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KARAKTÄRISERING AV BERGMASSAN MED KOMBINERAD GEOFYSISK BORRHÅLSLOGGNING

Arkivexemplar
Utlånas ej



SVERIGES GEOLOGISKA AB

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1 INLEDNING

En kombination av ett flertal geofysiska loggningsmetoder ger en möjlighet till en klassificering av bergmassan i borrhålets omedelbara närhet, exempelvis:

- karaktärisering av olika bergartsenheter specifierade av skilda fysikaliska egenskaper
- detektering av mineraliseringar och mineralogiska variationer
- bestämning av variationer i porositet och vatteninnehåll i bergmassan längs med borrhålet
- detektering av sprickor, sprickfrekvens (RQD) och krosszoner.
- identifiering av vattenförande permeabla zoner

I tabell 1 redovisas de olika loggningsmetodernas huvudsakliga respons på olika fysikaliska parametrar, modifierad efter Glenn and Nelson, 1979. I figur 1 visas ett exempel på en composite log där en kombination av ett flertal metoder ger en utmärkt karaktärisering av bergmassan avseende mineralogiska variationer, variationer i porositet och sprickfrekvens längs ett borrhål.

Loggmetoder	Objekt											
	Mafiska mineral	Klorit	U / Th / K	Magnetit	Sulfider	Grafit	Lermineral	Porositet	Öppna sprickor	Sprickfrekvens, RQD	Krosszoner	Permeabilitet
Susceptibilitet	3			1								
Naturlig gamma	3		3	3								
Gamma-gamma (density)	3	4	4	2	2			2	4	4	4	
Neutron-neutron (porosity)	3	4		2				2	4	4	4	
Enpunktsresistans	4			4	2	2	2	3	3	3	3	
Resistivitet - normal	4			4	2	2	2	3	4	3	3	
Resistivitet - lateral	4			4	2	2	2	3	4	3	3	
SP				4	2	2	2	4	4	4	4	
IP				4	2	2	2	4			4	
Sonic				4	4			2	2	2	2	
Temperatur								3	4	4	4	4
Borrhålsvätskans resistivitet												4
Caliper									4			
Tubewave								4	4	4	4	1
VSP								2		2	2	

1 Kvantitativt – bra
2 Kvantitativt – möjlig
3 Kvalitativt – alltid
4 Kvalitativt – möjlig

TABELL 1.

2 MINERALOGISKA VARIATIONER

Olika loggar kan användas för att detektera mineralogiska variationer som svarar mot olika fysikaliska egenskaper. Exempelvis kan variationer i halt av mafiska mineral (Fe) och variationer i halt av mineral med olika innehåll av radioaktiva isotoper av K, U, Th detekteras. Vidare kan kloritförande zoner, zoner med innehåll av lermineral eller grafit, mineraliseringar med magnetit eller sulfider detekteras. En identifiering av de mineralogiska variationerna är nödvändig för att kunna eliminera dessa vid en analysering av variationer i bergmassans porositet och vatteninnehåll.

2.1 Mafiska mineral

Variationer av mafiska mineral (Fe, Ca, Al, Mg) detekteras främst med följande loggningsmetoder:

	metod	parameter
-	susceptibilitet	vol-% Magnetit
-	gamma-gamma	densitet
-	neutron-neutron	Fe/H- innehåll
-	naturlig gamma	K/U/Th- innehåll

Ökat innehåll av mafiska mineral (Fe) eller magnetit registreras med ökad susceptibilitet, minskad gammaintensitet (ökad absorption av gammastrålning pga ökad densitet), minskad neutronstrålning (ökad absorption av neutroner pga ökat Fe- innehåll eller ökat innehåll av strukturellt bundet vatten (H- innehåll)). Bergarter med högre innehåll av mafiska (Fe- rika) mineral registreras av lägre naturlig gammastrålning i huvudsak beroende på lägre innehåll av kalihaltiga mineral (kalifältspat, muskovit).

2.2 Magnetit

Variationer i magnetithalt registreras i huvudsak av följande metoder:

	metod	parameter
-	susceptibilitet	vol-% magnetit
-	gamma-gamma	densitet
-	neutron-neutron	Fe- innehåll
-	naturlig gamma	K/U/Th- innehåll

Ökad magnetithalt motsvaras av ökad susceptibilitet, minskad gammaintensitet (ökad densitet) och minskad neutronaktivitet (Fe- absorption). Vid riktlig förekomst av magnetit (järnmalm) kan magnetitmalmen betraktas som konduktiv, se nedan. Ett exempel på detta visas i figur 1 mellan ca 140- 160 m, där en magnetitförande mafisk gångbergart (eventuellt magnetkisförande) tydligt framträder på förutom ovan nämnda metoder även på självpotential och resistivitet.

2.3 Konduktiva mineral

Konduktiva mineral som sulfider, grafit eller lermineral detekteras främst med följande metoder:

	metod	parameter
-	resistivitet	ledningsförmåga
-	självpotential	avvikande potential
-	IP	polarisationseffekt
-	gamma-gamma	densitet

Sulfidmineraliseringar, grafitzoner och förekomst av lermineral motsvaras av kraftigt sänkt resistivitet om de konduktiva mineralen bildar ett kontinuerligt nätverk. Förekomst av des-

sa mineral karaktäriseras av självpotential- och IP- variationer. Sulfidmineral vars densitet är cirka dubbelt så stor jämfört med silikatmineralen detekteras av minskad gammaintensitet (ökad absorption av gammastrålning).

2.4 Kloritförande zoner

Kloritförande zoner detekteras främst av följande loggar:

	metod	parameter
-	neutron-neutron	Fe/H- innehåll
-	gamma-gamma	densitet

Kloritförande zoner är ofta karaktäriserade av låg neutronaktivitet (Fe- innehåll och strukturellt bundet vatten/H) och minskad gammaintensitet (ökad densitet) (Nelson, Magnusson and Rachiele, 1982).

