiber optic cables have been designed for borehole use with the radar system. One cable contains 4 optical fibers and is to be used in two applications;

* single hole reflection measurements where both receiver and transmitter are connected to the cable.

* crosshole measurements where only the receiver is connected to the cable.

The other cable contains only one optical fiber and is connected to the transmitter in crosshole measurements.

Both cables each have a length of 1 000 m and are mounted on identical motordriven winches.

5.3 Data processing

The borehole radar software package is used both for control of measurement and for processing and final presentation of the radar data. The software package consists of a main program, called RADAR, and several subprograms which are used to perform different tasks. All subprograms can be reached from the main program and when the execution of a subprogram is completed control returns to the main program. The general structure of the program package is shown in Figure 5.6.

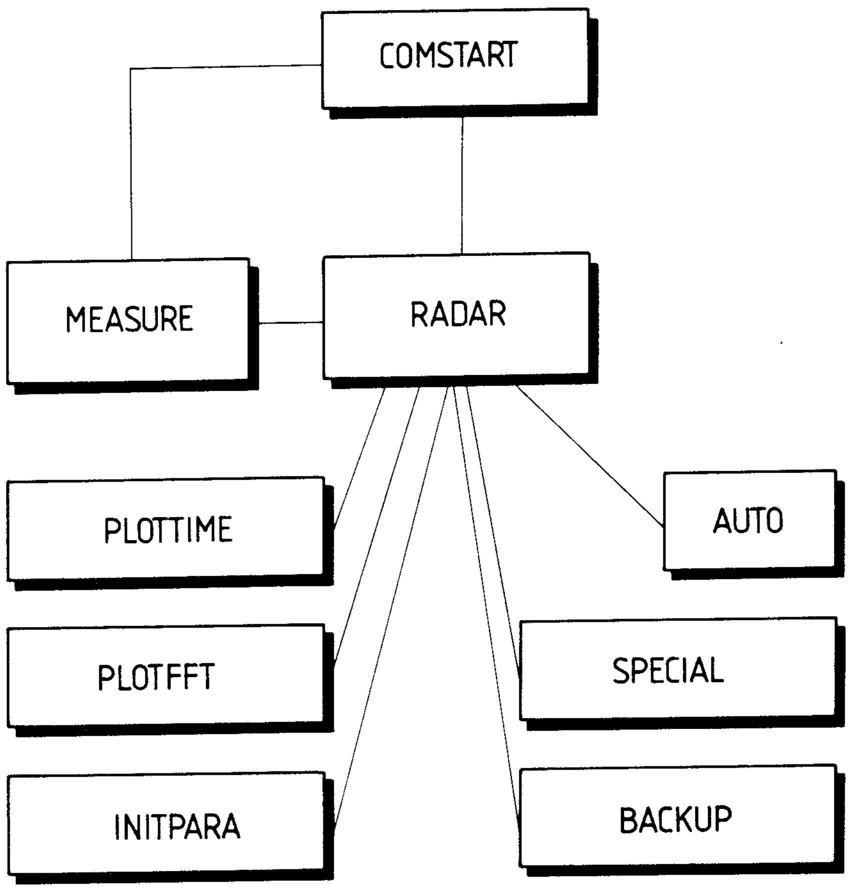


Figure 5.6 Block diagram of the RAMAC software package.

The software package consists of the following programs:

Program	Function
COMSTART	- startup program which sets default values
RADAR	- main program, includes facilities for control, spectral analysis, and filtering of individual measurements (traces)
MEASURE	- program which controls the measurement process, stores data on disc and displays the result on a color screen
PLOTTIME	- program for plotting of data on screen and printer from an entire borehole
PLOTFFT	- plot program for Fourier transformed data
INITPARA	- initialization of filter parameters
AUTO	- processing program, see below
SPECIAL	- some special options
BACKUP	- data backup program

The processing of a reflection measurement normally includes the following steps in order to enhance the quality of the radar data displays.

First a DC-level offset is removed from the raw data. This is normally done already on site and if possible a printout of this data is also made at the same time. (The rest of the processing is normally carried out at the office but could in principle be carried out in the field.)

Then a Fourier transform is made of the measured borehole and stored on disc. Filtering is done in the Fourier domain and as the transform of the measurement is stored on disc it may be used for several different filters, thus saving some computer time.

The next step is to generate suitable filters in the Fourier domain which can be applied to the data. The generation of filters is made in the program INITPARA while the filtering of an entire borehole is made by AUTO. The radar software package supports generation of bandpass, convolution and deconvolution filters. Arbitrary filters may be stored on file and used by the radar software. The selection of an appropriate filter normally includes tests of different types of filters with different parameters and subsequent checks of the resulting reflectograms.

When the data has been properly filtered the radar data is printed on a matrix printer and the printouts are mounted in frames with calibrated travel time and distance information. The conversion of travel time to distance requires knowledge of the radar propagation velocity in the rock, which must be obtained by special measurements (normally crosshole measurements).

5.4 Directional antennas

The present radar system uses antennas which have a cylindric radiation pattern relative to the borehole. This means that the present system in the single hole reflection mode, only gives information on the distance to a reflecting point from the borehole. Consequently the location of the reflector will be determined to lie somewhere on a circle around the borehole but it is not possible to tell where on this circle (Figure 5.7). This ambiguity in the radar results can in many cases be remedied through measurements in several adjacent holes, either as single hole or cross-hole measurements. The development of directional antennas which may determine the direction of the incoming wave will thus facilitate the determination of the location of the reflector on the circle through measurement in one hole only.

The development of directional antennas will include an initial analysis of the components of a directional radar system such as antennas, data collection procedures, data analysis, and data presentation. It is envisaged that the system will have a set of antennas for measuring two perpendicular components of either the electric or the magnetic field. Theoretical and numerical simulations will be made of different antenna designs; test antennas will be constructed and tested. New high frequency amplifiers will have to be constructed to compensate for the lower signal levels expected with directional antennas compared to dipole antennas. When a satisfactory directional antenna has been designed, a complete radar system will be constructed. Field tests will be made to test the functionality and accuracy achieved with the directional system. A considerable effort will also be put into the development of interpetation and presentation techniques for data obtained with the directional system.

The development of the directional antennas has already been initiated and is being carried out within the framework of Phase 3 of the International Stripa Project, funded by OECD/NEA.

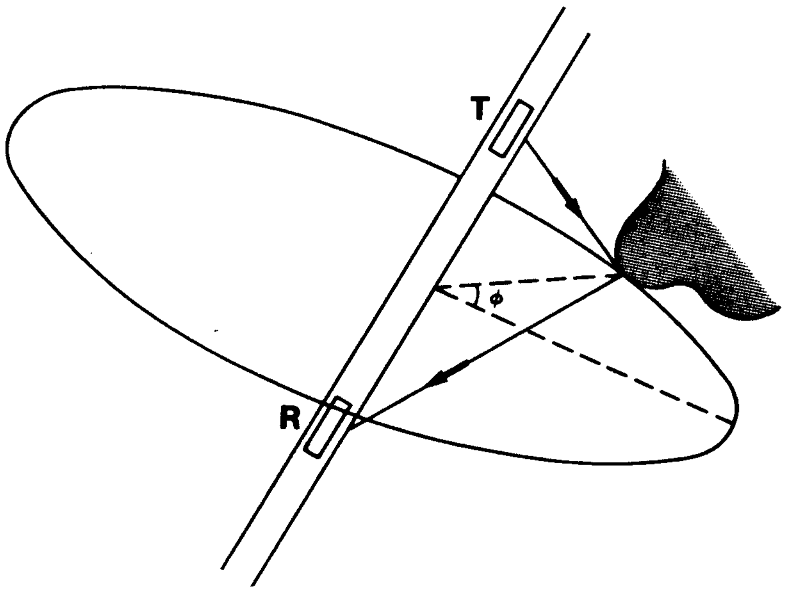


Figure 5.7 A directional antenna system will facilitate the determination of the azimuthal angle, Ø, which is not possible with the present borehole radar system.

6. EQUIPMENT FOR HYDRAULIC TESTING

The hydraulic conductivity of the rock may be determined by means of either single hole testing or interference testing. For single hole investigations at great depths two different systems for hydraulic injection tests have been developed: the umbilical hose system and the pipe string system. While the umbilical hose system is more fully automated to perform an entire injection test, the flow regulation in the pipe string system is manually operated.

Interference tests can be performed either as injection tests or as pumping tests. One type of equipment used for these tests is described in 7.3.

6.1 Umbilical hose system

Hydraulic injection testing is a time-consuming measuring method when c. 8000 m of borehole will be tested at each study site. When an increasing site selection program was planned in 1980, the development of the umbilical hose system was initiated.

The first equipment, developed by IPA-Konsult AB, was ready for use in 1981. The system has later been modified in order to improve the components and function.

The great advantages of the umbilical hose system are easy handling including both moving on the surface and in the borehole. The automatic operation of the injection tests also gives a standardized performance of the tests and low personnel costs.

6.1.1 General layout

The function of the umbilical hose system is to enable hydraulic injection tests to be automatically performed, based on one or more investigation methods. It means that inflation of packers, operation of test and relief valves, injection of water and measurement of waterflow, pressures and temperatures have to be performed after a certain test-programme. The principal overview of the equipment is shown in Figure 6.1.

The umbilical hose equipment consists physically of three separate mobile units: a measurement trailer, a recording trailer and an electrical generator unit.

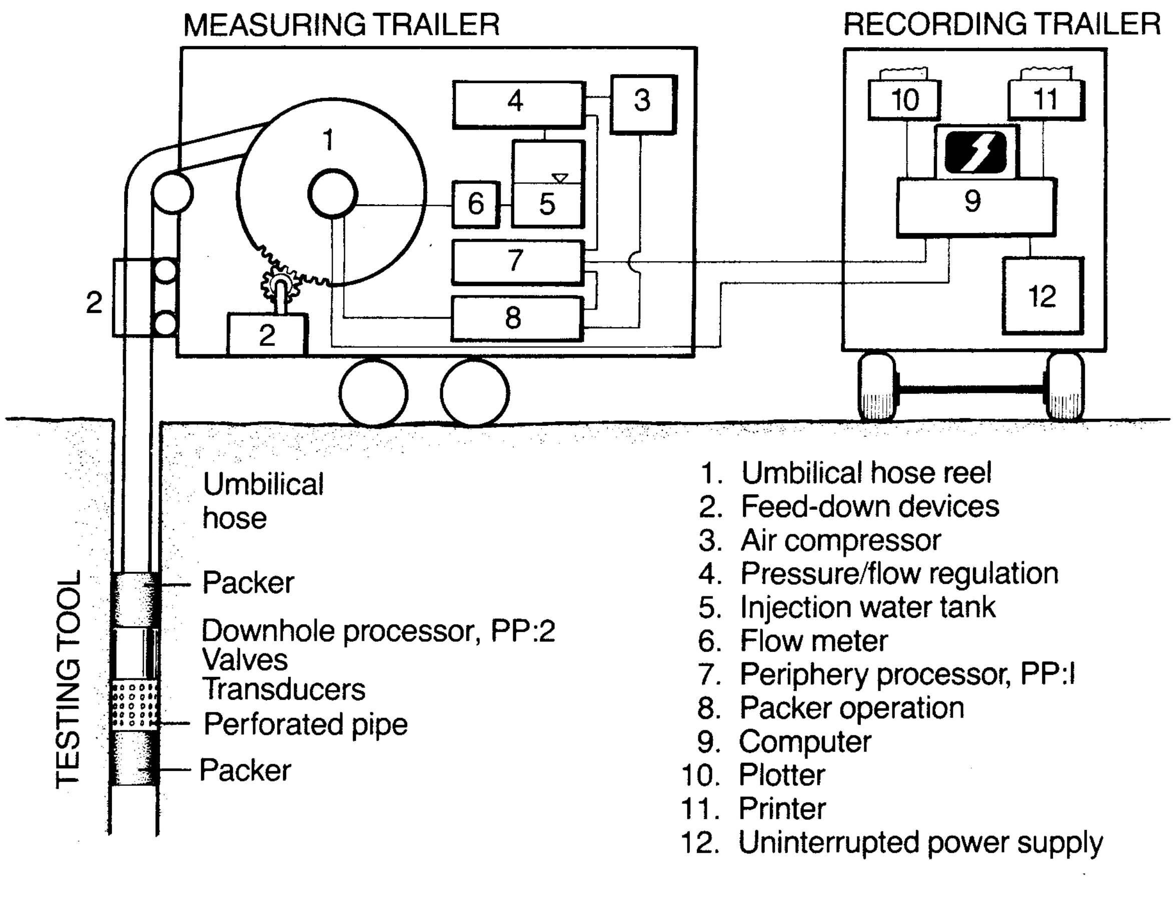


Figure 6.1 Principal overview of the umbilical hose system.

A brief description of the three units is presented below, while the functions of the components are presented under the main groups (6.1.2-6.1.5):

* down-hole equipment
* water injection system
* measuring instruments
* computer system - tasks and hardware
* computer system - software

Measurement trailer

The measurement trailer is built on a special chassis with detachable superstructure, installed with the following main units (also see Figure 6.2):

* umbilical hose with reel
* feed-down device
* hydraulic power unit
* air compressor
* water injection system
* measuring instruments
* testing tool

The function of most of these units is described later in the text, while only a few comments will be made here.

When setting up the equipment at the test site, a hydraulic winch is used to pull the trailer into position. The trailer will be placed on hydraulic jack-up legs, which give stability and make level adjustment possible.

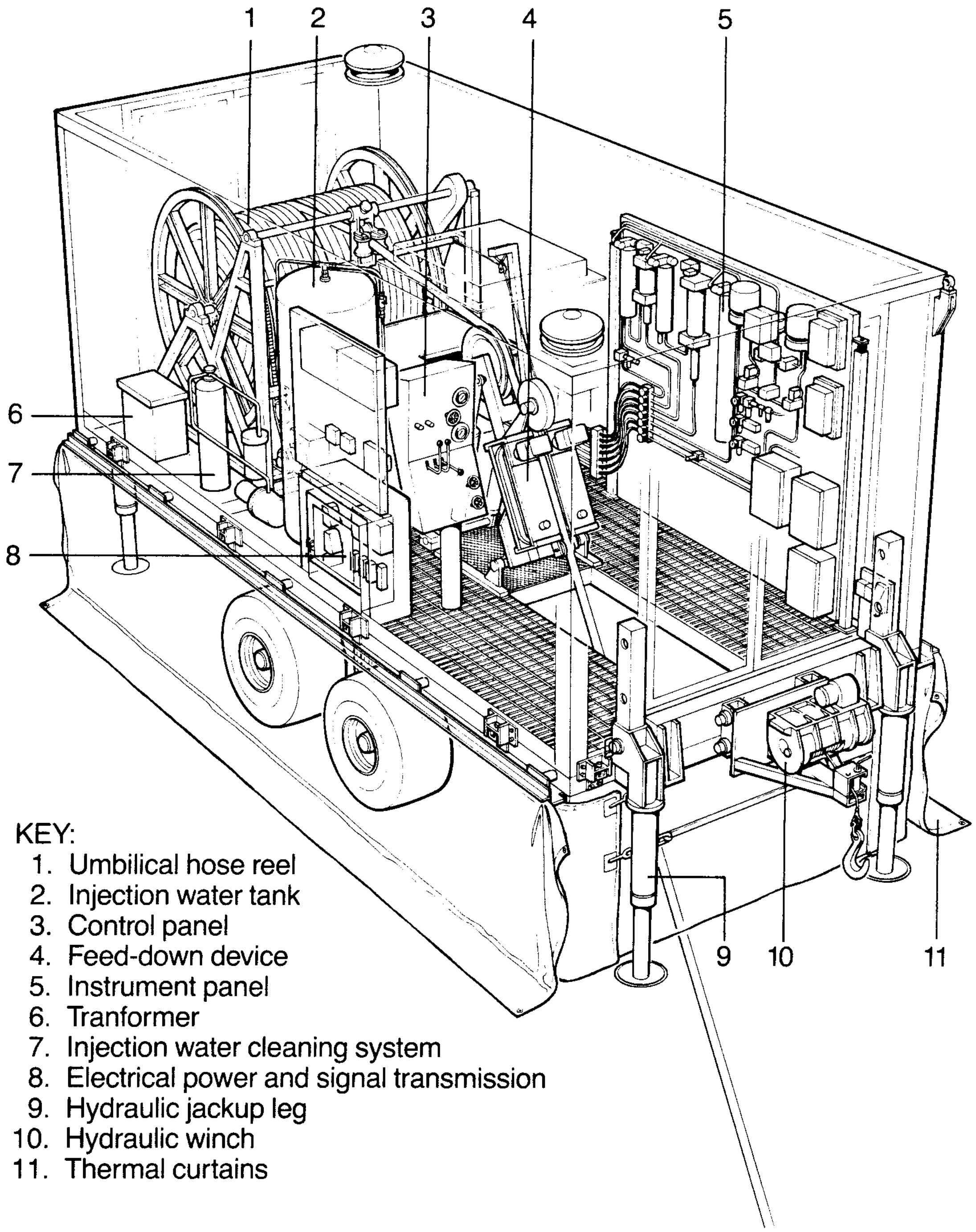


Figure 6.2 Measurement trailer of the umbilical hose system.

The air compressor used is a BIABINO, type 2093, with a 40 l air volume and a maximum pressure of 1.5 MPa. The compressor unit supplies primary-side air at c. 1.4 MPa. This primary pressure is used for the pressurizing of one tank connected to the packer system. The remaining air is reduced to 0.9 MPa for the operation of the water injection system, but is also used for cleaning air. After an additional reduction to 0.01 MPa the air is also used in the ground water level measuring system.

The measuring trailer has two separate heating systems, one system using thermostat-controlled electric radioators and a reserve system of the emergency type with thermostat-controlled and LP-gas operated heaters.

Recording trailer

The mobile recording trailer is equipped with a desk-top computer around which instruments for test control and data recording and processing are assembled. The function of this system is described in sections 6.1.5 and 6.1.6.
The recording trailer is electrically heated with an LP-gas-operated back-up system.

Electrical power unit

As the electrical network normally is not available at the test sites, a mobile electrical power unit is used. The electrical generator is driven by a diesel engine manufactured by Slanzi, Italy, and equipped with control cabinet and automatic regulation. The maximum power output from the 380 V generator is 12 kVA. A 5-kVA transformer for 220 V is installed in the measuring trailer.

6.1.2 Downhole equipment

The downhole equipment consist of a testing tool and an umbilical hose separately described in the following text.

Testing tool

The testing tool for hydraulic injection tests is a complex unit, with mechanics and electronics built together for operation in 56-mm boreholes (Figure 6.3). The testing tool may functionally be separated in the following devices:

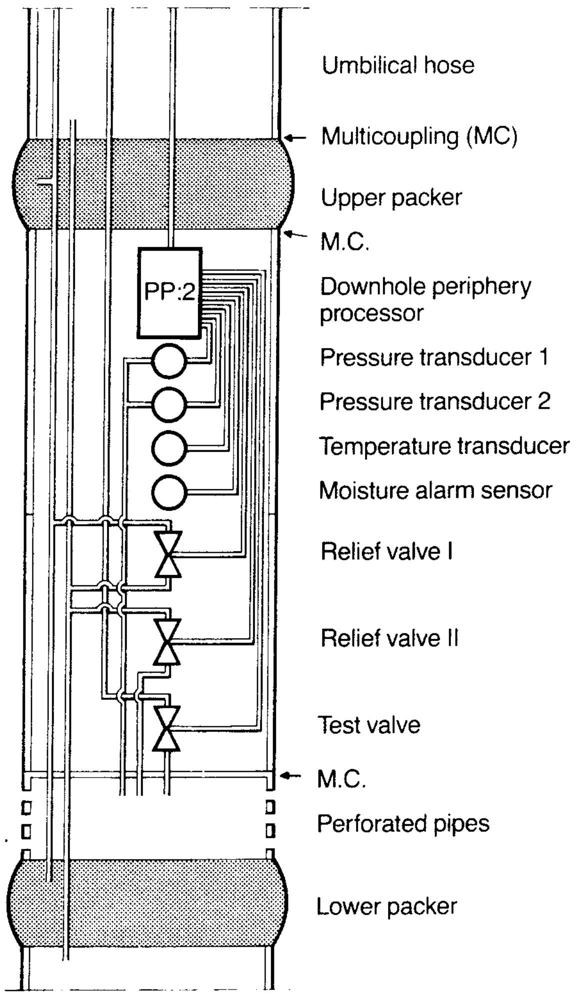


Figure 6.3 Principle design of the testing tool, two packer configuration.

* packers
* valves
* pressure and temperature transducers
* downhole electronics (periphery processor, PP:2)

Of these devices the packers and valves are described below while the two others are described in 6.1.4 and 6.1.5, respectively.

The following text describes a two-packer design. In an optional four-packer configuration outer sections are sealed off and additional valves, transducers and downhole processors have to be connected.

Packers

The test section is sealed off by two packers separated by infiltration pipes. The packer rubber-element, reinforced with canvas cord positioned crosswise, is attached to a stainless steel frame by means of compressed sleeves. A number of tubings go through the packer of which a larger one is for injection water to the test section. The smaller are to function as pressure lines, to the pressure transducers and pressure relief tubings. Separately packers are designed to work in 56-mm, 76 mm, 115-mm and 165-mm borehole diameters.

The packers are connected to a 15 litre pressure vessel via a 4-mm I.D. hydraulic tube in the umbilical hose, all filled with water or antifreeze liquid. The vessel is pressurized to a preset value, normally 1.4 MPa, with compressed air. By opening a valve the packers are inflated against the borehole wall, with the water functioning as a pressure transmitting medium. The test section is then sealed off from the other parts of the borehole.

During testing the valve is closed, and the packer pressure is recorded. The regulation and recording system is computer-controlled and if the packer-pressure decreases more than 0.2 MPa an alarm is set off and the injection test interrupted.

Downhole valves

Three valves are included in the testing tool:

* test valve
* relief valve I for the test section
* relief valve II for the packers

All three valves are bistable solenoid valves operated from the downhole processor PP:2 on order from the surface computer. The PP:2 and the valves are mounted just below the upper packer.

The task of the test valve is to distinctly open and close the injection test and to shut in the test section during the following pressure fall-off test.

The task of relief valve I is to relieve the pressure squeeze created during packer inflation. The relief tubing connects the test section to the sections below and above the test sections.

With relief valve II the packer deflation can be speeded up by downhole release of the packer pressure to the borehole. This valve may not be opened when an anti-freeze liquid is used.

Umbilical hose

All communication lines between the surface equipment and the testing tool are assembled in the umbilical hose. Hydraulic hoses, an electrical cable and a load wire are located inside a polyurethane outer jacket.

Via a specially designed multi-coupling all communications are connected to the testing tool (Figure 6.4). Furthermore, most parts of the testing tool have the multi-coupling at both ends, which means that these parts can be jointed in more than one configuration.

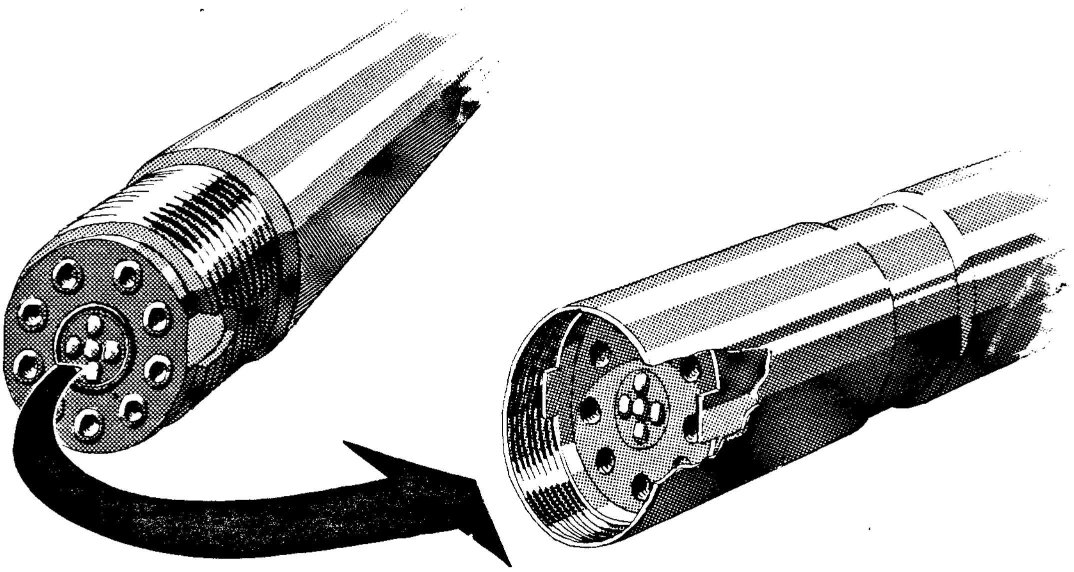


Figure 6.4 Multi-coupling for the connections in the testing tool, showing nine hydraulic tubes and five electrical conductors.

The 1000 m long umbilical hose with a diameter of 48 mm is wound on a reel in the measuring trailer. The feeding into the borehole is continuously performed by means of a hydraulically operated feeding device, with a maximum speed of 10 m/min (Figure 6.5). The top connection of the umbilical hose in the center of the reel is a rotating joint.

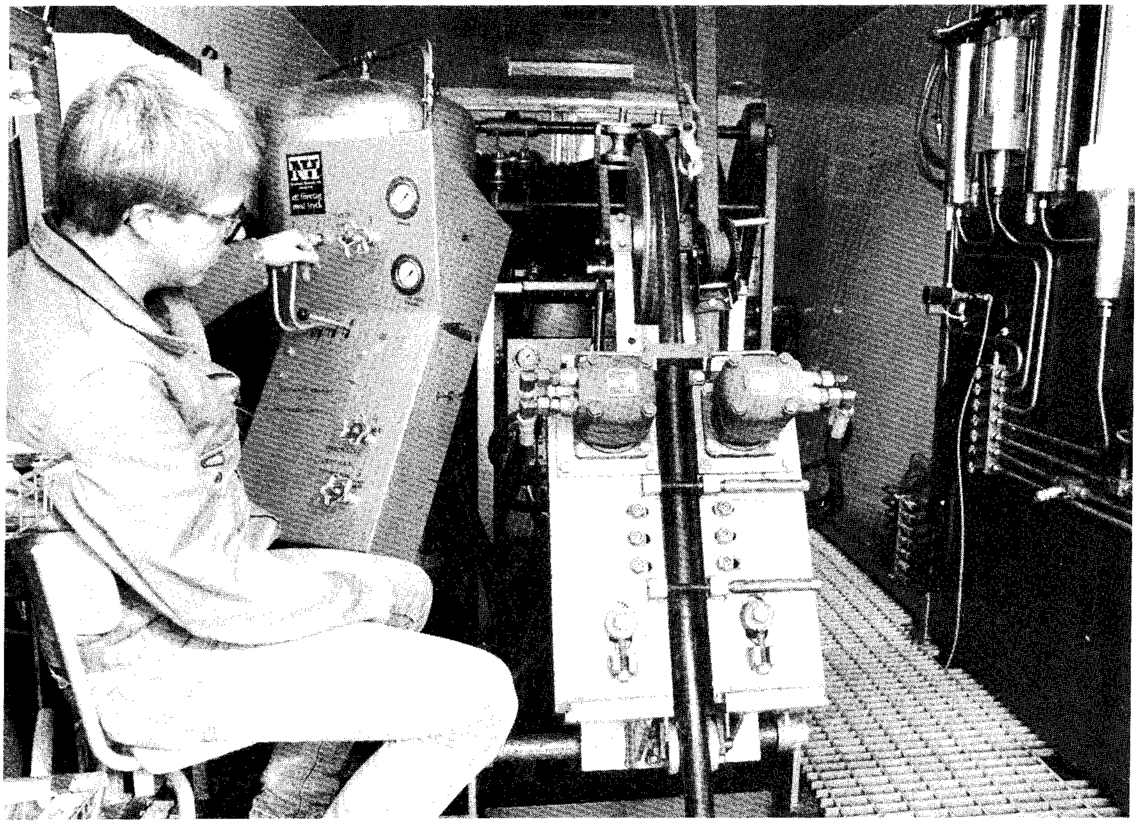


Figure 6.5 The feed-down device in the measuring trailer.

6.1.3 Water injection system

Water for the hydraulic injection tests is normally pumped from wells drilled in the same formation. In a filter particles >0.5 um are separated and the water is stored at the test site in 1,000 l tanks.

Before starting a water injection test the injection pressure is applied in the entire injection system down to the test valve by pressurizing a 500 l water tank with compressed air. A reference measurement is then made by opening a cannular tube in the system (the cannula test). The flow through the cannula is registered and simultaneously the pressure and temperature. The injection test is then momentarily started by opening the test valve.

The injection pressure measured in the test section, is then kept constant by regulating the air pressure in the water tank. This pressure regulation system is computer-controlled with the following functions (Figure 6.6):

A pressure signal from the injection water at surface is compared with a reference signal from the periphery processor PP:1. The electronic unit controls a number of solenoid valves which admit compressed air to be fed into or let out of the water tank. The solenoid valves are of three different sizes to permit rapid adjustments in a large water flow range. Every time a new pressure valve in the test section is transmitted from PP:2 to PP:1 a new reference signal is set, if necessary, to keep the injection pressure constant in the test section.

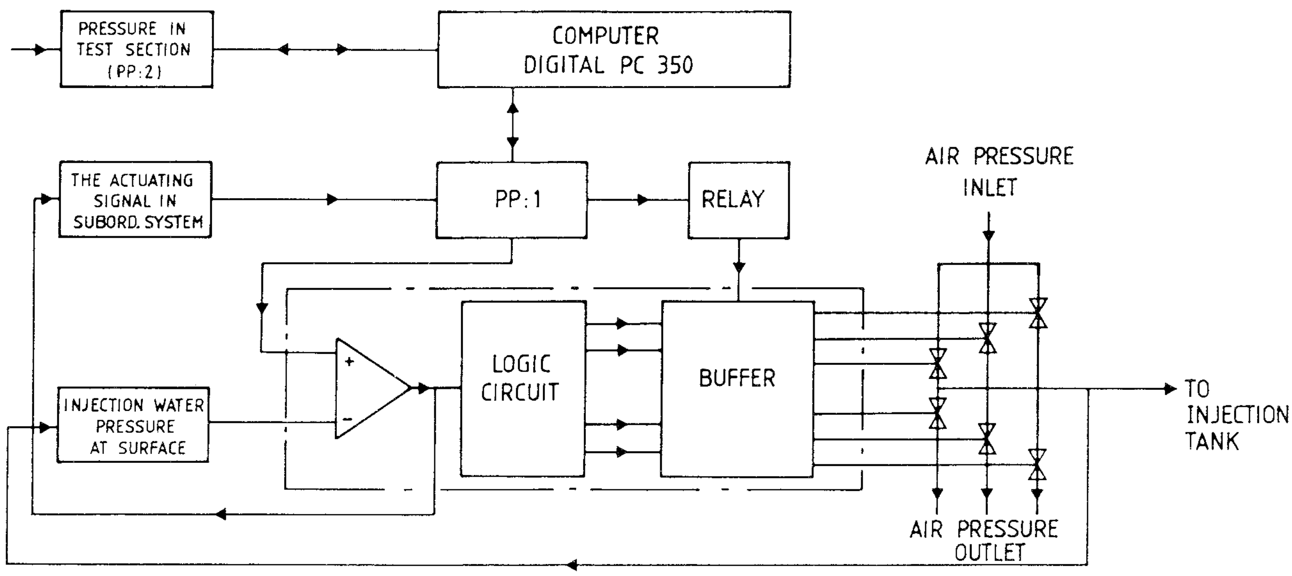


Figure 6.6 Pressure/flow regulating system.

Any injection pressure between c. 0.5 kPa and 900 kPa can be regulated (reduced range at great flow rates), but normally 200 kPa is used. The corresponding driving pressure at the surface is dependent on the flow rate as the pressure drop in the injection hose is flow-rate dependent. The accuracy of the pressure regulation system is ± 0.5 kPa.

All computer-operated valve functions in the system can also be manually operated from the measuring trailer via an electrical relay box.

6.1.4 Measuring instruments

Pressure transducers

For pressure measurements in the test section two piezoresistive transducers, Kistler type 4043 with a pressure range of 10 MPa are used. The unilinearity and repeatability of the transducer are better than 0.3 % and 0.1 % FSO, respectively. The transducers are mounted in the processor housing below the packers and connected to PP:2.

Similar transducers are used for measuring the packer pressure. Registration of the ground water level is performed by measuring the air pressure in a bubble pipe lowered to a specific depth in the borehole a few metres below the water level. The air drive pressure corresponds to the water head at the end of the pipe.

The barometric pressure is measured by a barometer transducer. All these surface pressure sensors are connected to the microprocessor unit PP:1.

Temperature sensors

Temperatures are measured at three points; the air temperature in the measuring-trailer, the injection water in the measuring trailer before entering the umbilical hose and the injection water in the test section. The sensors are connected to PP:1 and PP:2.

Flow meters

The measurement of flow rates is made by two different flow meters. One of them, Q1, is the Minimag flow meter manufactured by Fisher and Porter, while the other one, Q2, is Micro-motion model C6. They represent two strictly delimited measurement ranges:

Q1 : 0.09-7 l/min, acc ± 1.0% of rate
± zero stab. 0.1% FSO

Q2 : 0-0.1 l/min, acc ± 0.4% of rate
± zero stab. 9×10^{-5} l/min

The flow meter Q1 is always connected when flow measurement is performed. When the lower limit value 0.09 l/min for this flow meter is attained, the smaller flow meter, Q2, is automatically switched on. The total measurement range of the equipment will consequently be 0.1×10^{-3} - 7 l/min with continuous overlapping of measurements between the two flow meters. The flow meters are in connection with, and controlled by, the surface periphery processor PP:1.

6.1.5 Computer system - tasks and hardware

Tasks

The performance of an injection test is fully computer controlled. The task of the system is to collect, store and present measurement values, and to enable the operator to supervise and check the values during the test. Specific tasks are as follows:

* Collect c. 20 measurement quantities from the periphery processors.

* Correct certain measurement values according to a calibration curve and to process certain values in accordance with predetermined formulas.

* Display current measurement values on the computer screen.

* Upon request, display measurement quantities graphically on the monitor as a function of time.

* Register measurements on a diskette/Winchester in accordance with instructions given in advance.

* Apply control voltage in accordance with a predetermined mathematical formula on a D/A channel.

* Operate relays in conjunction with flow measurement.

* Operate, via relays, all valves needed in order to carry out a complete measurement sequence.

* Keep tabs on how much the umbilical hose has been fed down into the borehole.

* Regulate feed pressure sufficient to keep a constant overpressure down in the measurement section during the measurement process.

* Plot the measurement results after completed measurement.

* Emit an alarm in case of abnormal measurement values. The alarm may be constituted by a relay closing or by an acoustic signal.

In devising the system, the following overriding principles have also been applied:

* The system is to be simple to handle, so as to permit a person not accustomed to computers to perform data collection without special training.

* The system is to be flexible enough to permit the operator in the field to modify the function according to actual circumstances.

* The system is to permit simple extension with new functions when necessary.

Hardware

In addition to the computer the computer system includes two or more periphery processors, a plotter and a printer (Figure 6.7).

Computer

The system is operated by a desk top computer, Digital Equipment PC 350 or 380, with a 10 MByte Winchester hard disk unit and a floppy disk unit.

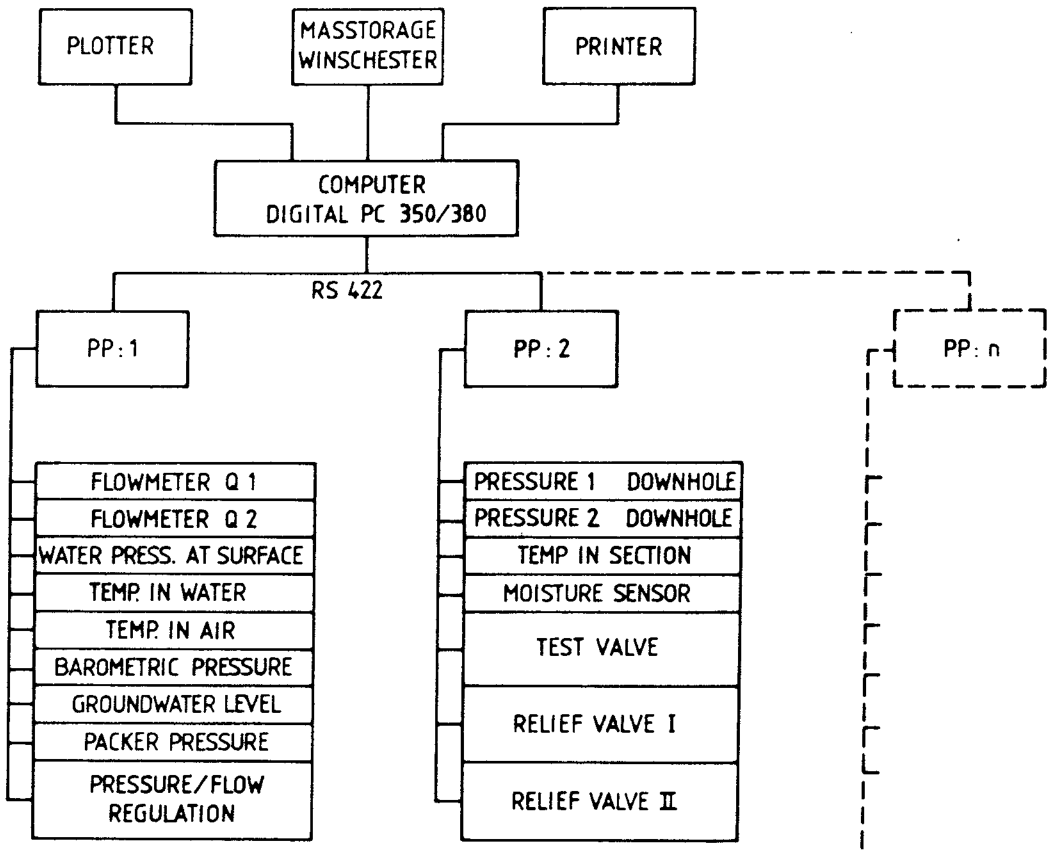


Figure 6.7 Block diagram of the computer system.