2.5 Uran, thorium och kalium

Variationer av radioaktiva isotoper av uran, thorium och kalium detekteras främst av följande metoder:

	metod	parameter
-	naturlig gamma	U/Th/K- totalt
-	gammaspektrometer	U/Th/K- halt

Bergarternas mineralsammansättning återspeglas av dess innehåll av radioaktiva isotoper av uran,thorium och kalium. Exempelvis har pegmatit och granit högre gammaaktivitet än mafiska bergarter som diabas och gabbro på grund av större innehåll av kalihaltiga mineral (kalifältspat, kaliglimmer etc). Med gammaspektrometer kan halter av respektive element bestämmas.

3 POROSITET OCH VATTENINNEHÅLL

Ett flertal loggar kan användas för att detektera bergmassans porositet och vatteninnehåll. För att analysera variationer i porositet och vatteninnehåll måste som tidigare nämnts de mineralogiska variationerna vara kända, exempelvis avsnittet 140- 160 m i figur 1. Volymsandelen av vattenfyllt porutrymme registreras främst av följande loggar:

	metod	parameter
-	neutron-neutron	vol- % vatten
-	resistivitet	ledningsförmåga
-	gamma-gamma	densitet
-	sonic	gångtid
-	temperatur	avvikande temperatur
-	självpotential	avikande potential

Ökat innehåll av vatten i sprickzoner registreras med minskad neutronaktivitet (ökad absorption av neutroner (H)), minskad densitet (minskad absorption av gammastrålning), ökad gångtid på sonic (lägre gånghastighet i vattenfyllda sprickzoner). Vattenfyllda sprickzoner registreras av temperaturloggning om hålet spolas med kallt ytvatten omedelbart före loggning. Det kalla vattnet tränger in i sprickorna som därmed kan registreras pga avvikande temperatur.

För att karaktärisera bergmassans porositet och vatteninnehåll är en kombination av ett flertal metoder att föredra. Ett exempel på detta är sammanställningen i figur 1 där porösa vattenfyllda sprickzoner tydligt framträder med ökad porositet, minskad densitet, ökad gångtid (sprickighet) och ökad konduktivitet, exempelvis avsnittet 380-395 m, 450-460 m etc.

4 SPRICKOR, SPRICKFREKVENS (RQD) OCH KROSSZONER

Vad avser detektering av öppna sprickor, sprickfrekvens (RQD), och krosszoner används samma metoder som vid detektering av porositet beroende på att det är samma fysikaliska

egenskaper som registreras.

	metod	parameter
-	sonic	gångtid
-	caliper	håldiameter
-	resistivitet	ledningsförmåga
-	neutron- neutron	volym- % vatten
-	gamma- gamma	densitet
-	VSP	gångtid

Öppna enskilda sprickor detekteras med calipermätning pga ökad håldiameter och med resistivitet, i synnerhet punktresistans, beroende på att sonden är tillverkad ett fåtal mm mindre än borrhålsdiametern och med en smal elektrod omgiven av isolatorer för att inverkan av borrhålsvätskan skall minimeras.

Resistivitet- normal ger information om bergkvalitet, sprick- och krosszoner i en större omgivning till borrhålet. Resistivitet- lateral ger liksom punktresistans en högre upplösning av enskilda sprickor.

Med VSP (vertical seismic profile) registreras ökad gångtid för den seismiska tryckvågen vilken är omvänt proportionell mot utbredningshastigheten i berget, och därmed bergkvalitet. Krosszoner registreras med ökad gångtid. Sonic är en akustisk metod där både sändare och mottagare sänks ner i borrhålet.

Exempel på enskilda sprickor som detekteras med minskad densitet, ökad porositet, ökad gångtid (sprickighet) och ökad konduktivitet föreligger vid ca 180, 240, 420 och 585 m, figur 1.

5 PERMEABLA, VATTENFÖRANDE ZONER

För detektering av permeabla vattenförande zoner kan som ett komplement till föregående metoder dessa metoder användas:

	metod	parameter
-	Tubewave	permeabilitet
-	Temperatur	avvikande temperatur
-	Vätskeresistivitet	avvikande salthalt

Tubewave är seismisk metod där tubvågor (Stonleyvågor), vilka fortplantas längs med borrhålsväggen, registreras med hjälp av hydrofoner nedsänkta i borrhålet, figur 2. Tubvågorna genereras av öppna vattenförande sprickor som skär borrhålet. Amplituden på dessa tubvågor är i stort sett proportionell mot sprickans permeabilitet och därmed vattenflöde. I figur 3 visas ett exempel på en registrering av tubvågor som fortplantas upp och ner i borrhålet genererad av en vattenförande spricka vid ca 270 m. Vid tubewavemätning registreras samtidigt den först ankomna tryckvågen (P-våg) vilket ger en möjlighet att presentera ett kontinuerligt gångtidsdiagram (VSP) längs med borrhålet.

Vattenförande sprickor registreras med temperaturmätning om vatten med avvikande temperatur strömmar in i, längs med och ut ur borrhålet. Dessutom kan vattenförande sprickor detekteras med temperaturmätning om borrhålet som tidigare nämnts injekteras med vatten med avvikande temperatur, förslagsvis kallt ytvatten. En inströmning av vatten med avvikande salthalt kan registreras med en samtidig uppmätning av vätskeresistiviteten.

6 REFERENSER

Glenn, W.E. and Nelson, P.H., 1979: Borehole logging techniques applied to base metal ore deposits; in Geophysics and Geochemistry in the Search for Metallic Ores; Peter J. Hood, editor, Geological Survey of Canada, Economic Geology Report 31, p. 273-294.