Periphery processor

Two or more microprocessor cards, called periphery processors PP:s, are connected to the computer via realtime interface RS-232/422.

The processor cards include an A/D converter giving a resolution of 0.1 kPa for a 1000 kPa pressure range. It also contains a D/A converter for two analog signals and a relay function for closing or breaking contacts.

PP:1 is mounted in the measurement trailer, controlling all regulation units and measuring sensors situated at the surface. PP:2 is mounted at the testing tool in a water-tight probe, controlling valves, pressure- and temperature transducers and a moisture sensor to protect the probe from water.

Plotter and printer

For drawing diagrams of processed data (see 6.1.6), a Hewlet Packard plotter, HP 7550A, with automatic paper feeding is used. The plotter is connected directly to the PC 350 computer. The printer Digital LA50 is also connected directly to the PC 350.

6.1.6 Computer system - software

The software includes two main programs. One measuring program used to perform a test and one plotting program used for the plotting of data from the data file.

Measuring program

The "WATER" program simultaneously performs three different main functions:

* controlling the measurement process
* showing the operator what is going on
* collecting measured data for subsequent evaluation

The control functions are included in the form of a sequence table where a complete hydraulic measurement cycle is automatically run through, once it has been initiated. The measurement cycle consists of an injection test immediately followed by a pressure fall-off test and is shown in the sequence table below.

For a normally performed test the "T" signifies minutes after the start of measurement, but can easily be changed to other times if wanted.

T = 0 Certain initial information, such as date, name of borehole, length of measurement section, etc, are stored.

T = 1 Relief valve I opens. Storage of measured data begins.

T = 2 Inflation of the packers. Controlling of the ground-water level system starts. Rapid storage of measured values starts (every other second). The large range flow meter connected and the hose pressuizred.

T = 3 Rapid storage of data stops.

T = 10 Checking that flow = 0 (i.e. no leaks). The cannular test valve is opened. Automatic exchange of flow meters initiated.

T = 15 Cannula test valve closes. The flow is stored for later check.

T = 25 Closing of relief valve. Repeat check that flow = 0. The large range flow meter is connected.

T = 29 Rapid storage of data is started.

T = 30 The inflation pressure in the packers is shut in. Monitoring of packer pressure continues. The test valve opens, starting the injection test.

T = 31 Automatic change of flow meters initiated. Regulation of the injection pressure initiated.

T = 32 Rapid storage of data stops.

T = 149 Rapid data storage starts.

T = 150 Regulation of the injection pressure stops. Test valve closes and the injection test stops while the pressure fall-off test starts.

T = 152 Rapid storage of data stopped. Checking that flow = 0.

T = 170 Cannular test valve is opened.

T = 174 Checking that cannular flow is the same as previously. Flow meters disconnected. Test of pressure decrease in the test section initiated. If the pressure decrease is sufficiently slow, the test can be interrupted, i.e. the computer jumps to T = 270.

T = 270 Packer pressure released. End of pressure fall-off test. Packer is deflated.

T = 300 The measuring cycle is completed. Data storage stops. Comments may be entered on the data file.

For normal measurements the operator needs only to initiate the measurement sequence. An acoustic signal warns if something is wrong or when the measurement sequence ends. However, the operator is always able to intervene in the sequence and simply cut out the automatic function.

Plotting program

The program for plotting can produce all necessary diagrams (Table 6.1). One of the diagrams gives a summary of the test and preliminary hydraulic conductivity as well as a summary of the borehole information. The diagrams give surveyable information on all measured values. The B-, and C-diagrams correspond to different theories of evaluation.

The data collection and the plotting can be done at the same time, i.e., it is possible to plot the results from one test in the background while making another test.

For test purposes two additional types of plots are available. The operator can plot any of the measurement quantities as a function of either time or any other measurement quantity. Each quantity can be obtained with linear, logarithmic, squared, square root and inverted scale. The computer then automatically proposes a scale for maximum utilization of the paper, displaying the result on the screen. After possible adjustment of the scale the curve can be drawn on the plotter. These two types of test plots cannot be performed in background, but may be done at the same time as another test is measured.

Table 6.1 The plotting program include the following diagrams.

A-plots (background information about the test performance):		
pressure (test section)	-	real time
pressure (surrounding section)	-	real time
injection flow rate	-	real time
packer inflation pressure	-	real time
barometric pressure	-	real time
groundwater level	-	real time
temperatures	-	real time

Continued on the next page

Table 6.1 Continued

B-plots (evaluation of injection test)	C-plots (evaluation of fall-off test)
P — log t	P — log (dt/(tp+dt), dt
1/Q — log t	P — log (dte), dt
1/Q — $\sqrt{t}$, t	P — $\sqrt{dte}$, dt
1/Q — $\sqrt[4]{t}$, t	P — $\sqrt[4]{dte}$, dt
Q — $1/\sqrt{t}$, t	P — $\sqrt{t_{pp} + dt} - \sqrt{dt}$, dt
log (Q) — log t	P — $1/\sqrt{dt} - 1/\sqrt{t_{pp} + dt}$, dt
log (1/Q) — log t	log dP_p — log dt
	log dP_p — log (dte), dt

Note:

P = pressure (test section)
Q = flow rate
t = injection test time
dt = fall-off test time
t_p = total injection time
t_{pp} = corrected t_p ($t_{pp} = V_{tot}/Q_p$)
V_{tot} = total injected volume of water
Q_p = flow rate when the injection stops
dP_p = differential pressure in relation to the pressure at the injection stop
dte = $t_{pp} \times dt / (t_{pp} + dt)$

6.2 Pipe string equipment

6.2.1 General layout

The pipe string equipment used in hydraulic injection tests is developed by the Swedish Geological Co. The system consists of the following units (fig 6.8)

* down hole equipment
* water injection system
* measuring instruments
* data collection system
* hoisting equipment and electrical power supply

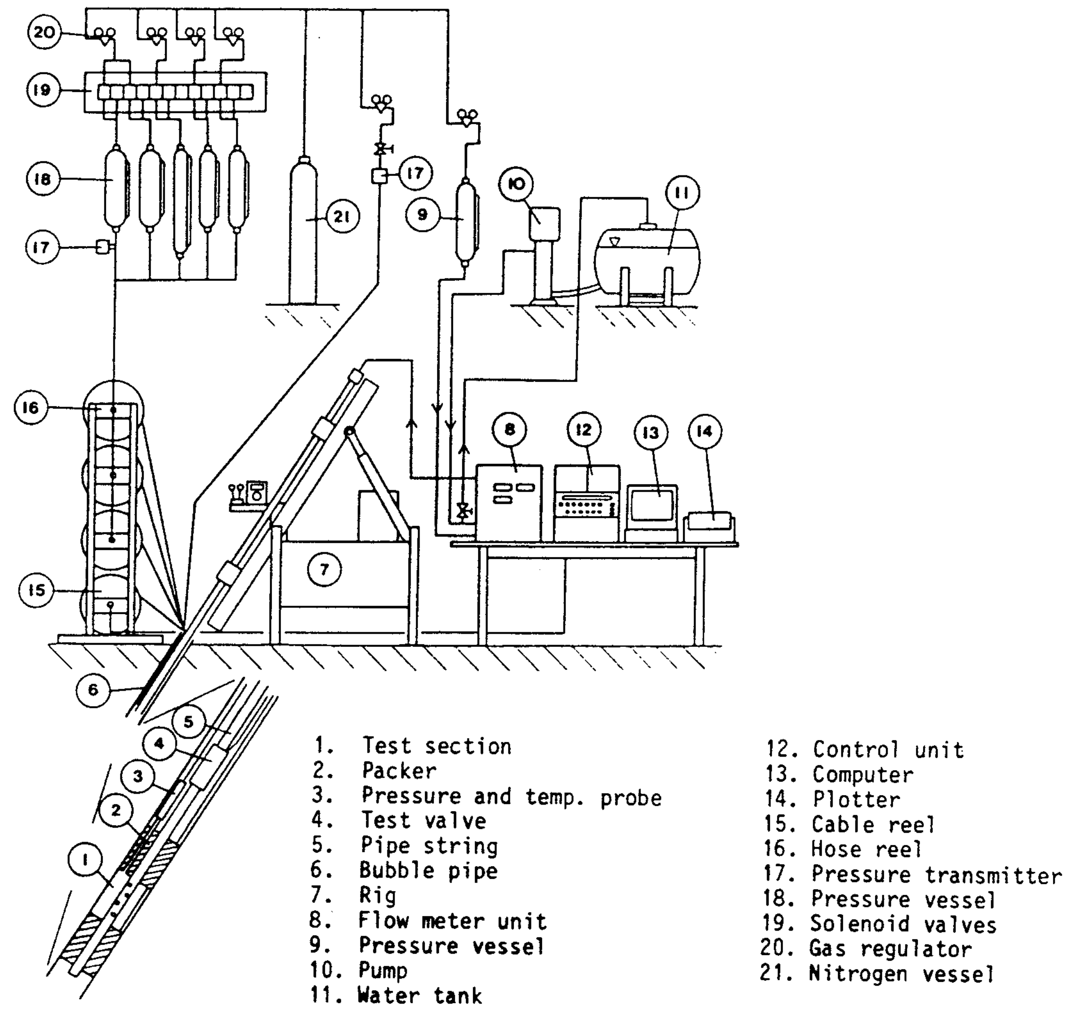


Figure 6.8 Principal layout, Pipe string equipment

Hydraulic tests with the pipe string equipment may be done from the surface as well as from tunnels. During tests from the surface the equipment is installed in an easily mounted aluminum house.

In a hydraulic injection test the water is pumped from the surface through the pipe string down to the test section which is sealed off by packers. Flow rate and water temperature are registered on the surface and pressure and water temperature are registered in the test section. A hydraulic injection test is normally performed with constant head, which means that the pressure down in the test section is kept constant by regulating the water flow.

6.2.2 Downhole equipment

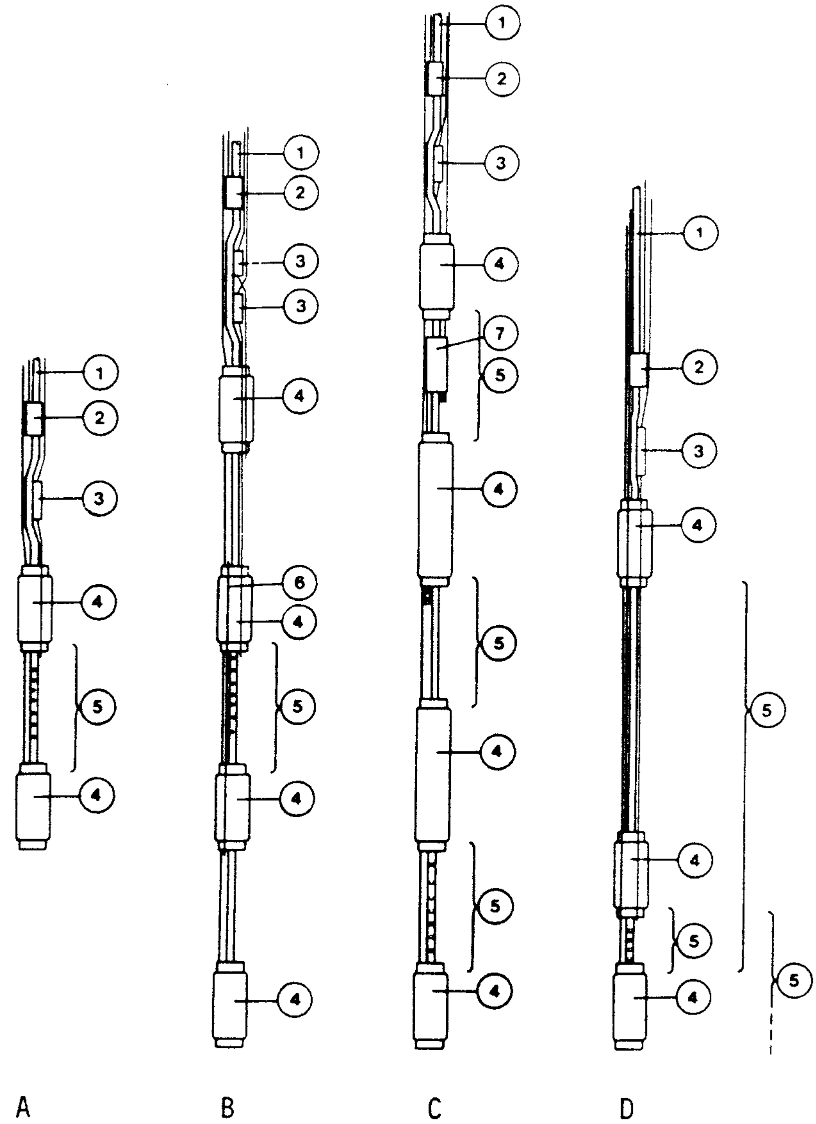
The downhole equipment consist of packers, test valves pressure and temperature transducers, pipe string and hydraulic hoses. These units may be shifted into a number of configurations. Four testing tool configurations are shown in Figure 6.9.

The most commonly used test configuration, A) consists of a straddle packer system with a hydraulically operated test valve, which can shut off the communication between the pipe string and the test section. The pressure in the test section is measured by a transmitter. In test configuration B) a four packer system may be used for tests in fractured parts of a borehole. With this system pressures in the surrounding sections are registered in order to check any eventual leakage around the packers. If only two pressure transmitters are used, the two surrounding sections are connected together with a pipe.

Tests of short duration and low measurement limit still require a relatively long packer sealing period. The testing tool for three test sections, C) in Figure 6.9, consists of a hydraulically operated three-way valve, two outer packers with 1 m sealing length and two inner packers with 2 m sealing length.

- It is specially designed for short duration tests, section by section, with a section length of 2 m.

After simultaneous sealing of all packers the water flow is injected into the three sections in sequence by using the three-way valve. The equipment is then lowered two meters and the same procedure is followed. After the second test sequence the equipment is lowered ten meters, and the total testing time of a borehole might be considerably shortened.



1. Pipe String
2. Test Valve
3. Pressure Probe
4. Packer
5. Test Section
6. Pipe (hydraulic connection between surrounding sections)
7. Three-way Valve

Figure 6.9 Four different configurations of the testing tool.

In some investigations it is of interest to perform tests either with a "short" or a "long test section", or to perform single packer tests without lifting the test tool out of the borehole for shifting the test configuration. With configuration D) a test with a "long section" is created by sealing the upper and the lower packer. In a test with a "short section" all the packers are sealed, while for a "single packer test" only the central packer has to be sealed.

Packers

The test section is usually sealed off by two packers separated by performed pipes. The packer rubber, reinforced with canvas cord positioned crosswise is attached to a stainless steel frame by means of compressed sleeves. Two or more tubes pass through the packer, a larger one for injection water to the test section, and the smaller to function as pressure line to the pressure transducer and as packer inflation tubes. By pressurizing the packers the rubber expands against the borehole wall and the test section is sealed off from the other parts of the borehole.

The packers are connected to a pressure vessel via hydraulic hoses. The system is filled with water or antifreeze liquid. For the sealing of the packers the vessel is pressurized at the top by regulated nitrogen gas.

The packers seal at an overpressure of 0.4 MPa, but in order to achieve as rigid section boundaries as possible an overpressure of 1.5 MPa is used. The pressure is controlled by a pressure transducer connected to the pressure vessel. Separate packers are designed to work in 56 mm, 76 mm, 115 mm and 165 mm boreholes.

Downhole valves

Test valve

In order to shut off the test section so as to permit piezometric pressure to be measured, to evacuate the air in the pipe string without influencing the section, to permit an immediate start and stop of the injection test and for the subsequent pressure fall off test, a hydraulically controlled test valve is used (Figure 6.10). The valve is located between the pipe string and the testing tool.

In the test valve a spring-loaded slide closes in the pressure state and opens when pressurized. In the same way as with the packers, gas overpressure is set for operating the water-filled hydraulic unit consisting of a pressure vessel and a hydraulic hose.

1. Injection water connection
2. Operation water connection
3. Slide
4. Return spring 1
5. Return spring 2 (B only)
6. Channel in slide (B only)
7. Filter (A only)
8. Injection port 1 (B only)
9. Injection port 2 "
10. Injection port 3 "

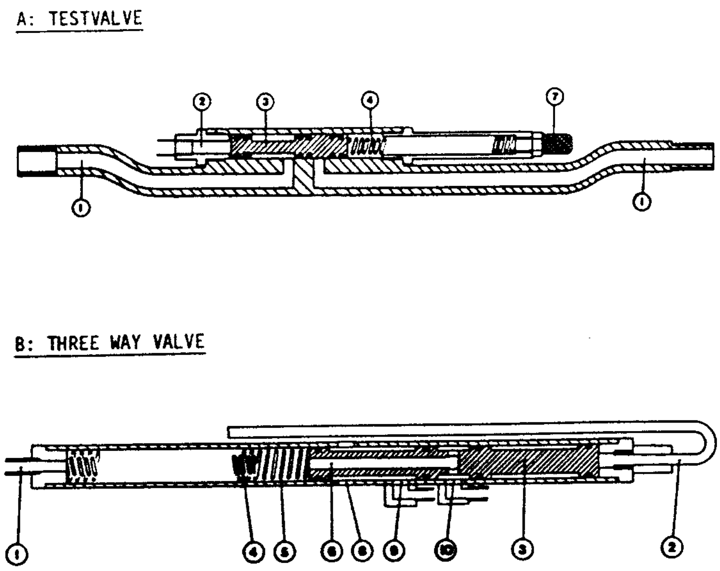


Figure 6.10 Downhole valves

Three-way valve

A three-way valve is used in the short duration detail measurement earlier presented. The valve is positioned in the upper test section Figure 6.9. The valve is hydraulically regulated so that the spring-loaded slide moves to the actual position by application of one of three specific-regulated nitrogen gas overpressures in an otherwise water-filled system consisting of two pressure vessels and a hydraulic hose (Figure 6.10).

Pipe string

The injection water is led via the pipe string down to the measurement section. The pipe string is also a carrier of the testing tool.

There are two different types of pipe strings. One is composed of 2 m (± 1 mm) long steel pipes with an external and internal diameter of 20 and 10 mm, respectively. With male respectively female M 16 threads on the ends of each pipe and sealing O-rings, a completely tight pipe string is achieved without change of interior or exterior dimensions. This pipe string can take a load of approximately 4 tons.

The other pipe string is made of aluminum with specially designed threaded couplings of stainless steel and O-ring sealings. This pipe is 3 m (± 1 mm) long and has an external and internal diameter of 33 mm and 21 mm, respectively, without any reduction through the couplings. The maximum load is approx. 9 tons.

Hydraulic hoses

The hydraulic hoses for the packer and the test valve systems are Alencoflex HRI, a 1/4" steel-reinforced high-pressure hose (operating pressure 29 MPa). The hoses, which can be jointed, are 450-650 m long and wound on hose reels with a rotating quick-connection in the center. In the packer configurations the lines between the packers and the pressure transducer are polyamide tubing (Tecalan TR 6/4) with an operating pressure of 4.5 MPa.

6.2.3 Water injection system

Water for the hydraulic injection tests is normally taken from wells drilled in the same rock formation and pumped through a filter where particles of 0.5 µm are separated. The water is stored at the test site in 1,000 l tanks where the temperature is kept constant by an electric heater.

During the injection test the water is pumped through a combined flow meter and regulator unit (flow meter unit), and via a copper pipe to the pipe string. The pump used is a Grundfos centrifugal pump Type CP 2-200 or CP 2-120 with a flow capacity of 20 respectively 45 l/min at 1.0 MPa pressure increase.

If the flow rate is small (< 0.1 l/min) the water injection driving force can be changed from the pump to a nitrogen gas regulated pressure vessel.

The flow meter unit shown in Figure 6.11 consist of two mass flow meters, described in 6.2.4. The flow meters are connected in series and the flow through the small one may be regulated with two different sizes of regulation and shut-off valves while greater flows through the other one are regulated by a single set of valves. The maximum line pressure of the flow meter unit is 5 MPa. The flow rate of each flow meter, the inlet and the outlet pressures in the flow meter unit are presented on four separate displays with 4 1/2 digits. The temperature of the water in the flow meter unit is also measured (see 6.2.4).

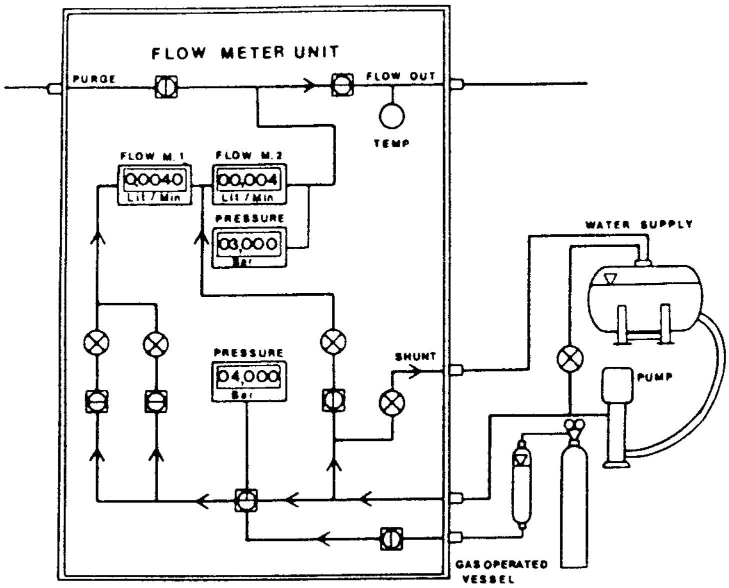


Figure 6.11 Water injection system

6.2.4 Measuring instruments

<u>Pressure transducers</u>

The pressures are measured with piezoresistive transducers, integrated by means of electronics to transmitters (Druck PTX). The transmitter supply power is 9-30 Vdc (unregulated) and the current 4-20 mA is propotional to the measured pressure. In this way the cable length has no effect on the transmitter signal. Acording to information from the manufacturer the accuracy of the pressure sensors (combined linearity, hysterisis) is better than 0.1%.

In order to control the transmitters a portable calibration unit with a quartz crystal pressure transducer is under development.

One, two or three of the transmitters are placed in the testing tool just above the packers (PTX 160, 13.5 MPa), one of them connected to the test section while the others are used for measuring pressures in the surrounding sections (see 6.2.2).

The signal from the pressure transmitter is received at the surface by the data collection system. The pressures are displayed with 5 1/2 digits, giving a resolution of the pressure measurements of 0.1 kPa.

The packer pressure is measured in the pressure vessel for the packers (PTX 110, 4 MPa).

The groundwater level in the borehole is registered by measuring the air pressure in a bubble pipe lowered to a distinct depth in the borehole a few metres below the groundwater level (PTX 110, 200 KPa).
The barometric pressure is measured with PTX 100 ABS 120 KPa.

<u>Flowmeters</u>

As mentioned earlier, the flow rate is measured with two mass flow meters (Micromotion) in the flow meter unit. These flow meters are operated by vibrating a U-shaped sensor while the water flows inside. The combination of fluid and tube vibration creates a force which is detected by position sensors. This force is directly and linearly proportional to the massflow rate. The flow rate signal is converted to a signal of 4-20 mA.

The two flow meter models used are Micromotion D 6 and D 25 with the following ranges:

D 6: 0 - 1 l/min acc. $\pm$ 0.4 % of rate
$\pm$ zero stab. 9×10^{-5} l/min

D25: 0 - 40 l/min acc. $\pm$ 0.4 % of rate
$\pm$ zero stab. 4.5×10^{-3} l/min

Calibration of the flow meters is performed at regular intervals at the test site.

Temperature sensors

Four temperature sensors are used in the system, of which one registers the temperature of the water in the flow meter unit, and another one registers the air temperature around the equipment. Two of the pressure transmitters in the testing tool also include temperature sensors. All temperature sensors are of the semiconductor type with integrated electronics in the temperature transmitters. As for the pressure transmitters, the power supply is 9-30 V dc (unregulated) and the current is proportional to the absolute temperature. The range of the temperature transmitter is -55 - +130^{o}C; the accuracy is 1^{o}C while the resolution of the measurements is 0.5^{o}C.

Signal cable

For the transmission of pressure and temperature signals to the data collection system a 6-wire cable of c. 800 m length is used. The signal cable is shielded, polyurethane isolated and has submersible connections in both ends. The cable and connections seal against water pressures up to 35 MPa and are designed to permit jointing when necessary.

By means of specially designed cable-splitting devices one, two or three combined pressure and temperature transmitters may be connected to the signal cable. Registration is limited by the six-conductor cable to one of the optimal configurations:

* three pressures, and one temperature
* two pressures and two temperatures

6.2.5 Data collection-hardware

The data collection system consists of a desk top computer, a control unit and a plotter, see Figures 6.12 and 6.13. The control unit consists of power supply, multimeter, scanner, display (three pressure + time), keyboard and relay unit for solenoid valves.

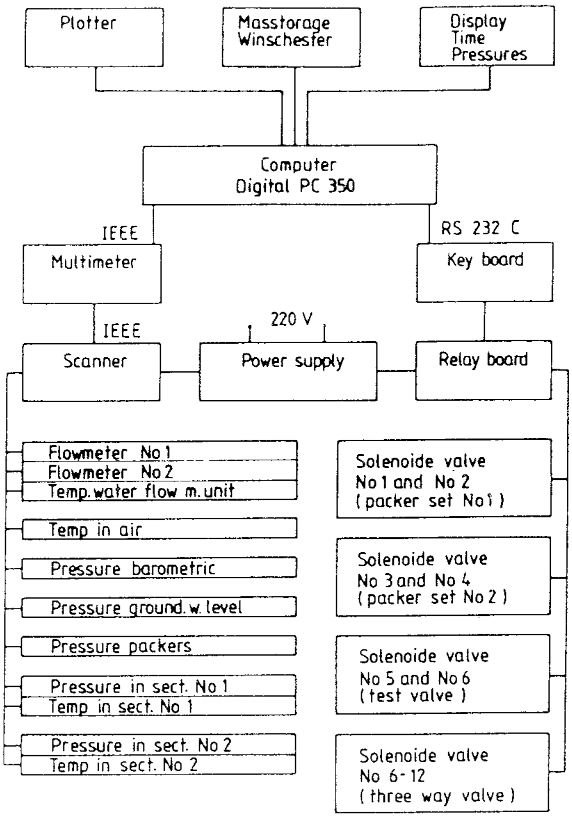


Figure 6.12 Block diagram of data collection system.

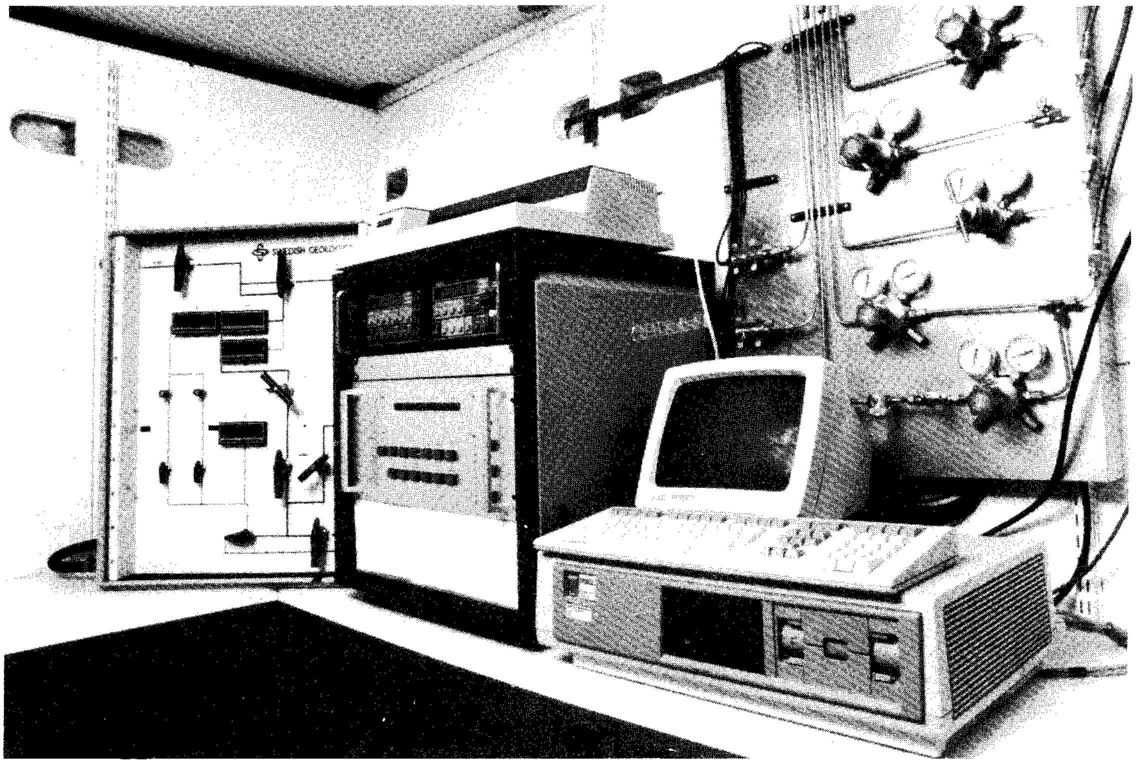


Figure 6.13 Data collection system and flow meter unit.

Computer

The central unit of the collection system is a desk top computer, Digital Equipment PC 350 or 380 with a 10 MByte Winschester hard disk unit and a floppy disk unit.

Scanner and Multimeter

All the measuring sensors are connected to a scanner, Kiethley 705, multiplexing up to 20 different 2-pole channels. A multimeter, Kiethley 195, measures the current from the different sensors with up to 5 1/2 digits resolution. The multimeter and the scanner are connected to the computer through the IEEE interface. The scanning intervals, by which sensors shall be measured, and the resolution of the different measurements are different during the test program. All these are controlled by the computer measuring program (described in 6.2.6).

Key board

The key board unit has two different functions, working in parallel at the same time. When a key is pushed, a periphery processor in the control unit activates the solenoid valves on the different pressure vessels which regulate the test valve, the three way valve and the packers. At the same time it sends a message to the computer indicating a test phase in the test program. The key signal lamps which are turned on or off by the periphery processor on command from the computer show the test phase, packer inflation and valve operation.

By means of this two function system the packer and valve operation can be performed without a computer.

Display

The display showing time, phase number, injection pressure and absolute pressure in the test section are controlled by the computer via the RS 232 interface. The pressures are shown with a resolution of 0.1 kPa. The time is set at zero at every phase shift.

Plotter

For drawing diagrams of processed data (see 6.2.6) a Hewlet Packar plotter, HP 7475 A, with six pens is used. The plotter is operated from the computer (plotting program).

6.2.6 Data collection - software

Injection test program

A constant head injection test with a fall off test is normally divided into eight different phases as follows:

Phase 0 Registration of pressures at the test level with deflated packers.

Phase 1 Choosing of reference pressure for the test.

Phase 2 Inflation of packers.

Phase 3 Closing the test valve. In this phase the pipe string and tubes are evacuated from air bubbles and the tightness of the whole pipe string is checked.

Phase 4 Injection phase. The injection starts when the test valve is opened to the test section. The pressure in the test section (normally 200 kPa above the reference pressure) is regulated on the flow meter unit.

Phase 5 Fall-off phase. The fall-off phase starts when the test valve is closed, the pressure is registered and the time is indicated.

Phase 6 Stop of fall-off phase.

Phase 7 Deflating of packers.

Phase 8 Stop of the test. Comments on the test are typed in and the computer makes itself ready for the next test.

Computer programs

The application consists of two different programs. One program is for collecting measured values and one is for plotting of diagrams for analysis.

Collecting program

The collecting program begins with some questions to the operator on measurement background data; calibration-constants for the sensors, borehole location, test section location, type of test, personnel and equipment involved. After that the program collects values without needing an operator.

The time interval between two scans is 2 seconds in the beginning of the test, but will become longer in a semi-logarithmic way.

Most of the sensors are measured with 4 1/2 digits but the pressures in test sections are measured with 5 1/2 digits.

Plotting program

The plotting program for the pipe string system is identical to the plotting program for the umbilical hose system (see 6.1.6 and Table 6.1).

6.2.7 Hoisting equipment and electrical power unit

Hoisting system

The RA 2100 is a hoisting rig specially designed for the pipe string system. The rig is adjustable for boreholes of different inclinations (0-90^{o}) and can be used on surface as well as down in tunnels, see Figure 6.14.

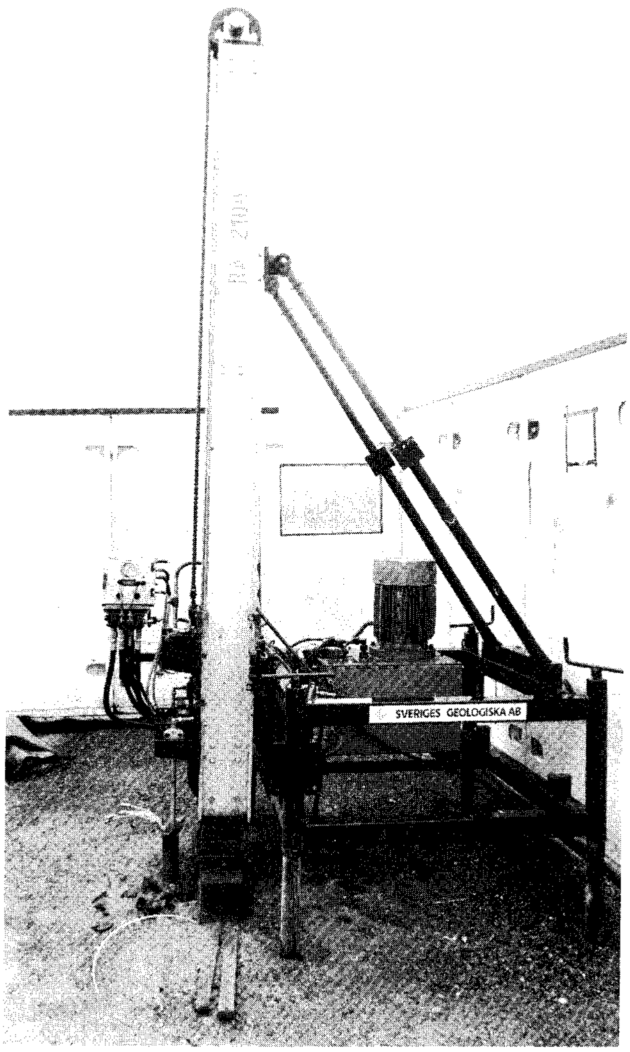


Figure 6.14 The hoisting rig RA 2100.

The rig is electrically powered and hydraulically controlled. A hydraulically operated chuck clamps against the pipe string. The equipment in the borehole is then lifted or lowered by means of the feeding unit driven by an orbit motor. The maximum feeding length is 2.1 m and while jointing additional pipes to the pipe string it is locked by means of a second chuck. A built-in safety system prevents more than one chuck at a time to be opened. The lower chuck is opened hydraulically but closed by a spring. If the hydraulics or power fail it will grip the pipe. There is also a load measuring system on the rig visualizing the actual weight of the pipe string. When the load exceeds a preset value, the feeding system will stop immediately.

The hoisting equipment has a lifting capacity of 3.2 ton and pushing capacity of 2.6 tons. The feeding speed including pipe-jointing, taping of hoses and cable around the string is 60-80 m/h. The power needed is 7.5 kW, 380 V.

Electrical power unit

As the electrical network normally is not available at the test site, a mobile electrical power unit is used. The electrical generator is driven by a Volvo diesel engine, automatically regulated and designed for continuous operation. The maximum output from the 380 V generator is 15 kVA. The unit also includes a transformer for 220 V power supply.

7. EQUIPMENT FOR PIEZOMETRIC MEASUREMENTS

Data on the hydraulic head is important information as a basis for describing and calculating groundwater flow in a geological formation. In order to collect reliable data for this purpose two different monitoring systems have been developed: one for registration of the groundwater table and another one for monitoring pressures in several sections in deep boreholes.