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7 BILAGOR

SGAB COMPUTERISED GEOPHYSICAL WELL LOGGING SYSTEM

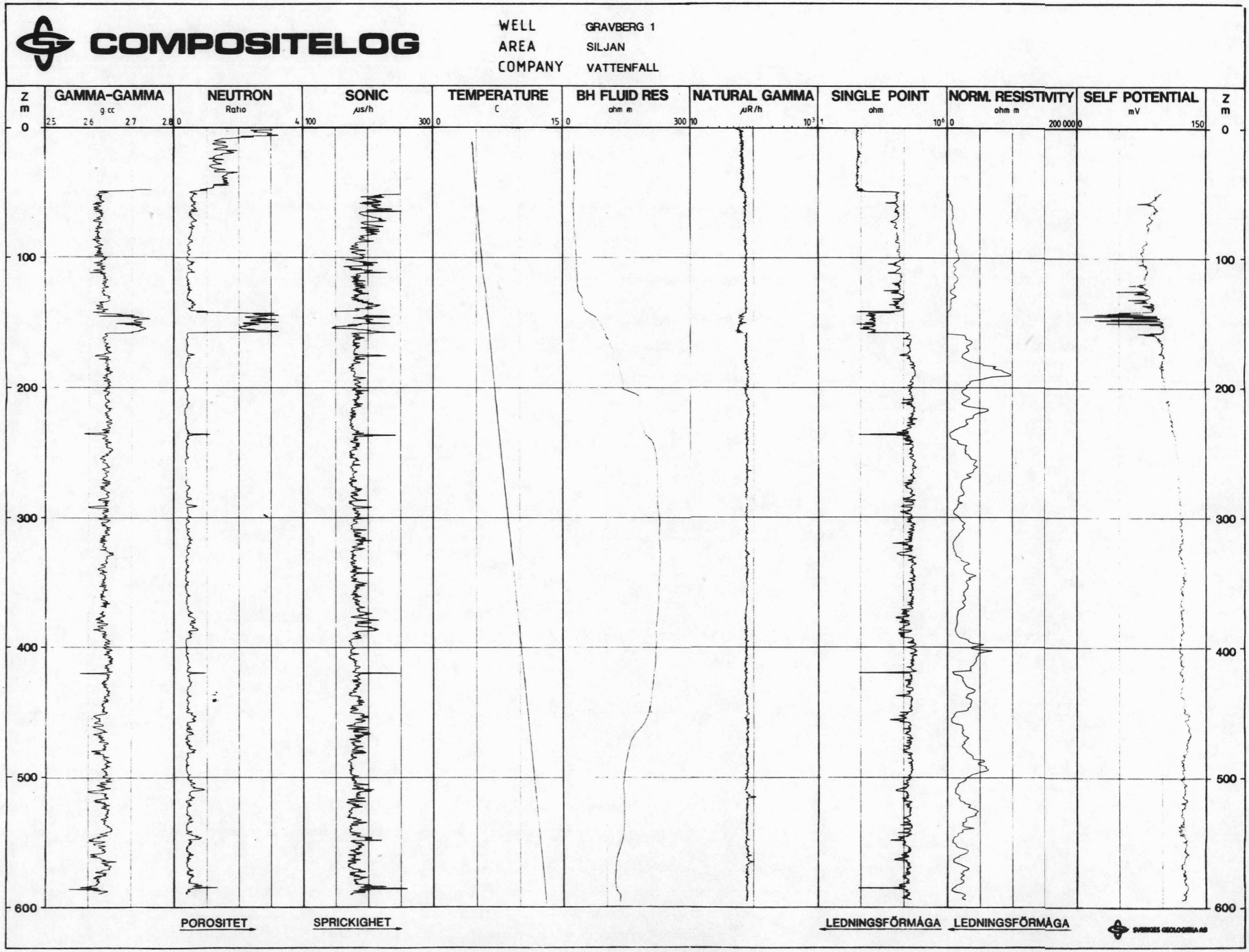
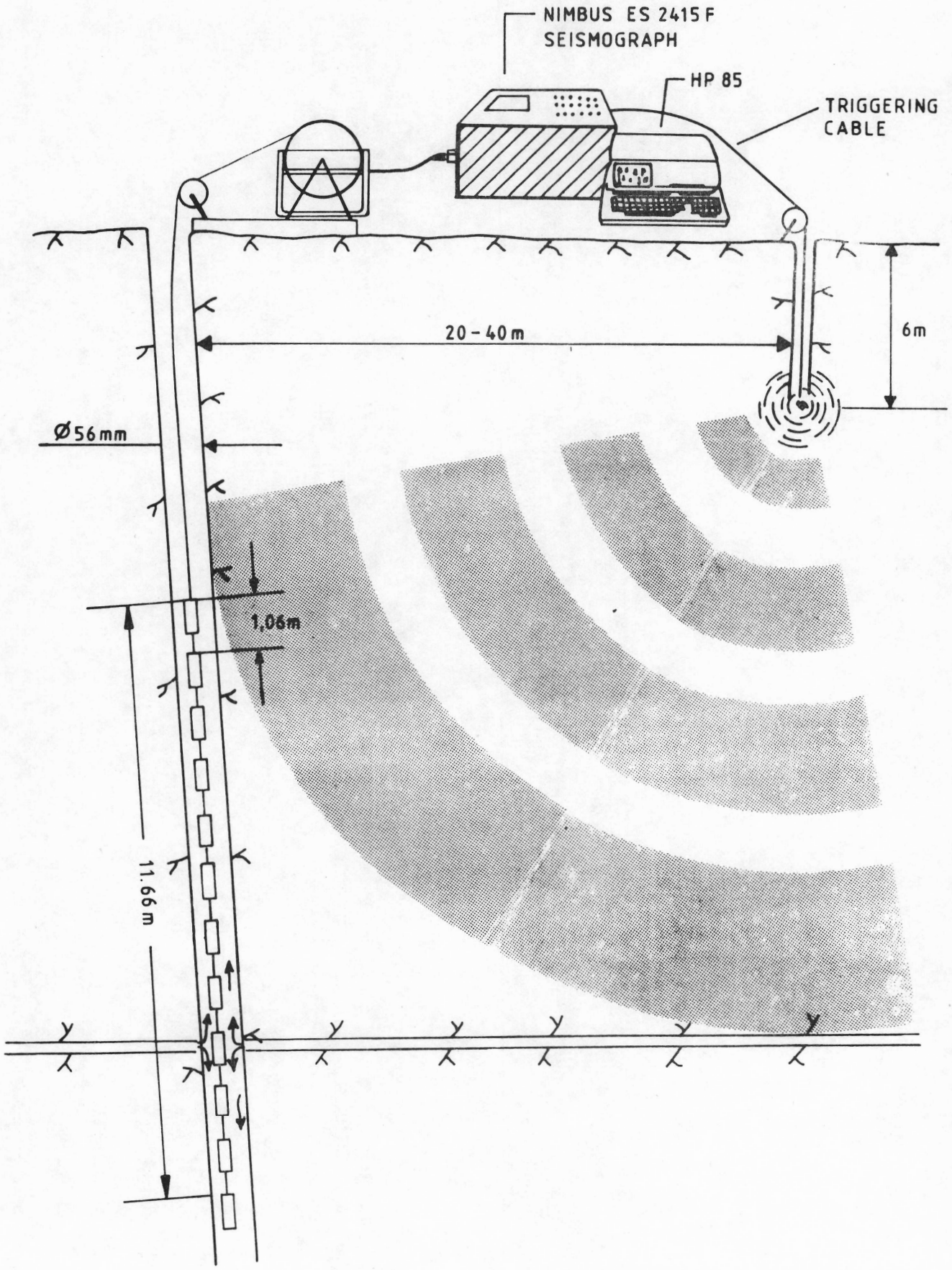
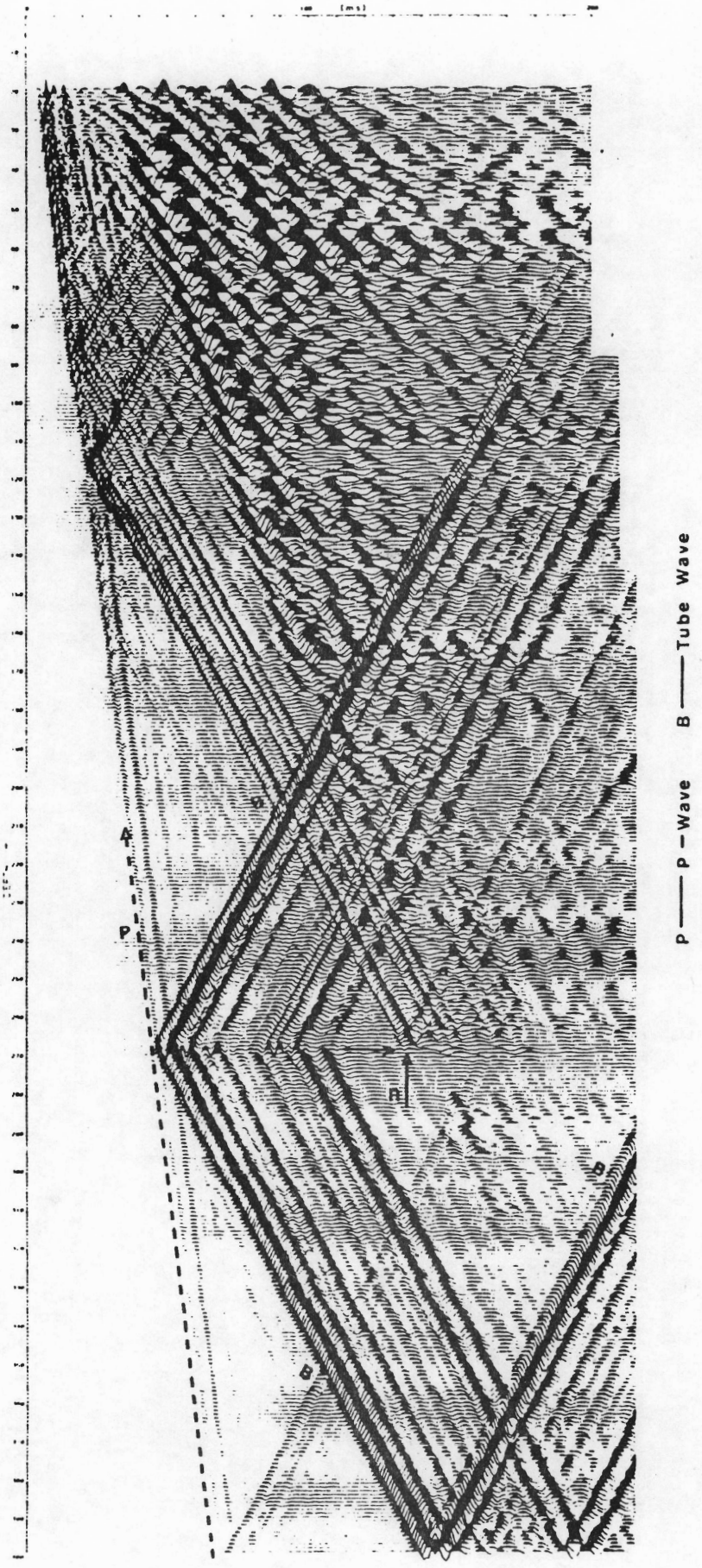