7.1 Groundwater table monitoring system GRUND

The specially designed groundwater table monitoring system GRUND, developed by IPA-Konsult AB, consists of the following parts (Figure 7.1):

* monitoring probe
* packer
* wire, hoses and cable to the surface
* portable computer

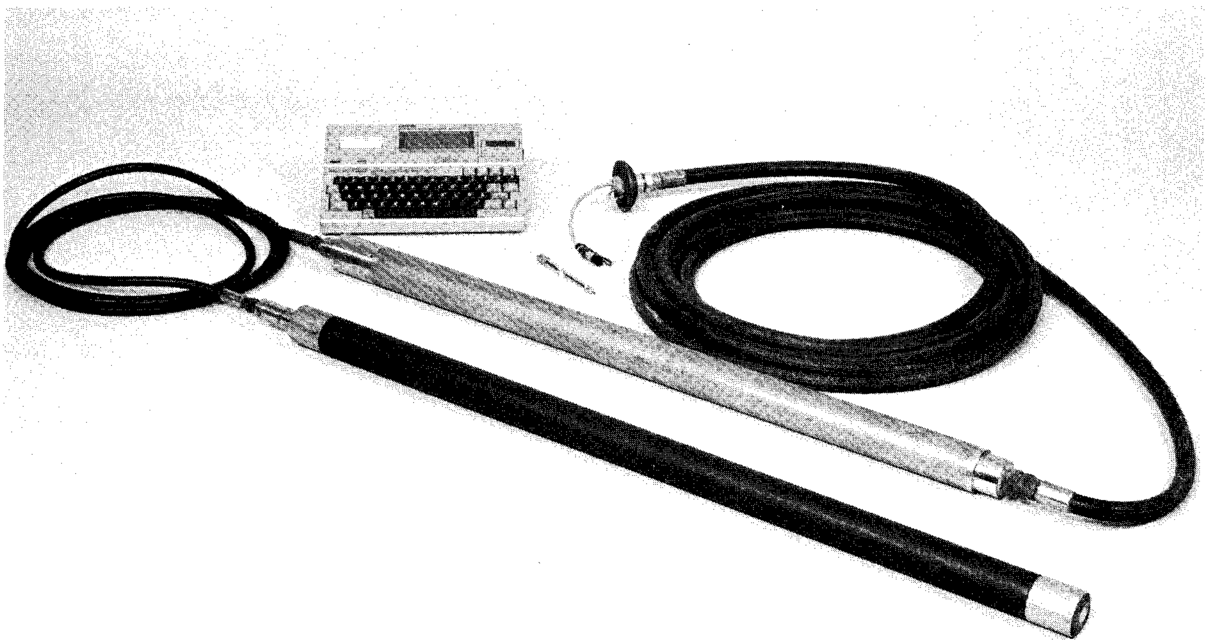


Figure 7.1 Components of the groundwater table monitoring system GRUND.

The monitoring probe is a microprocessor-controlled unit designed to measure the groundwater level in a borehole. For deep boreholes a packer is integrated to the unit in order to isolate the upper part from the rest of the borehole. Installed 5-10 m below the groundwater table the instrument can be left for several months without maintenance (Figure 7.2). The equipment is not visible when the borehole cap is mounted. The portable computer is used only for initiating the registration process and for dumping of data.

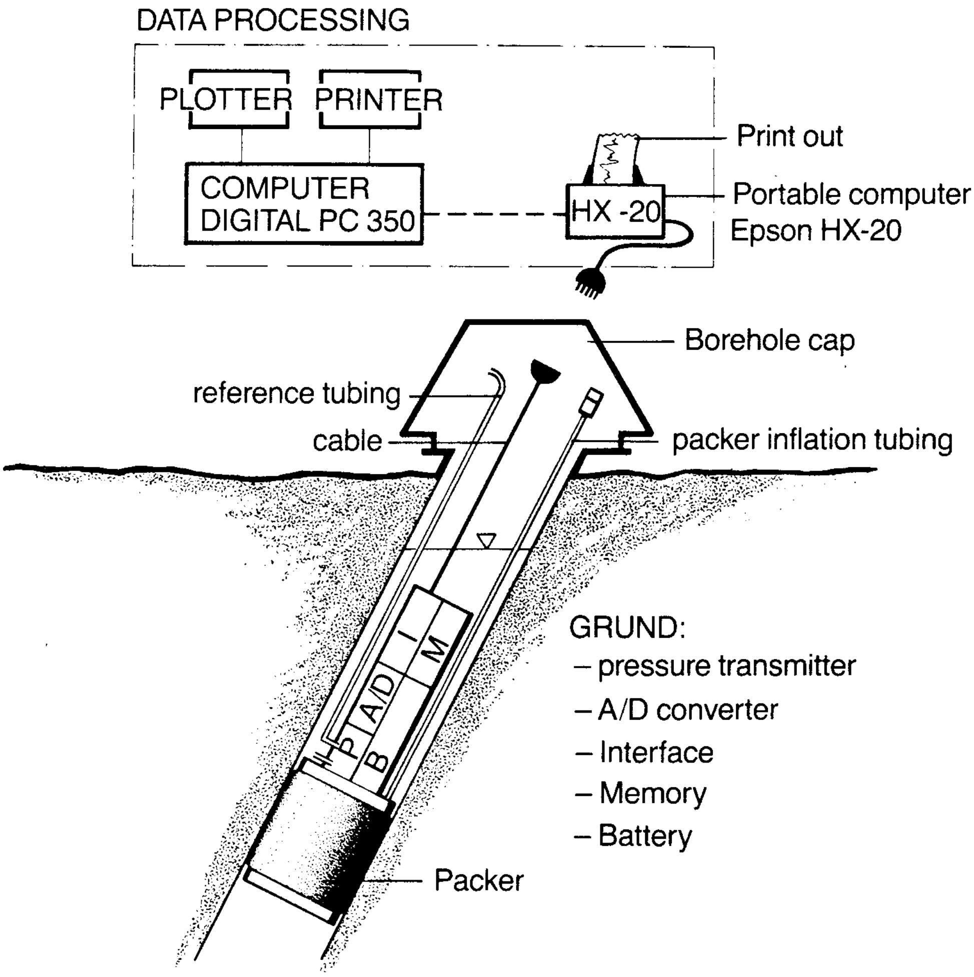


Figure 7.2 Principle design of the GRUND system.

7.1.1 Downhole instrument

The monitoring instrument is designed for 56 mm boreholes, but greater boreholes may be equipped easily by changing the packer.

The GRUND unit is encapsulated in a waterproof probe together with accumulators and a pressure gauge. It is based on a CMOS processor and an integrating A/D converter. A 4 kByte RAM provides data storage and an EPROM circuit holds the program. The unit also contains a crystal controlled osillator, a counter that can be fine tuned to a proper frequency and a DC/DC converter. The circuit board is equipped with protective circuits against electrical damage such as lightning and improperly connected cables.

The supply voltage for the DC/DC converter, the A/D converter and the gauge is normally turned off and will be turned on when a measurement is to be made. During measurement the current consumption (< 5 mA) is dominated by the pressure gauge while the standby consumption between measurements is very small (< 0,05 mA).

The probe is vented via a hose to the surface, which means that the registered pressure values represent the groundwater head. For a pressure range of 10 m water column the resolution of the readings is 4 mm. Other transducers may be connected. The temperature range of the probe is 0 - 30 ^{o}C, but normally the temperature in the boreholes is very constant.

The pressure tubing for the packer inflation and the electrical cable is situated inside the ventilation hose. The accumulator in the probe may be recharged in the downhole position.

7.1.2 Measuring program

The unit measures and registers the groundwater levels at preset time intervals. A special storage technique is used: compulsory data storage at preset time intervals, with conditional data storage between these intervals. This means that every measured value that differs from the last stored value by at least the amount of a given limit, also is stored.

The 2096 most recently collected values are stored in the memory, and depending on the fluctuations of the groundwater the corresponding measuring period may be several months.

7.1.3 Communication and data presentation

Stored data in the monitoring probe may be dumped to a portable computer, Epson HX-20. The communication is handled by a serial I/O channel, 300 baud, via the cable to the surface.

The computer is also used for starting measurements and checking certain functions such as clocks and accumulator voltage. The software consists of seven self-instructing programs:

"Fetch"

Fetches the status message and all the data stored in the GRUND unit. The information is stored in the memory of the Hx-20 together with the time of fetch operation. The RAM FILE of the computer will contain all the data.

"SIO"

The Hx-20 acts as a terminal. The operator can use the GRUND commands. The characters are transmitted from the keyboard and the answers are displayed on the LCD display.

"Tape out"

Data stored in the RAM FILE is saved on a microcassette.

"Printer"

Data from the RAM FILE is listed and simply plotted by means of the built-in printer.

"Read tape"

Data stored on a tape cassette is read to the RAM FILE.

"Start"

Enter the measurement interval, the interval between compulsory storages, and the limit value for conditional storage.

"Export data"

Data files can be transferred to another computer.

For the evaluation process stored data will be transferred to the desk top computer Digital Equipment PC 350. A plotting program enables the groundwater data to be presented as groundwater pressures, groundwater heads or levels related to any chosen reference level.

7.2 Multichannel piezometric system, PIEZOMAC II

The multichannel piezometric system PIEZOMAC II is developed by Swedish Geological Co and designed to measure the hydraulic head in five different sections simultaneously in up to eight boreholes (Figure 7.3).

The sections is sealed off by means of packers, and extra packers may be used to arrange blind sections between the sections chosen to be measured. This will avoid interference from vertical water flow in the borehole as well as focus the measurements on sections of special interest.

Data transfer can be made via radio and a modem to the telephone network. Such operations as reprogramming and transfering of measured data to a host computer are then possible. The system has very low power consumption, and the batteries may be charged with solar cells. This enables long field operations.

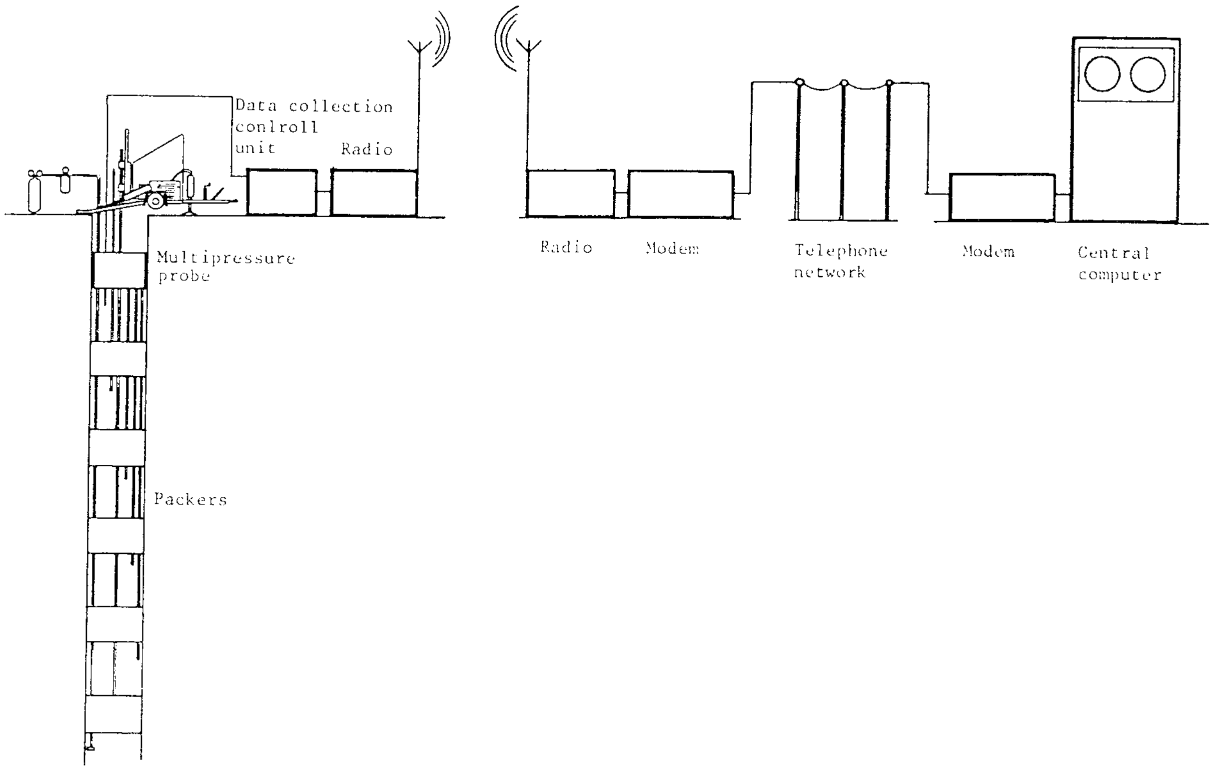


Figure 7.3 PIEZOMAC II system, principal overview.

The multichannel piezometric system may also be used for monitoring interference tests, which will be described in 7.3.

7.2.1 General layout

The PIEZOMAC II system contains the following main units (Figure 7.4):

* data collection and control unit
* multipressure probe
* analog probe
* packers and pressure tubings
* data transfer and communication unit
* solar cell
* hoisting device

In the following text, the multipressure probe, the packers and pressure tubings are described under downhole units, while the data collection and control unit also describe the solar cell.

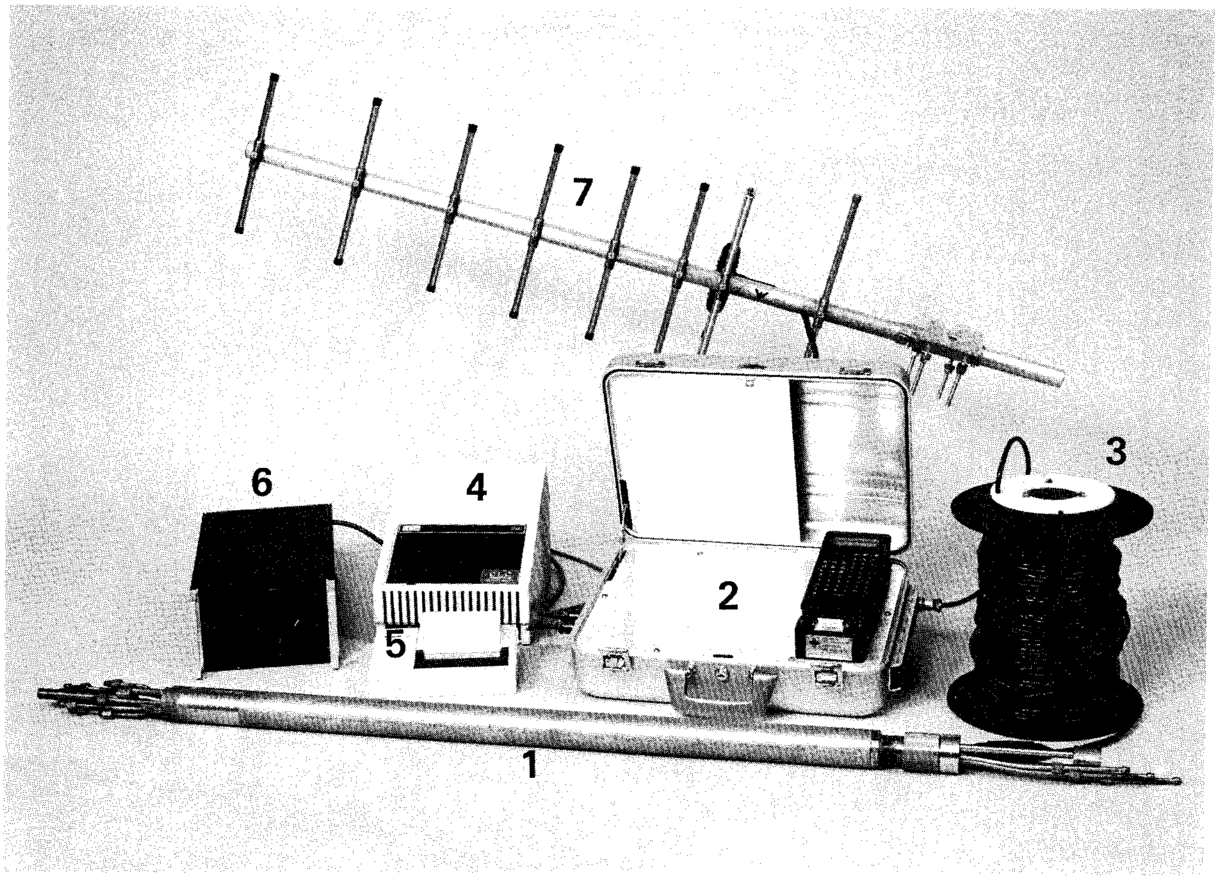


Figure 7.4 The components of the PIEZOMAC II system.
1. Multipressure probe, 2. Data collection and control unit, 3. Signal cable, 4. Data recorder 5. Matrix printer, 6. Radio, 7. Antenna

7.2.2 Downhole units

The multipressure probe is designed to measure variations of hydraulic head in five different sections with one single pressure transducer. Errors caused by individual differences between transducers can then be avoided.

The downhole system is designed for 56 mm boreholes but larger boreholes may be easily equipped by changing the packers. An optional design of the downhole units enables up to 9 sections to be measured in boreholes with a diameter of 76 mm.

Packer system

The measuring sections are sealed off by specially designed packers with five feed-through pipes for the connection of pressure tubings. These tubings transmit the different sections to the multipressure probe.

The packers are separated by aluminium string, which is also used for lowering the equipment in the borehole. The multipressure probe is positioned above the uppermost packer.

Multipressure probe

The multipressure probe contains a multiport valve, a pressure transmitter, A/D converter, valve control and interface for serial communication with the data collection and control unit, all mounted inside a waterproof housing (Figure 7.5).

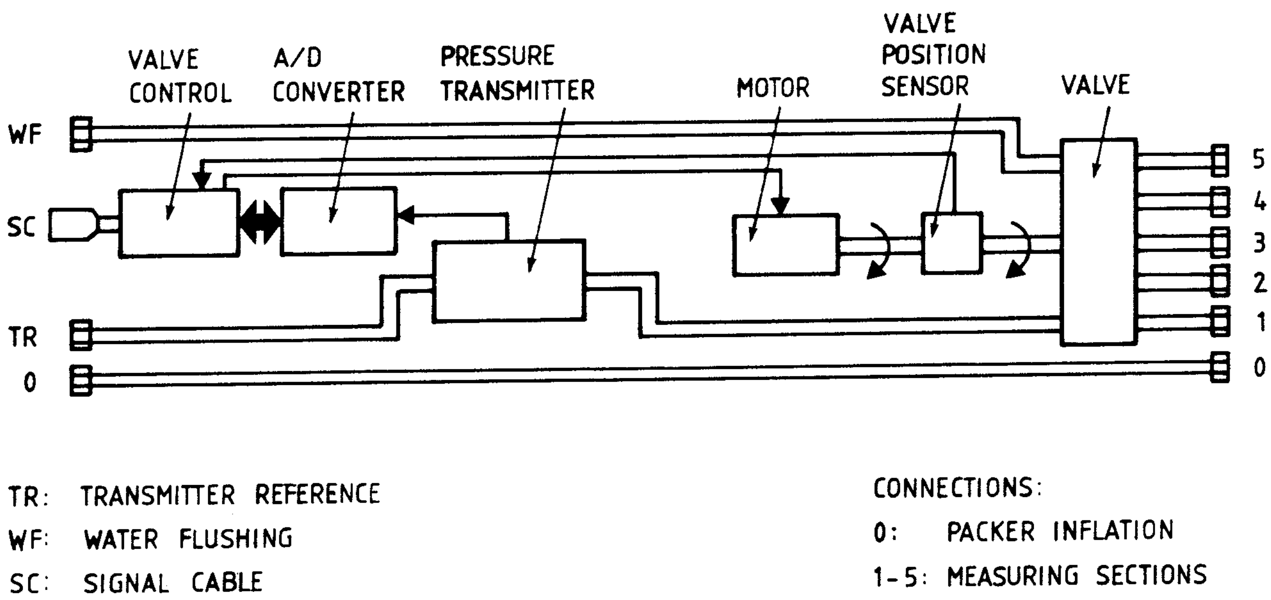


Figure 7.5 Multipressure probe, principle design.