COMPOSITELOG
WELL GRAVBERG 1
AREA SILJAN
COMPANY VATTENFALL
Z m
GAMMA-GAMMA
g cc
2.5 2.6 2.7 2.8
NEUTRON
Ratio
0 4
SONIC
µs/h
100 300
TEMPERATURE
C
0 15
BH FLUID RES
ohm m
0 300
NATURAL GAMMA
µR/h
10 10³
SINGLE POINT
ohm
1 10⁶
NORM. RESISTIVITY
ohm m
0 200 000
SELF POTENTIAL
mV
0 150
0
100
200
300
400
500
600
POROSITET
SPRICKIGHET
LEDNINGSFÖRMÅGA
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Figure 2



Principle of the tube wave method using a multiple hydrophone array lowered into the borehole.

Figure 3



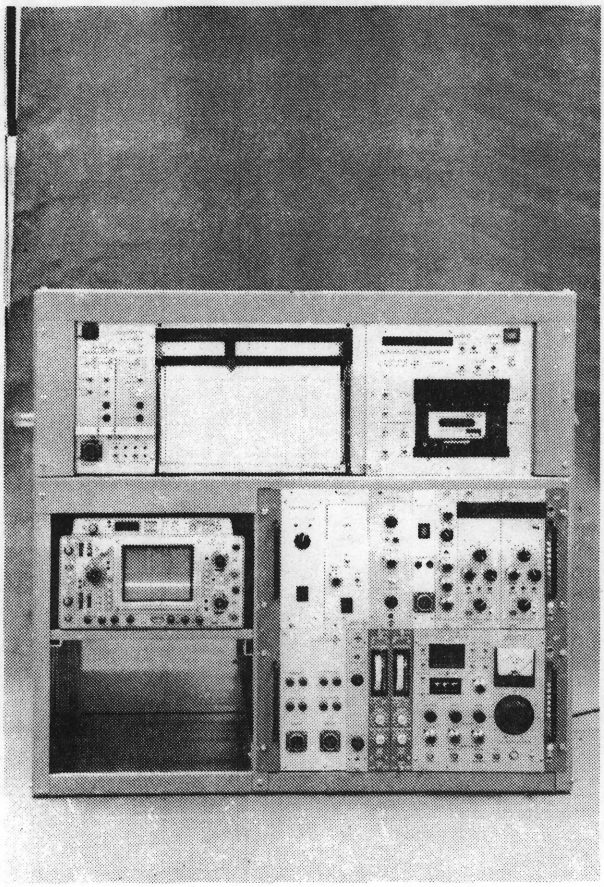
COMPUTERISED

DRILLHOLE LOGGING

EQUIPMENT

Figure 1

SGAB COMPUTERISED
GEOPHYSICAL WELL LOGGING SYSTEM



Measuring System



On Site Computation System

1 SGAB GEOPHYSICAL DRILL-HOLE LOGGING SYSTEM

Geophysical drill-hole logging may be used for exploration, hydrogeology and engineering geology to reduce the necessity of costly core assays, to give more information from a larger rock volume than the core and to provide information in zones of lost core.

Geophysical borehole logging methods provide information on rock stratigraphy, fractures and porosity of the rock, properties of the borehole fluid and the existence of certain minerals.

SGAB can offer the following instruments and logging services for slimhole logging:

1.1	Borehole deviation/ wedge orientation
1.2	Three-arm caliper
1.3	Single point resistance
1.4	Differential resistance
1.5	Normal resistivity
1.6	Lateral resistivity
1.7	Self potential (SP)
1.8	Induced polarization (IP)
1.9	Borehole fluid resistivity
1.10	Temperature
1.11	Borehole slingram (induction log)
1.12	Borehole VLF
1.13	Borehole magnetometer
1.14	Susceptibility/ inductive resistivity
1.15	Natural gamma
1.16	Pulsegamma
1.17	Gamma spectrometer (K, U, Th)
1.18	Gamma-gamma (density)/ one-arm caliper
1.19	Neutron-neutron (porosity)
1.20	Sonic velocity (acoustic)
1.21	VSP (downhole seismics)
1.22	Tube wave
1.23	Borehole radar

1.1 Borehole deviation/ wedge orientation

The borehole deviation sonde will measure the direction of the borehole in the vertical and horizontal plane. The system is also constructed to orient wedges in the borehole. Thus directional drilling may be accomplished.

The direction in the vertical plane is measured by a resistance wire on a loaded wheel. The direction in the horizontal plane is measured by a compass needle, whose direction relative to the magnetic North is measured electrically.

1.2 Three-arm caliper

The caliper sonde measures the borehole diameter using three motor-actuated spring loaded arms. The caliper can be closed and opened by control from surface. The caliper is closed during lowering the sonde. After reaching total depth tne arms are opened electrically and then a log is produced running the sonde up the borehole.

The sonde is calibrated by manually putting a jig with known calibration diameters onto the sonde. In the field the caliper response can be controlled when putting the sonde into the casing.

1.3 Single point resistance

The single point resistance sonde (Figure 2) measures the contact resistance between the probe and the borehole wall. The log is sensitive to changes in the resistivity of the rock in the borehole wall, i.e. conducting minerals and fractures will be detected. The log may be run with a sonde with a small electrode (length 5 cm) surrounded by an insulator slightly less than the diameter of the borehole, to reduce the effect of conductive fluid in the borehole. Thus, high resolution of small fractures will be obtained.

The resistance may be measured at any of 4 different frequencies, 3, 11, 33 or 110 Hz.

Calibration of the resistivity systems are done in the field by connecting a variable resistor to the system thus calibrating the response to a known resistance.

Measuring range: Two ranges:1 - 10 000 ohm and 10 - 100 000 ohm.

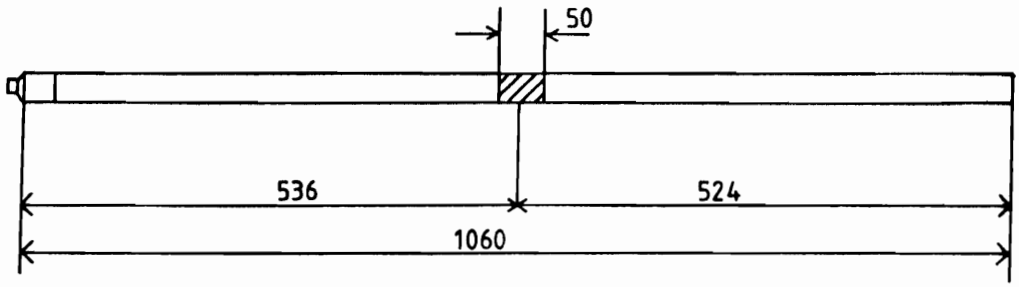


Figure 2. Single point resistance sonde

Diameter	52 mm
Length	1 060 mm
Weight in air	2.4 kg
Sensitivity	1 ohm at low values

1.4 Differential resistance

Differential resistance will indicate small fractures which increase the diameter of the borehole. In effect this log will work as an electrical caliper in the abscence of conducting minerals.

This sonde measures the resistance between two electrodes separated by an insulator. The insulator is made to fit closely in the borehole. This forces the current between the electrodes to pass through the rock if the borehole wall is smooth. If a fracture is present the borehole will become a

little wider and the current will tend to flow in the borehole fluid, thus the resistance between the electrodes will be lower.

1.5 Normal resistivity

The normal resistivity sonde (Figure 3) will indicate zones with anomalous resistivity such as fractures containing water or conducting minerals or the presence of mineralizations. It is possible to make quantitative estimates of rock quality in general and the width and resistivity of fractures. In many types of rock it is possible to find a direct relation between resistivity and porosity.

The apparent resistivity of bedrock is measured with one current electrode and one potential electrode in the borehole. The other potential and current electrodes are situated on the ground some distance from the drillhole. Several different separations of the potential and current electrodes in the borehole can be used. Normally separations of 16" (0.4 m) and 64" (1.6 m) are used.

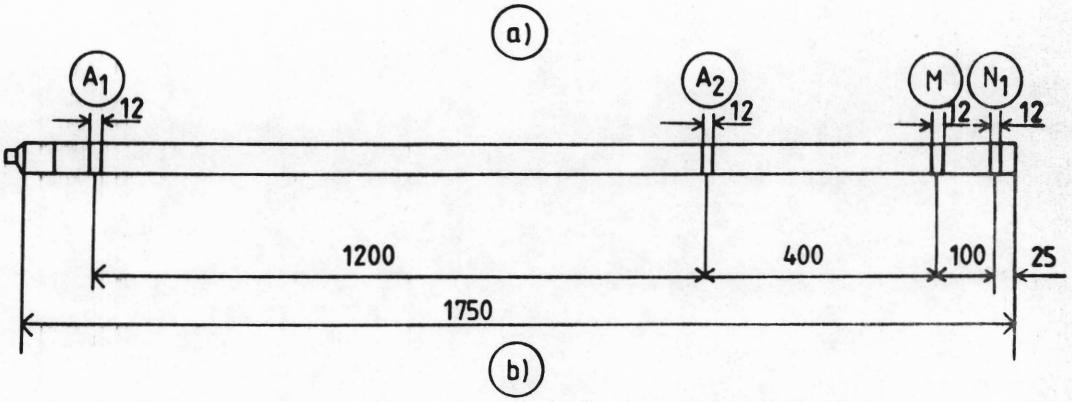
Calibration of the resistivity systems are done in the field by connecting a variable resistor to the system thus calibrating the response to a known resistance.

The instrumental geometrical factor is dependent on the electrode configuration and is constant for a constant energizing current.

1.6 Lateral resistivity

Lateral resistivity is often used together with normal resistivity log to indicate the presence and character of fracture zones. The lateral resistivity log will normally give detailed information about the boundary between conducting and resistive bedrock.

The lateral resistivity is measured with the same sonde as the normal resistivity, by simply change the position of one



A_1 = current electrode (64")
A_2 = current electrode (16")
M = potential electrode
N = potential electrode
N_1 = potential electrode (used when measuring lateral resistivity)

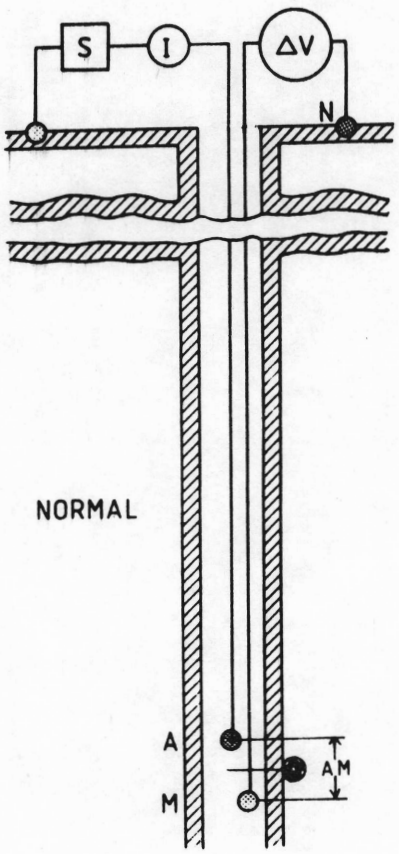


Figure 3. a. Schematic electrode arrangement for normal resistivity measurements. b. Normal resistivity sonde.