By means of the multiport valve, one of the incoming five pressures is transmitted to the pressure transmitter. The electrical valve is operated on command by the surface unit. The valve position is controlled by a special sensor.

The pressure is measured by a pressure transmitter DRUCK PTX 120/WL differential, with a pressure range of 700 kPa, accuracy of 0.1% of full scale. Other transmitters may be connected. The probe is vented to the surface via a pressure tubing which means that the pressure is monitored with reference to barometric pressure. The pressure signal is converted from analog to digital with a resolution of 60 Pa (6 mm water column).

Pressure data and all other communication with the data collection and control unit are transmitted via an RS-232 C interface, 300 baud.

In order to provide high precision measurements, all air bubbles have to be released from the pressure tubings between the section and the probe by flushing with water.

The probe is placed below the groundwater level at a depth given by the maximum predicted amplitude of the pressures, normally 30-50 m.

Other technical specifications of interest:

Weight:	10 kg
Size:	1540 x 51 mm
Temperature range:	0^{o} to $50^{o}C$
Power supply:	15-30 V, < 250 mA
Cable length:	100 m (normal), 1000 m (maximum)

7.2.3 Analog probe

When measuring hydraulic head and in interference test applications (see 7.3) it may sometimes be of interest to measure other parameters, e.g. air pressure and water flow. For this purpose an analog probe is developed for measuring analog parameters in a similar way as for the multipressure probe.

With the analog probe up to eight independent analog signals from transmitters or transducers can be collected. The connection to the data collection and control unit is the same as for the multipressure probe. The transmitters connected can be powered from the central unit via the analog probe.

Technical specification

Weight:	7 kg
Size:	300 x 400 x 200 mm
Temperature range:	-25°C to 70°C
Analog Input	8
Signal	+/-10 V ot 4(0)-20 mA
Resolution	14 bit + sign
Drift temp.	5 ppm/degree C
Power supply:	15-30 V, 150-300 mA
Cable length:	Up to 500 m

7.2.4 Data collection and control unit

The PIEZOMAC II data collection and control unit is a computer-controlled unit for simultaneous operation of the probes. It also receives and stores data from the probes together with time data, and transfers the results to other units.

The design is briefly shown in Figure 7.6. The computer Geomac II communicates with other units via an interface, including eight measuring channels and three channels for communication with an external terminal, printer or radio.

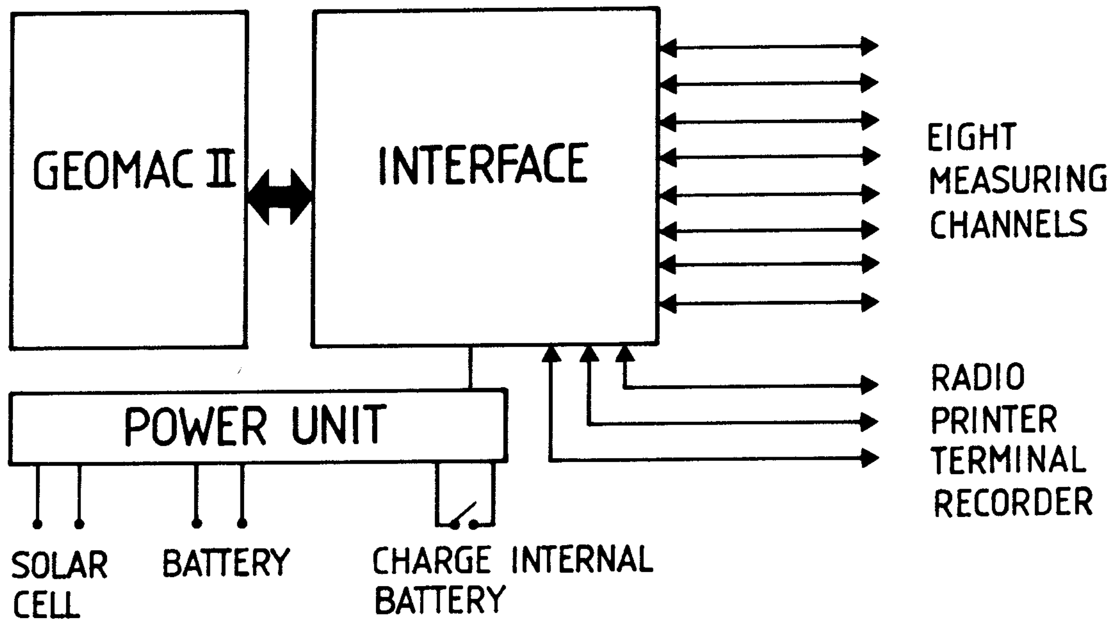


Figure 7.6 PIEZOMAC II, data collection and control unit, principle design.

The unit is built in a case for all-weather conditions with waterproof connectors on both sides of the case. Data and the measuring program are stored on a built-in microcomputer RAM-disc.

Normally, and always when measuring, the data collection and control unit is powered externally with 24 V. For up to a few hours, it can be powered with an internal battery, and switching is automatic. With continuous measurement this is useful when data is transferred to a data recorder far away from the test area. The unit can be transported without reprogramming when it is connected for measuring again.

As the system consumes very little current, it can be powered continuously with a solar cell and external battery back-up for the nighttime operation.

Technical specification

Weight:	9 kg
Size:	500 x 360 x 160 mm
Temperature range:	-25 ^{o}C to 70 ^{o}C
Microcomputer:	Geomac II Field computer
Storage capacity:	2500 measurements (value and time)
Display:	2 x 16 character alphanumeric LCD.
Power supply,	
Voltage	24 Vdc (20-28 V) external battery
Current	< 20 mA, without any probe powered on
Internal battery	18 V, 1 Ah
Solar cell	16 V, 2A max
Probe connections	8 serial RS-232 C, 300 baud and power supply.
Ports (channels)	Radio, Printer, Terminal all with serial RS-232 C, software selected baud rate.

7.2.5 Measuring program

The measuring program is divided into the following main routines:

* Presentation of previous measurement on selected channel
* Measuring information (start time, user, probes, valves etc)
* Commands, how measurement, presentation of data etc is performed
* Measuring sequence (see below)
* Radio transfer sequence.

The measuring sequence within a single scan is defined as follows:

* Store the time for start and display the time
* Calculate time for next scan
* Power on probes. Valves connect the first section to the transmitter in all probes with sections connected

* Wait for preset delay (a few seconds). Read pressure from all probes and store them together with time (year, month, day, hour, minute and second).
* Measure next section etc
* Print to selected channel

The power supply to the probe is then switched off until the time for the next measurement. The interval between measurements can be set between c. 1 minute (depending on the number of connected probes) and 12 hours. Measuring with logarithmic time interval may be done. Delay time can be set to between 0 and 999 seconds.

7.2.6 Data transfer and presentation

Data may either be transferred to a data recorder or via radio and telephone network to a main computer, as seen in Figure 7.1. Data is checked and identified in order to be subsequently processed, and successively plotted on a monitor or paper. In this way the measurement sequence can be continuously supervised from the office. From the main computer, the field instrument can also be reprogrammed during the measuring process.

The main computer used is the Digital PC 350. By using the plotting program described in 6.1.6 the data from each individual section can be presented either as raw data or calculated groundwater pressures or groundwater heads. A calibration equation is then used with constants unique for each transmitter.

In addition to this, preliminary drawings can be shown in the field on a matrix printer, commanded by the data collection and control unit.

7.2.7 Hoisting equipment

A low-weight, hydraulically operated hoisting device is used for lowering and lifting of the downhole unit. The unit is powered by a diesel engine and built on a two-wheel trailer.

The hoisting capacity is c. 4 tons (also pushing, provided that the equipment is firmly anchored to the ground). The feeding speed is c. 100 m/h, including jointing of the aluminium string and taping of hoses and cables around the string.

7.3 Interference test application

The PIEZOMAC II system can be used as a registration unit for interference tests between two or more boreholes. Interference tests can be performed either as injection tests or pumping tests. In Figure 7.7 the principal design of an interference pumping test is shown.

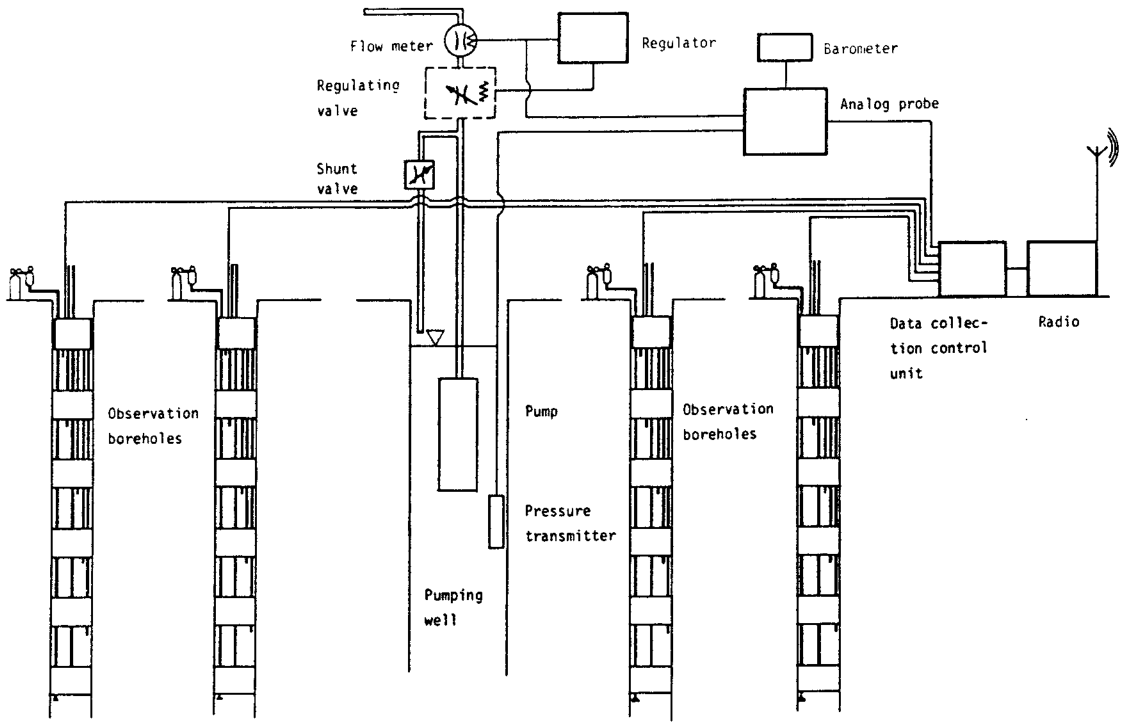


Figure 7.7 Interference pump-test application of the PIEZOMAC II system.

In the application shown the groundwater level in the pumping well, the flow rate and the barometric pressure are measured by transmitters connected to an analog probe. Observation boreholes are equipped with multipressure probes. If desired, the pumping can be performed from a sealed off section of the pumping well by means of packers.

The water is pumped from the well at a constant flow rate by means of a submersible pump and an automatic flow rate regulator unit. This unit keeps the flow constant within 1 %.

The measuring process, data transfer and data presentation are identical to the piezometric measurements described earlier.

8. EQUIPMENT FOR HYDROCHEMICAL INVESTIGATIONS

8.1 Background

From the experience gained in the early stages of the site selection studies, it was found that, although many groundwater components can be accurately analyzed at a later stage on well preserved samples, some sensitive components should be analyzed immediately in the field. As a matter of fact, the most sensitive parameters like the pH and the Eh are preferably measured in situ, downhole in the test section. Examples of these three categories of less sensitive, sensitive and very sensitive parameters are

* the main cations; sodium, potassium, calcium, magnesium and anions; chloride, fluoride, sulphate

* the conductivity, alkalinity and all redox sensitive components; iron and manganese ions, sulphide, oxygen and nitrogen compounds

* the pH and the Eh

Samples on isotopic chemistry of the groundwater, i.e. carbon-14, carbon-13 in carbonate and deuterium, tritium and oxygen-18 in water, have to be carefully collected and isolated. However, these samples will of course have to be sent to specialized laboratories. This is also true for certain other components like gas content, colloids, dissolved organic material and trace elements.

It is difficult to obtain a representative water sample from a low permeable crystalline rock. Any activity like drilling, hydraulic testing and even withdrawal of water samples from a section increases the risk of contamination. There is always a risk that surface water enters the formation through the long open borehole.

8.2 General layout

Against the background described, SKB decided to develop new equipment for analyzing and measuring all the sensitive and important parameters of the groundwater. The development has been performed in collaboration between the Royal Institute of Technology, IPA-Konsult AB and Swedish Geological Co on commission by SKB. In total, the sampling and analyzing equipment consists of:

* a pumping unit containing pump, packers and umbilical hose.
* a computerized unit for measuring of groundwater characteristics.
* a mobile field laboratory for on-site water chemical analysis.
* downhole gas sampling unit for the collection of pressurized water samples for analysis of dissolved gas.
* mobile electrical generator, powered by diesel engine.

All the equipment set up is built in mobile trailers as shown in Figure 8.1

8.3 Pumping unit

The pumping unit normally used for investigations in 56 mm boreholes is described in the following text. Other pumps and packers for different borehole diameters may be preferable in other applications.

Pump

A downhole piston pump is used for the pumping of groundwater samples from isolated sections of a borehole. The pump is hydraulically operated by means of pressurized water from the surface via a hydraulic hose. The piston is spring loaded and the cyclic operation is controlled by time relays. The normal pumping capacity is 100-200 ml/min of water transported to the surface through a hydraulic hose. All parts of the pump that come in contact with the sampling water are made of stainless steel.

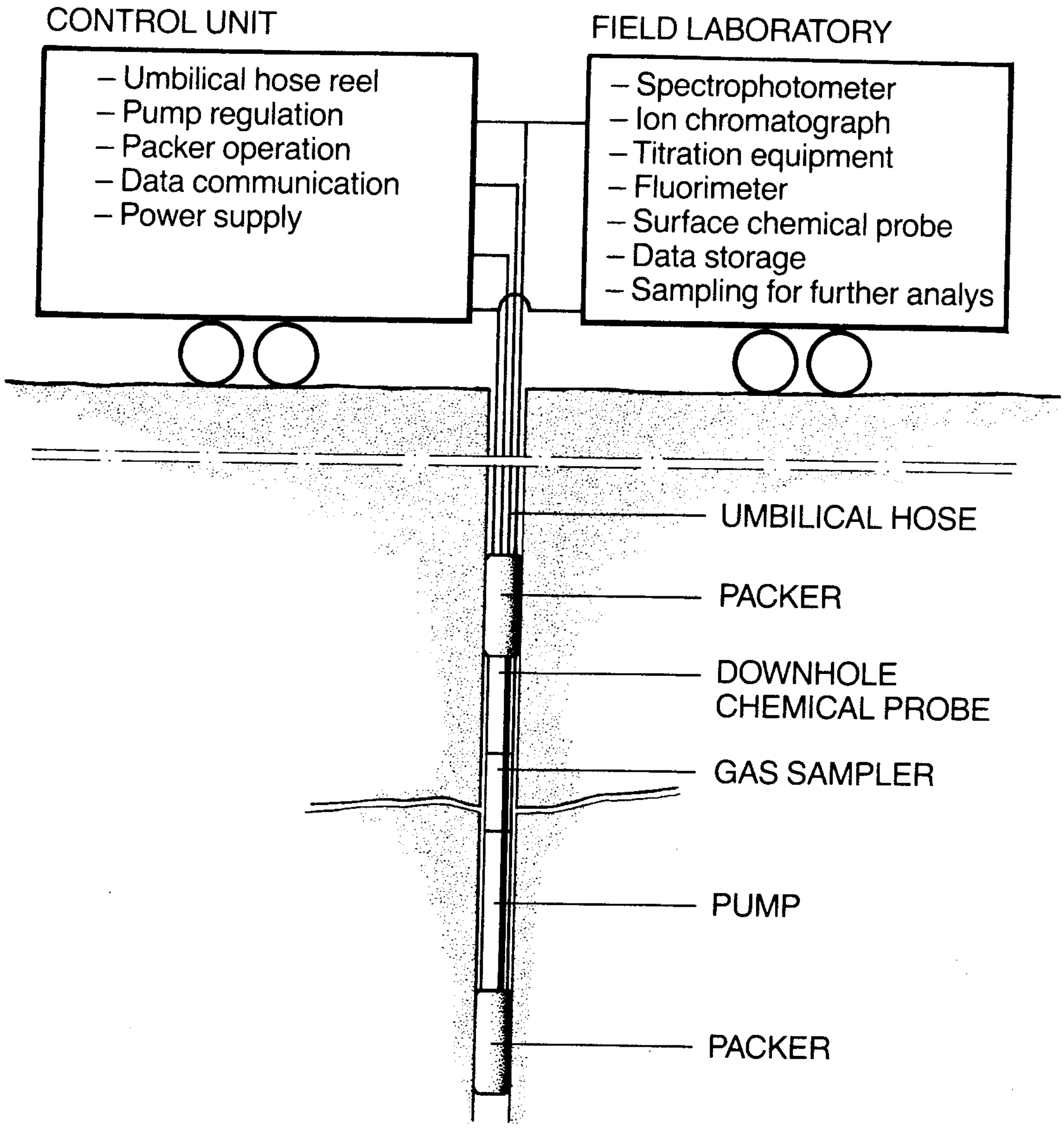


Figure 8.1 Equipment for deep groundwater characterization.

Packer

The packers used are of similar construction to the injection packers earlier described (see 6.1.2). They are inflated from the surface by means of pressurized water through a pressure tubing.

Umbilical hose

The umbilical hose contains all pressure tubings and hoses needed for the pump and packer operation, water transport to surface and electrical conductors for data communication from the downhole chemical probe.

The umbilical hose, the multi-coupling to the probe, the hose reel and feeding equipment in a mobile trailer are similar to the units described in 6.1.2.

The downhole equipment can also be connected to a pipe-string system for lowering into the borehole.

8.4 Equipment for measuring water characteristics

The equipment for measuring water characteristics contains one downhole chemical probe, one surface chemical probe and a computer system for data collection and control.

8.4.1 Downhole chemical probe

The downhole chemical probe is normally situated inside the sealed-off section, but can also be placed just above the upper packer.

The probe consists of a measuring chamber including an electrode head and connections for electrodes and an electronic device for data transmission. When the water enters the probe it fills up and flows through the one-liter measuring chamber.

The inert Eh-electrodes are gold, platinum and glassy carbon, of which the gold and platinum electrodes are permanently mounted on the probe. The pH electrode is a pressure compensated glass electrode, the pS-electrode is a solid Ag/Ag_2S electrode and finally the reference electrode is an Ag/AgCl double junction gel-filled electrode. All these electrodes are specially designed and can be disconnected. The temperature is measured with a thermistor permanently mounted on the probe. A pressure transducer is installed in order to prevent the tested section from unacceptable pressure drawdown.

The downhole probe (Figure 8.2) is connected via a multi-coupling to the multihose and uses four conductors for power supply and data communication. The probe electronics also contain an A/D-converter, a multiplexer which connects the electrodes to the input of a differential amplifier and receive-transmit circuits for serial data communication. The communication between the computer and the downhole probe is frequency shifted data, 300 baud full duplex.