Diameter	42 mm
Length	1 750 mm
Distance AM	0.4/1.6 m
Weigth in air	3.5 kg
Sensitivity	1 ohmm at low values

potential electrode. This is manually controlled from surface by changing the connector on a box. Normally separations of 16" (0.4 m) and 64" (1.6 m) between the current and the first potential electrode in the borehole are used (Figure 3). The separation between the potential electrodes is normally 4" (0.1m).

1.7 Self potential (SP)

The self potential (SP) is generated by a number of different causes mainly of chemical origin, but also due to flow of ground water. The SP sonde (Figure 4) gives information about the presence of conducting and reducing minerals.

The natural or self potential is measured between a probe in the borehole and a reference electrode situated on the ground. Non-polarizing copper-copper-sulphate electrodes are normally used to reduce electrode polarization effects which occur at the surface of metallic electrodes put into the ground.

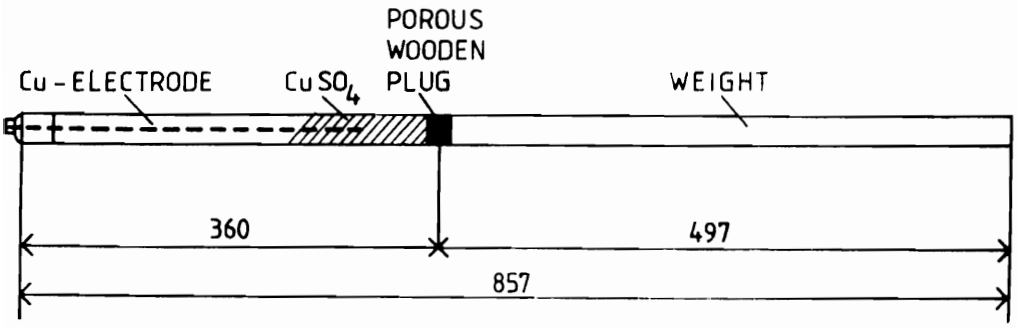


Figure 4. Self potential sonde

Diameter	42 mm
Length	857 mm
Weight in air	3.8 kg
Sensitivity	1 mV

1.8 Induced polarization (IP)

The induced polarization (IP) sonde will indicate the presence of conducting minerals such as sulphides and graphite. Several different electrode configurations may be used but normally a three electrode array is used in the borehole. One current electrode is positioned on the ground surface some distance from the borehole. The separation between the electrodes in the borehole are normally 1 or 5 m. Non-polarizing copper-copper-sulphate electrodes are normally used as potential electrodes. A square wave current with a frequency of 0.25 Hz is transmitted by a regulated power supply.

1.9 Borehole fluid resistivity

The resistivity of the borehole fluid will effect the readings of the other resistivity methods espessicially if the borehole fluid is saline. Thus, the borehole fluid resistivity is often used for the correction of the data obtained from the resistivity logs. A simultaneous measurement of borehole fluid resistivity and temperature makes it possible to accurately determine the salinity of the ground water. Changes in borehole fluid resistivity may indicate water flow in the borehole.

The resistivity of the borehole fluid is measured by a five electrode system (Figure 5). The electrodes are positioned in a plastic tube open at both ends. The insulation from the formation is nessecary for reducing the effect of conducting minerals and fractures present in the formation.

Calibration of the borehole fluid resistivity sonde is performed in the laboratory where the probe is lowered into a tank filled with a water solution with very accurate determined salinity and temperature. During calibration the salinity concentrations and the temperatures are varied so that the system is calibrated corresponding to actual measuring range in the field.

1.10 Temperature

The temperature of the borehole fluid will indicate the temperature of the surrounding bedrock. But in some cases jumps in the temperature log are present, which is an indication of water flowing in or out of the borehole. Water which has flown along fracture zones for a considerable time period will change the temperature of the formation in the vicinity of the fracture zone, and will give rice to a change in the normal temperature gradient measured in the borehole.

If water bearing fracture zones under different pressure status are connected through a borehole, water will flow along the borehole. Water flowing along the borehole will be indicated by a less temperature gradient.

The temperature of the borehole fluid is measured by a thermistor situated at the bottom of the temperature/borehole fluid resistivity sonde (Figure 5).

The temperature sensor is calibrated both in the laboratory and in the field with a very accurate quartz thermometer.

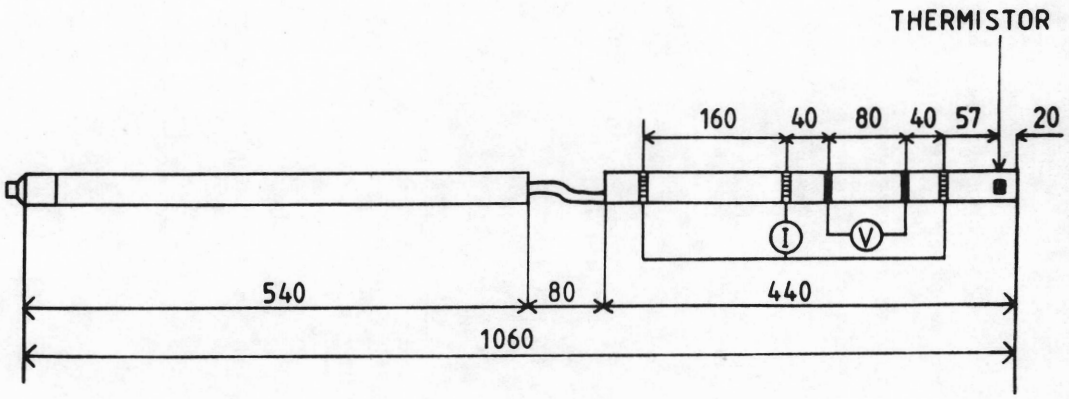


Figure 5. Temperature/borehole fluid resistivity sonde

Diameter	42 mm
Length	1 060 mm
Weight in air	2.0 kg
Sensitivity	1 ohmm

Accuracy: Absolute accuracy 0.06 degrees.
Relative accuracy 0.004 degrees.