In order to eliminate the flow of any current through the electrodes, high input impedance amplifiers are mounted on each electrode input. The probe is powered with 24 V DC from the surface. The ground level in the probe is galvanically isolated from earth with a DC/DC converter and an opto coupler.

The probe is constructed in stainless steel and covered with a 54 mm diameter stainless steel pipe. The probe length is 1.6 m.

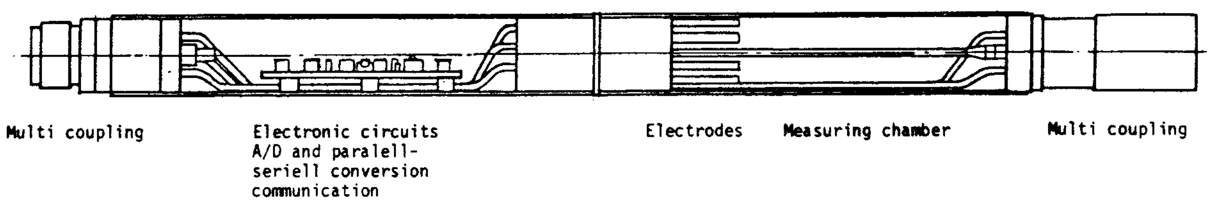


Figure 8.2 Principle design of the downhole hydrochemical probe.

8.4.2 Surface chemical probe

From the multihose the water enters the field laboratory through a flow meter into a surface chemical probe, which consists of chambers connected with stainless steel pipes and valves. After passing the probe the water can be collected for a number of different analyses in the field laboratory or other external laboratories. The entire, unbroken water flow system from the borehole section to the sampling point is shown in Figure 8.3.

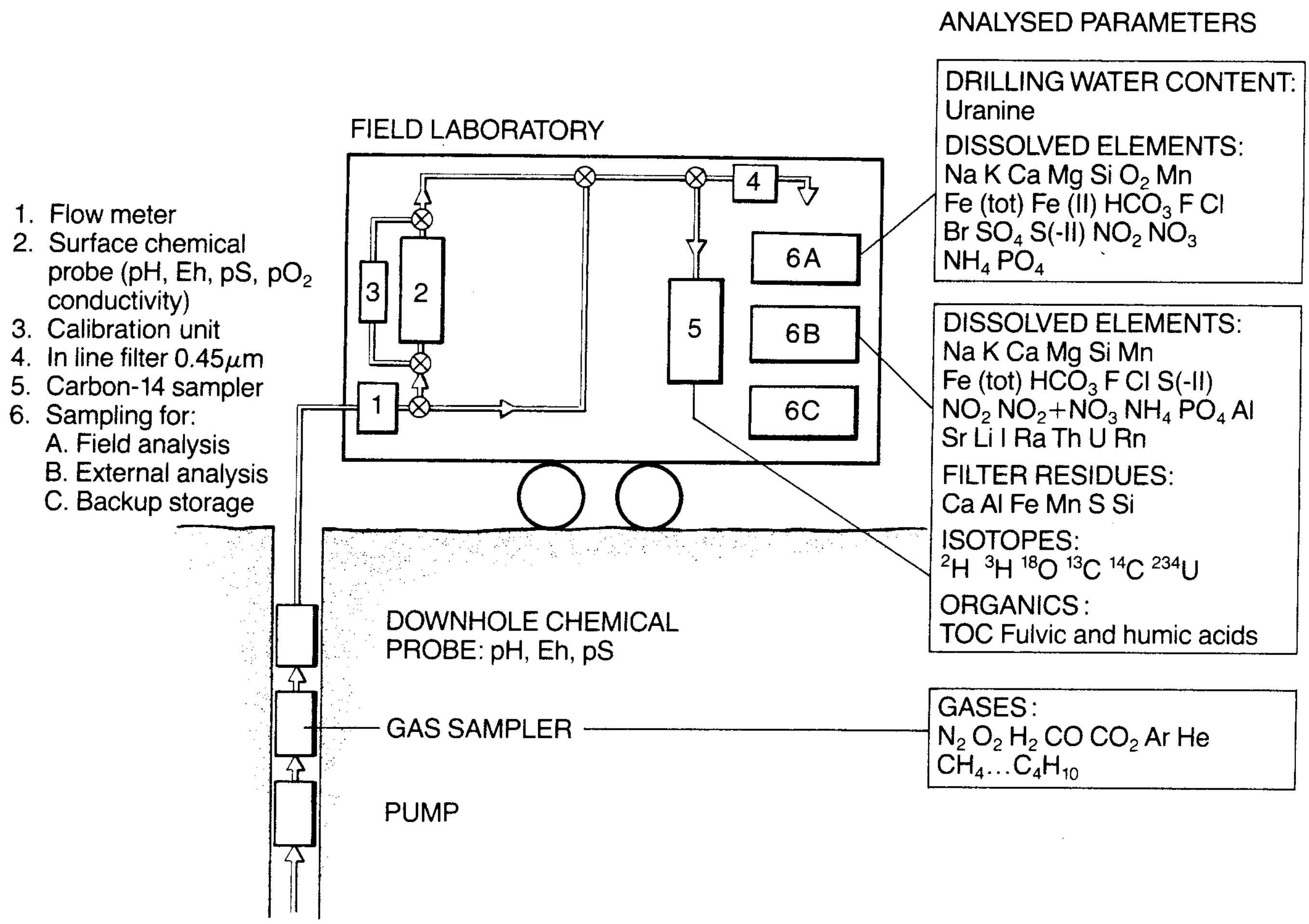


Figure 8.3 The water flow system from borehole to analysis.

The surface chemical probe is equipped with electrodes for surface measurements of pH, Eh, pS and temperature in a similar way to the downhole measurements. One common reference electrode is used and five ion selective electrodes. Commercial electrodes are used, except for the sulphide electrode, which has the same design as in the downhole probe. The reference electrode is a gel-filled Ag/AgCl double junction electrode. The Eh electrodes are made of solid gold, platinum and glassy carbon. pH, as usual, is measured with a glass electrode.

Ten ion selective electrodes, two reference electrodes and two thermistors can be used simultaneously in the flow-through cell. All electrodes can be disconnected and changed. They are connected with shielded wires to the electronics.

Conductivity and dissolved oxygen are also measured in the flow-through cell. Two separate instruments are used for this purpose, interfaced to the flow-through cell electronics so that the measured parameters are read and stored in the computer.

The electronics of the surface equipment are principally of the same design as the downhole electronics. There are high input impedance amplifiers to prevent current flow through the electrodes. The electronics also consist of multiplexers, differential operational amplifiers, A/D-converters and serial data communication circuits.

A separate loop for calibration of the measuring electrodes is built into the system. The pumped-up water is then allowed to bypass the measuring chambers, and instead a calibration solution is pumped into the chambers and circulated through the surface chemical probe.

8.4.3 Computer system

The mobile field laboratory is equipped with a computer, MDX-11, manufactured by Scientific Micro System Inc., which is compatible to Digital Equipment PDP-11/23 computer. It runs under RSX-11M+, a multiuser, multitask operating system. The computer is provided with 1 MByte memory, 33 MByte Winchester hard disk unit, 8" floppy disk unit and RS-232 serial channels.

The peripherial equipment consists of a terminal, matrix printer and plotter.

The purpose of the computer is (Figure 8.4):

* to collect and store data from the downhole chemical probe and the surface chemical probe
* to present data on the terminal both as figures and curves during measurements
* to plot the results from the measurements
* to print out the results
* to process raw data
* to store the results of the analyses made in the laboratory
* to store data on floppy diskettes for distribution to SKB data base.

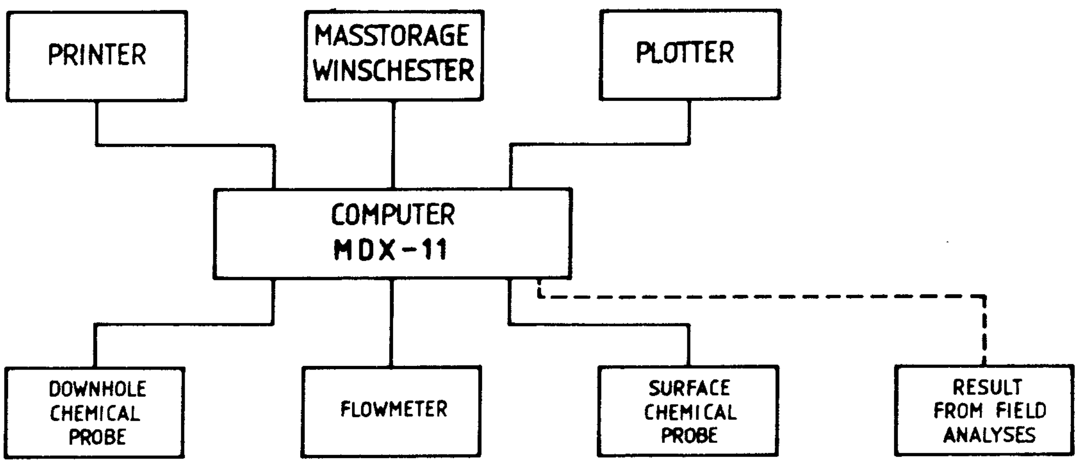


Figure 8.4 Block diagram of the computer system for data collection.

The software consists of a main program from which a number of other programs can be started.

It is possible to run several programs concurrently, e.g. to process old data while measuring.

8.5 Field laboratory

8.5.1 General

The mobile field laboratory (Figure 8.5) is built into a modified work barrack on bogie wheels. The external dimensions are 7 x 2.5 m. Both ends have doors, one of which is 1 m wide and is used for the loading and unloading of equipment. This door is normally used only as an emergency exit. The door at the other end is the normal entrance and is airlocked in order to minimize contamination from the outside. The long sides have two windows each.

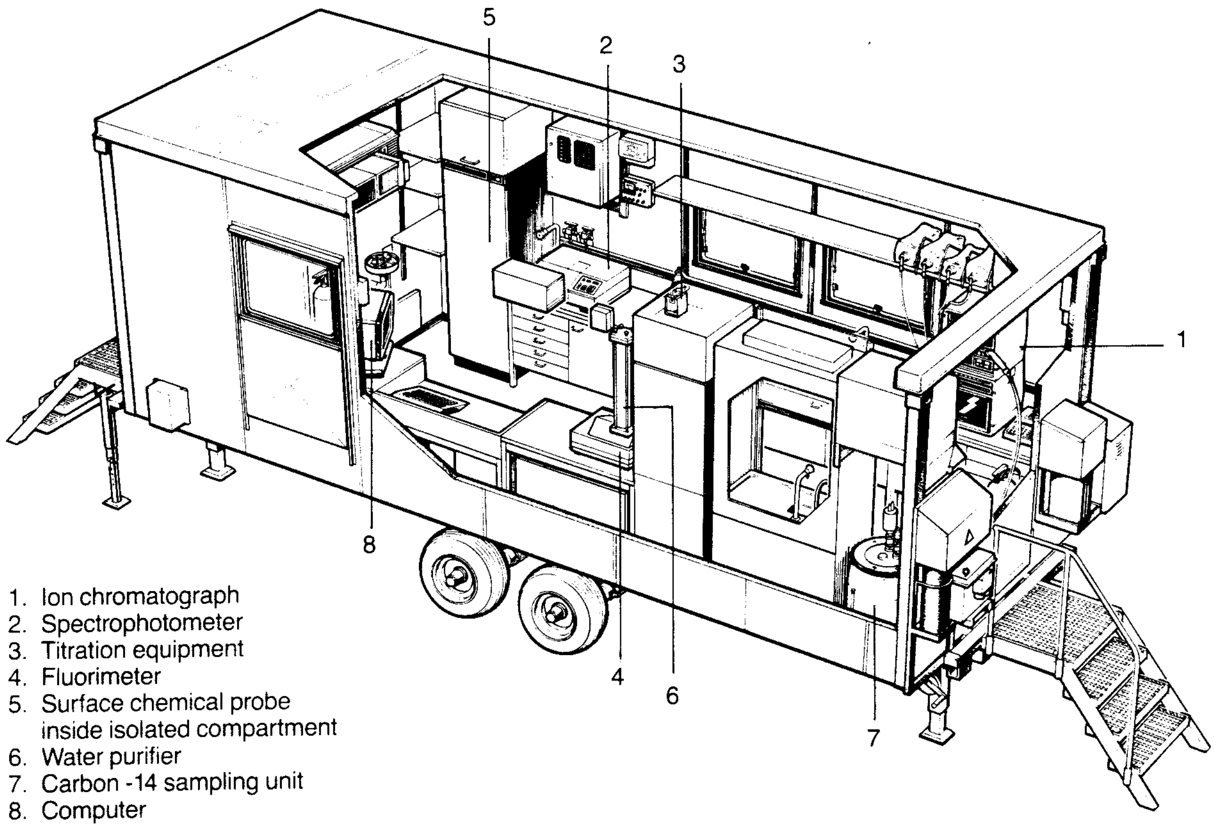


Figure 8.5 Field laboratory.

The laboratory is furnished with work benches and shelves. These are anchored to the wall and the floor. There is also a sink, a ventilated hood, a combined refrigator-freezer and a writing desk with a computer.

There is a separate compartment in the airlock which houses a toilet and back-up power for measuring equipment, a heating unit, emergency light and burglar alarm.

Water is supplied by a liquid elevator connected to a 200-liter stainless steel water tank. There are two kinds of water pipes, stainless steel and polyamid plastic. The steel pipes provide ordinary tap-water, while the plastic tubes are used for leading the water to an ion exchanger and then on to teflon-coated water taps.

The heating is provided by four electric radiators. There is an air-conditioning unit and two suction fans, one at each end of the laboratory. On the wall outside the barrack are holders for a nitrogen gas cylinder and a butane gas cylinder. The butane gas cylinder is connected to an emergency heating unit connected to a thermostat. There is also a gas outlet in the fume box connected to a small burner.

8.5.2 Instruments for chemical analysis

The purpose of the analytical program was to make a complete analysis of the main groundwater elements during one working day. The unstable constituents can be analyzed immediately as the water enters the surface (Figure 8.6). In order to achieve this, great care was taken in choosing instruments and methods which would allow fast and accurate analyses. Also, there was limited space available, and therefore the analytical methods were chosen to make as many analyses as possible on the same instrument (Table 8.1).

The analytical methods used for the different elements are taken from APHA, 1975, HACH 1985 and Swedish Standard 1976. The most suitable and commonly used method was selected except for the total and ferrous iron analysis, for which a colorimetric method based on ferrozine was used, Nordström et al, because of its much lower detection limit.

The water passes through a 0.45 um inline filter.

Table 8.1 Groundwater elements analyzed in the field laboratory. Detection limits are given in mg/l except for Uranine.

Ion chromatograph			
Sodium	0.1	Fluoride	0.2
Potassium	0.1	Chloride	0.1
Ammonium	0.1	Bromide	0.05
Nitrate	0.05	Sulphate	0.05
		Phosphate	0.1
Titration			
Calcium	2	Alkalinity	0.6
Magnesium	0.4		
Spectrophotometer			
Iron (II)	0.005	Silicon (SiO_2)	1
Iron (total)	0.005	Sulphide (total)	0.01
Manganese	0.01	Phosphate	0.005
		Nitrite	0.001
Fluorimeter			
Uranine	<0.1%	drilling water contamination	

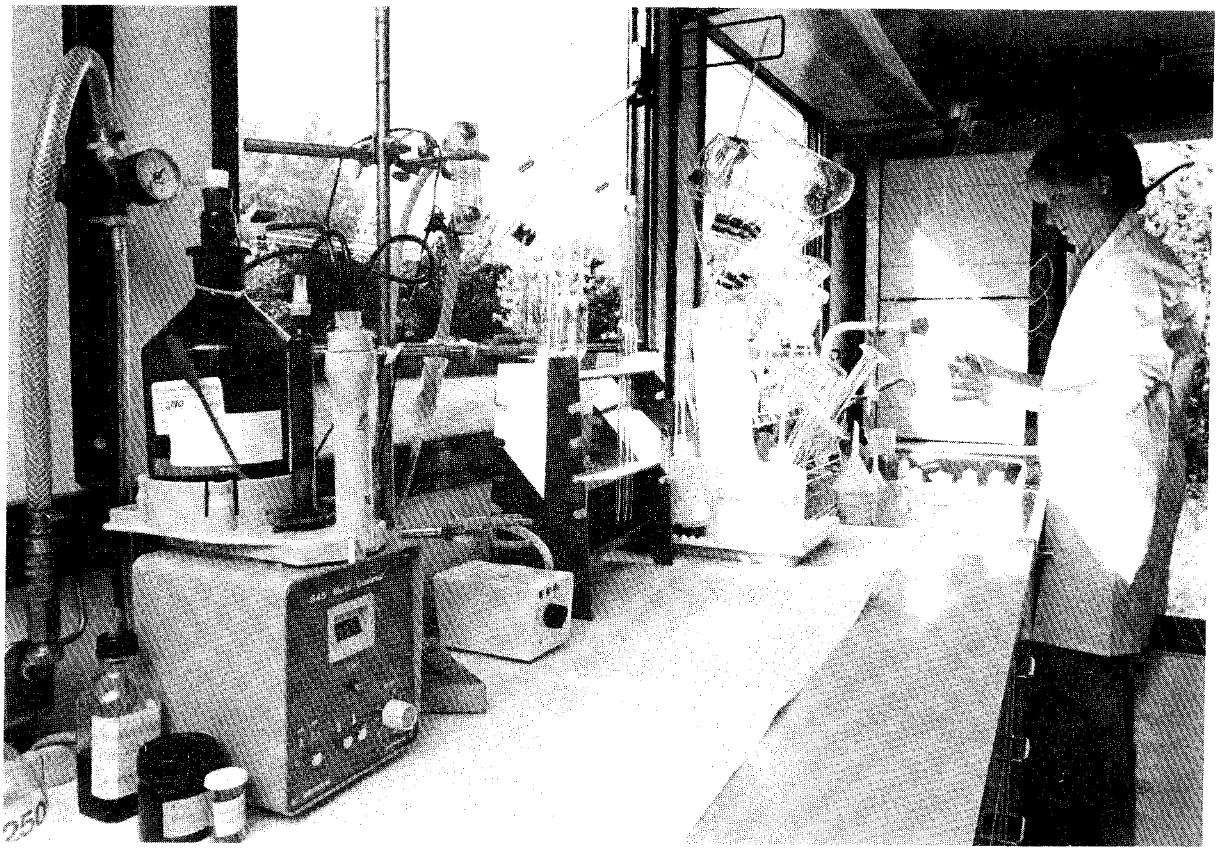


Figure 8.6 Interior of the field laboratory.

Spectrophotometer

The spectrophotometer used is a Perkin-Elmer Model Lambda 1 single beam for the visual range, 300-800 nm, with a bandwidth of 2 nm. Glass cuvettes of 1 cm and 5 cm length are used.

Reagents are added using dispensers or ready-made plastic powder pillows containing the different reagents. The glassware used for a certain analysis is reserved for that purpose and is not used for other analysis.

Duplicate samples are always run. A standard solution and a reagent blank are run parallel to the water analysis.

Titration equipment

A Methrom model Multidosimat E415 automatic buret is used in the titrimetric methods. The buret is provided with three exchange units containing the different titrator solutions.

The titrations are made in Erlenmeyer flasks using a magnetic stirrer. A special titration vessel is used for the alkalinity titrations in order to purge the solution of released carbon dioxide during titration.

Ion chromatograph

The ion chronomatograph is a Dionex model 2010i, equipped for anion and cation analysis with conductimetric detection. The anion column used is an AS4 column with an AG4 guard column, and the cation column is a CS1 with a CG1 guard column.

The eluents used for separation are 0.0029 mol/l $NaHCO_3$, 0.0023 mol/l Na_2CO_3 for anion analysis, and 0.005 mol/l HCl for cation analysis. The anion and cation analyses are run alternately by switching a valve. Fiber suppressors are used to suppress the eluent background conductivity. These are continuously regenerated using 0.0125 mol/l H_2SO_4 for the anion analysis and 0.08 mol/l tetramethylammonium hydroxide for the cation analysis. The signal from the conductive detector is fed to a Hewlett-Packard integrator model 3392-A. The evaluation is made by calculating the peak area.

The 0.45 um filtered water sample is injected in a loop of 10, 50 or 500 ul size, and introduced in the system by switching a valve. The ions separate in the separator column and are then pumped through the fiber suppressor where the counter ions are exchanged with protons or hydroxide ions increasing the conductivity response for the different ions. The eluent background conductivity is reduced by neutralization, carbonate in the anion eluent to carbonic acid and protons in the cation eluent to water.

The signal from the conductivity cell is registered by the conductivity detector and the integrator. By comparing the signal size of runs with known concentrations, the integrator calculates the sample concentrations.

Determination of drilling water content

Since 1984, the water used for drilling has been tagged with the tracer uranine. Before that, iodide was used for the same purpose. The uranine content in the borehole water is measured with a fluorimeter in the mobile laboratory. A Perkin-Elmer Fluorimeter LS2 is used. The drilling water content is measured during pumping, three times per day.

8.5.3 Water sampling for external analysis

In addition to the field analyses, samples are also collected and sent to external laboratories for special analyses of trace elements, filter residues, organic substances, isotopes and gases. The samples for the special analyses have been collected in plastic bottles with a volume of 1-5 l. The samples for trace element analyses are acidified, the others untreated. A few samples are collected in a different way and will therefore be mentioned.

Organic substances

The characterization of humic and fulvic acids requires that the organic substances can be extracted from a large volume of water, a few cubic metres. The organic substances are collected on a resin in a column through which the groundwater is pumped.

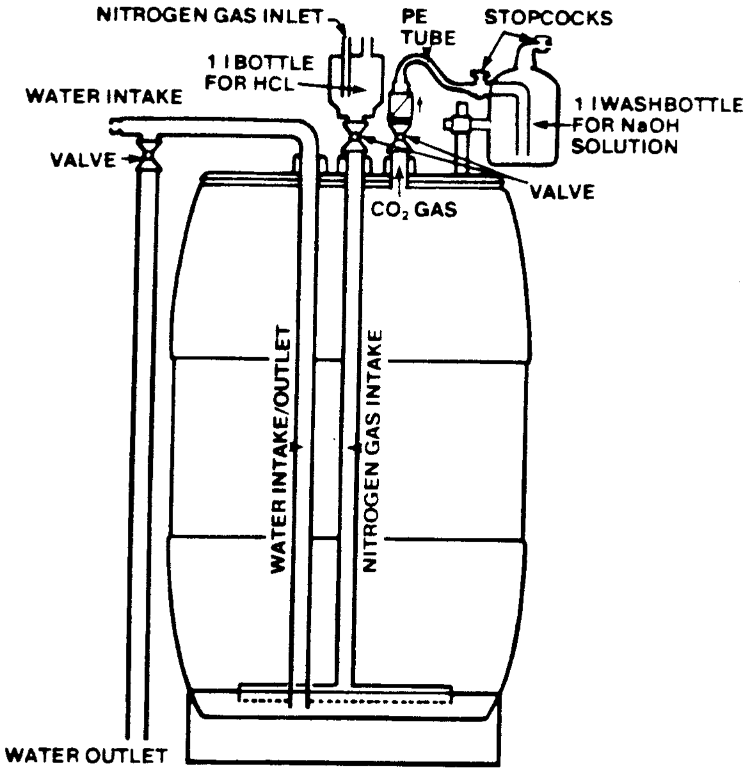


Figure 8.7 Equipment for collecting C-14 samples.

Carbon-14

The amount of carbon needed for a C-14 analysis corresponds to the total carbonate content of ca 100 l of natural ground-water. In order to obtain a convenient sample volume the carbon dioxide is expelled from 130 l of acidified ground water and collected in a wash-bottle containing a NaOH solution. A schematic drawing of the equipment is presented in Figure 8.7.

The barrel is filled up with water through the water inlet tube. Then 1 litre of HCl is pressed into the water by nitrogen. The nitrogen also serves the purpose of mixing the acid and the water and of expelling the carbon dioxide from the water. The CO_2 is then trapped in the wash-bottle whereas the nitrogen passes right through it.

The barrel is emptied afterwards by applying an overpressure with nitrogen when all the valves except the water outlet valve are closed.

8.6 Gas sampling system

8.6.1 Gas sampler

The equipment used in taking pressurized water samples for the analysis of the total amount of dissolved gas has been designed by Bengt-Arne Torstensson, BAT AB in close collaboration with the laboratory which will perform the analysis. The aim has been to develop an unbroken chain of procedures and equipment all the way from the sampling elevation to the laboratory analysis. In this way the risk of sample contamination will be minimized.

The gas sampler is operated through one of the hydraulic tubes in the multihose. By applying pressure on the top of it the gas sampler is activated. When the pressure is released, the sample is isolated in gas tight sample cylinders.

The sampling system consists of either one cylinder with a maximum volume of 250 ml or two cylinders in series with a volume of 100 ml and 50 ml, respectively. The different cylinders can be connected in series in any desired configuration.

The reason for the varying sizes of the cylinders is that the amount of gas trapped from the groundwater may vary considerably. In some water the volume of gas is in the same order of magnitude as the volume of water whereas some waters do not contain any detectable amount of gas at all. The optimal volume of gas for the analysis is 1 - 5 ml.

The sample cylinders are made of stainless steel. The cylinder is sealed at both ends by a rubber disk which functions as a one way valve. Prior to sampling, the cylinder is flushed by nitrogen and evacuated to vacuum. A sample is collected by penetrating the rubber disk with a double-ended hypodermic needle so that the cylinder is waterfilled (Figure 8.8). When the needle is withdrawn the disk will reseal the sample cylinder and the in situ pressure will be kept inside the sampling cylinder.

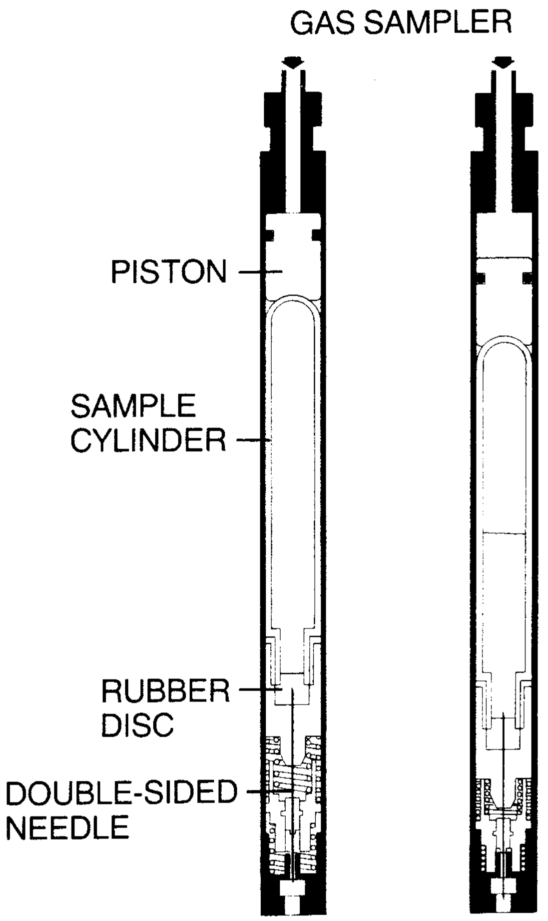


Figure 8.8 Working principle of the gas sampling unit.

8.6.2 Gas analysis

At the gas laboratory the contents of the sample cylinder will be transferred into a high vacuum compartment. In this compartment all the gas dissolved in the water will be released and pumped into a gas burette where the amount of gas is measured. From this burette a small volume is extracted for injection into a gas chromatograph.

The amount of nitrogen, carbon dioxide, carbon monoxide, helium, hydrogen, methane, ethane, propane, isobutane, normal butane, argon and oxygen will be determined with a typical quantification limit in the order of one ppm (volume gas/ volume of sample). However, another limitation is also set up by the fact that the largest sample amount is 250 ml and the smallest amount of gas needed for the analysis is 1 ml.

9. DILUTION EQUIPMENT

9.1 Introduction

The point dilution equipment provides a method for in situ determination of groundwater flow in fractures and fracture zones under natural hydraulic gradient and in the natural flow direction.

The approach relies upon the use of a dye tracer, which is introduced into a borehole section sealed off by rubber packers, Figure 9.1.

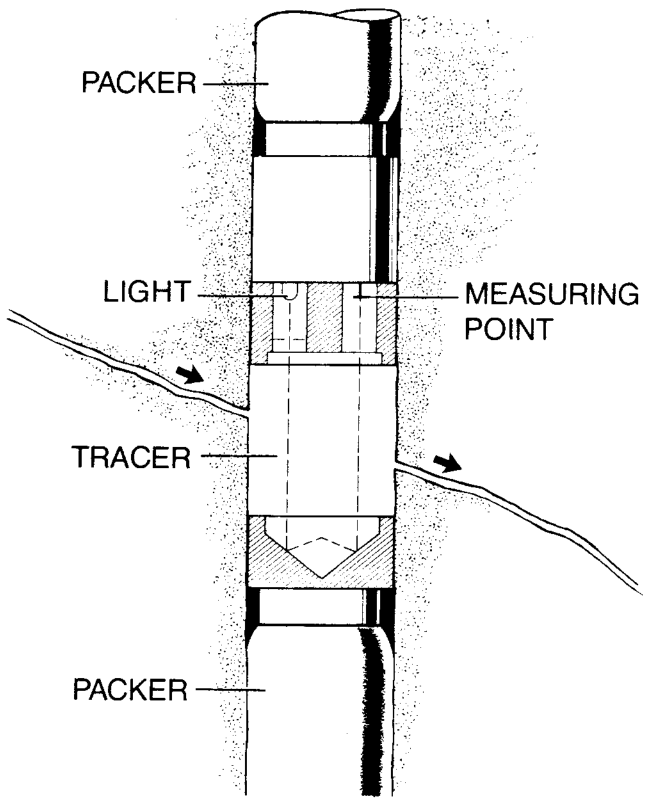


Figure 9.1 Principle design of the dilution equipment.

Within the borehole section, the tracer is always completely mixed and the concentration is measured as a function of time with a borehole transmission meter. The tracer will be diluted due to non-labelled groundwater from the fracture zone flowing through the borehole. This dilution is proportional to the water flow through the borehole section and thus to the groundwater flow in the fracture zone.

The development of borehole point dilution equipment is in progress. The equipment described below is a prototype developed by Swedish Geological Company and the final version will be changed in some details in order to improve the operation.

With interchangeable packers and dummys it is possible to conduct dilution measurements down to 500 m depth in boreholes with a diameter of 76 mm and greater. The lower limit of detection is set by the rate of molecular diffusion of the tracer into the fracture zone. Therefore the accuracy in determining a low groundwater flow increases with decreasing hydraulic conductivity in the fracture zone.

Eight dilution tests have been performed with the prototype in percussion drilled boreholes of 110 mm diameter in granite at the Finnsjön test site. A comparison of the groundwater flow evaluated by dilution tests and by two well tracer tests proves the point dilution method and equipment to be reliable. The development of a dilution equipment adapted to 56 mm diameter boreholes is planned.

9.2 General layout and function

9.2.1 Downhole equipment

A transmission meter which optically measures the tracer concentration is fixed between packers straddling the fracture zone in which the groundwater flow is to be determined, see Figure 9.2. Above the upper packer a circulation unit is mounted. This unit includes a tank for tracer solution and a circulation pump with intake and outlet emerging through plastic tubes into the test section between the packers. The tracer solution is injected from the tank into the test section via a shunt on the pump outlet. The tank contains tracer solution enough to perform 4 dilution tests. The circulation pump keeps the tracer completely mixed within the test section, i.e. no concentration gradient within the test section.

The dilution rate, at constant groundwater flow, is inversely proportional to the water volume in the test section. Therefore this volume is minimized by dummys in order to reduce the time neccessary for an accurate measurement of the dilution.

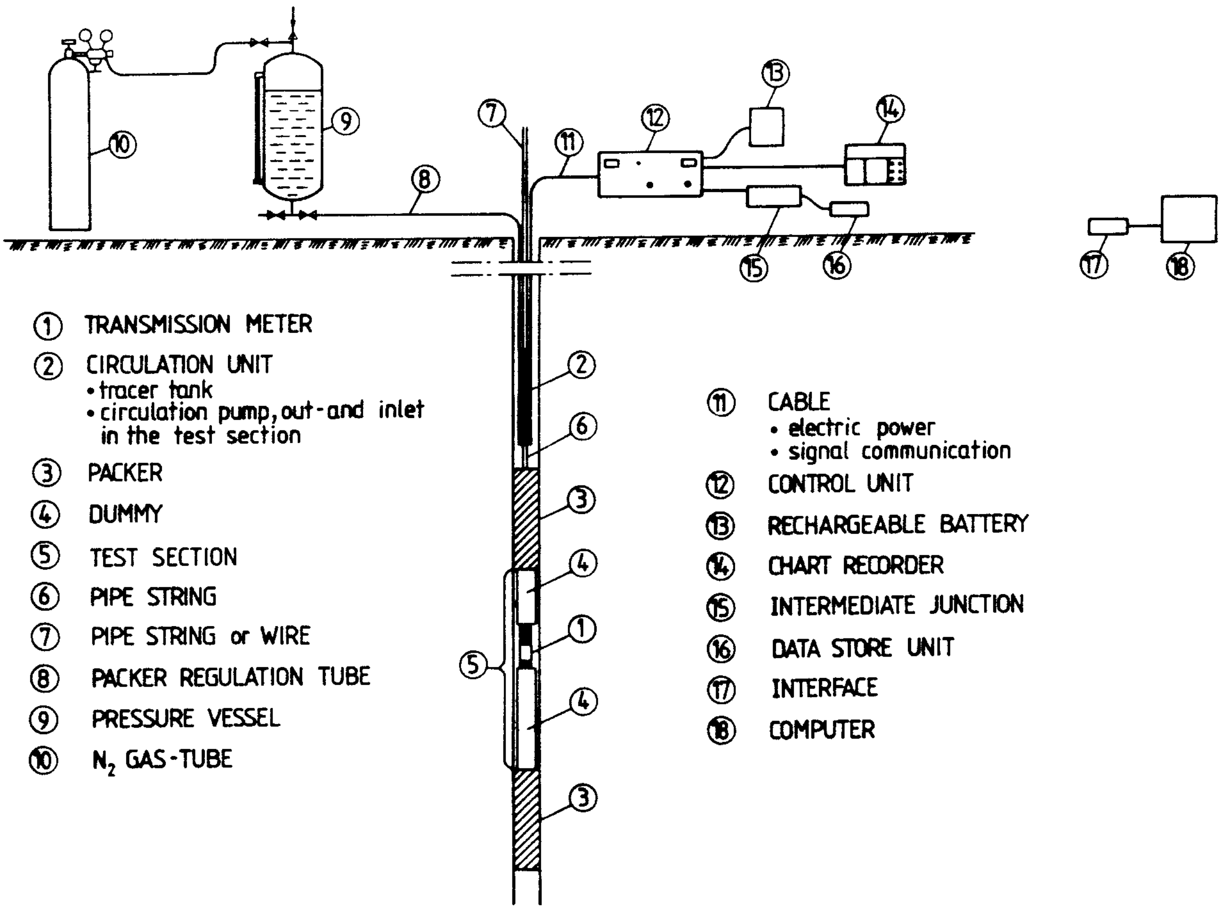


Fig 9.2 Borehole point dilution equipment

9.2.2 Surface units

The control unit (Fig 9.3) is designed to perform the following tasks:

* electric power supply to the downhole equipment
* generation of trig pulses to circulation pump, tracer injection device and transmission meter
* display tracer concentration, i.e. transmission
* data transfer to external data store unit and/or strip chart recorder.

The tracer concentration, i.e. transmission as a function of time, is registered analogously with a strip chart recorder and/or stored digitally in a data store unit with a storage capacity of 500 measured values as 16-bit data words. The scan interval is chosen between 7.5 minutes and 8 hours in seven steps.

The processing of the data is made at the office with a standard desktop microcomputer type ABC 800. The data store unit is thereby disconnected at the intermediate junction (where another data store unit can be connected), brought to the office and connected to the interface.

The dilution equipment operates on mains voltage 220/240 V AC or a rechargeable battery 24 V DC, 18 Ah. With the rechargeable battery and digital data storage the operating time is approximately 300 hours.

9.3 Additional equipment facilities

For a determination of the groundwater flow not only the transmission, i.e. tracer concentration, but also the water volume in the test section must be known. Especially in percussion drilled boreholes this may cause a problem due to uncertain diameter values in the drillers log. By measuring the volume of water necessary to inflate the packers up to a certain operating pressure, it is possible to determine the borehole diameter and thus the water volume in the test section with great accuracy.

Besides the dilution of the tracer and the volume of water in the test section the following environmental conditions are measured in the test section ((5) in Figure 9.2):

* piezometric pressure
* temperature
* turbidity

The piezometric pressure is measured during the dilution tests, because in a fractured medium a change in the piezometric pressure normally indicates that the hydraulic gradient, and thus the groundwater flow, is changed.

The temperature gauge has several modes of application. One is temperature logging of the boreholes, where hydraulically active fracture zones or strata for dilution measurements can be found as temperature anomalies. Another is temperature measurements of the water in the test section, which is essential if viscosity is taken into consideration, if measured groundwater flow values should be converted to hydraulic conductivity.

When lowering the equipment into the boreholes, suspended particles such as drilling debris precipitations etc. interfere with the optical measurement of the tracer concentration. Therefore the turbidity is measured. The tracer is injected when the suspended particles have settled, which, besides high tranmission, corresponds to a constant low value of the turbidity.

The equipment also includes a water injection device with which it is possible to measure/check the hydraulic conductivity of the test section by means of a standard water injection test.

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