1.11 Borehole slingram (induction log)

The induction log is used to measure resistivity of low resistivity bedrock lower than 100 - 1000 ohmm. The borehole slingram can also detect conductive mineralizations, which either intersect the borehole or are situated at a small distance from the borehole.

A small loop situated in the borehole is used as a source for the electromagnetic field (Figure 6). At a fixed distance varying from 5 up to 40 m from the transmitter another loop is used as the receiver of the secondary magnetic field. Normally the magnetic field component along the direction of the borehole is measured. The frequency used varies from a few kHz up to hundreds of kHz depending on the application of the system. In our system the frequency 3.6 kHz and 18 kHz can be used.

1.12 Borehole VLF

The VLF log is used to indicate the presence of conductors in the vicinity of the borehole. Good conductors can be detected at a considerable distance from the borehole.

The VLF- method (Very Low Frequency) utilizes distant radio transmitters as signal source. The transmitters usually operate in the frequency band 15-25 kHz and have a very high output power which make measurements possible at a distance of several thousand kilometers from the transmitter. The transmitters are mainly used for communication with submarines.

The borehole-VLF equipment uses two measurement coils (Figure 7). One is situated in the borehole which measures the magnetic field component along the borehole and one is placed at the ground surface and is used as a reference coil. The reference coil are oriented to get maximum coupling with the primary field. The inphase and out-of-phase components of the secondary magnetic field in the borehole are measured relative to the field in the reference coil.

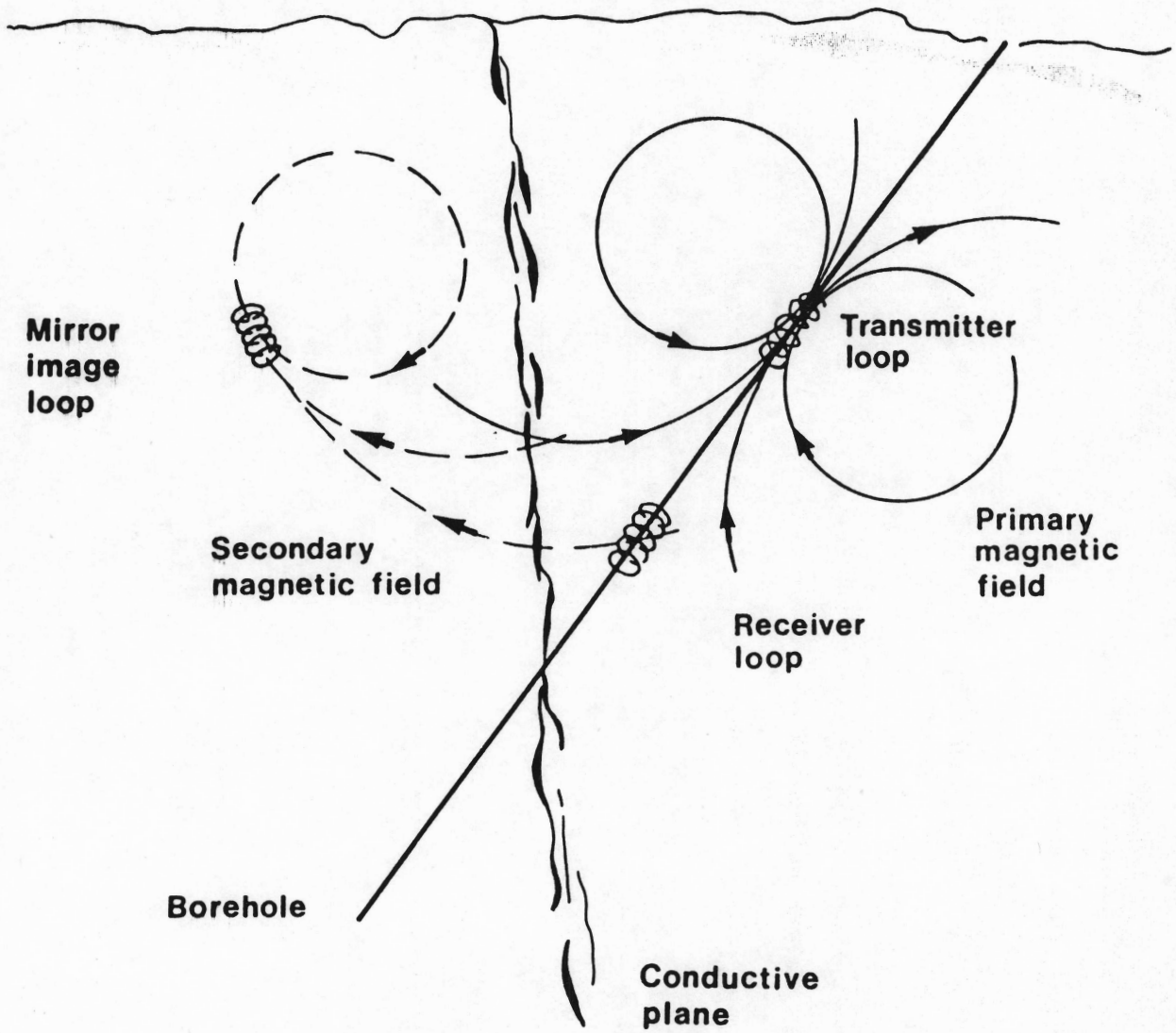


Figure 6. Principle of the borehole slingram method.

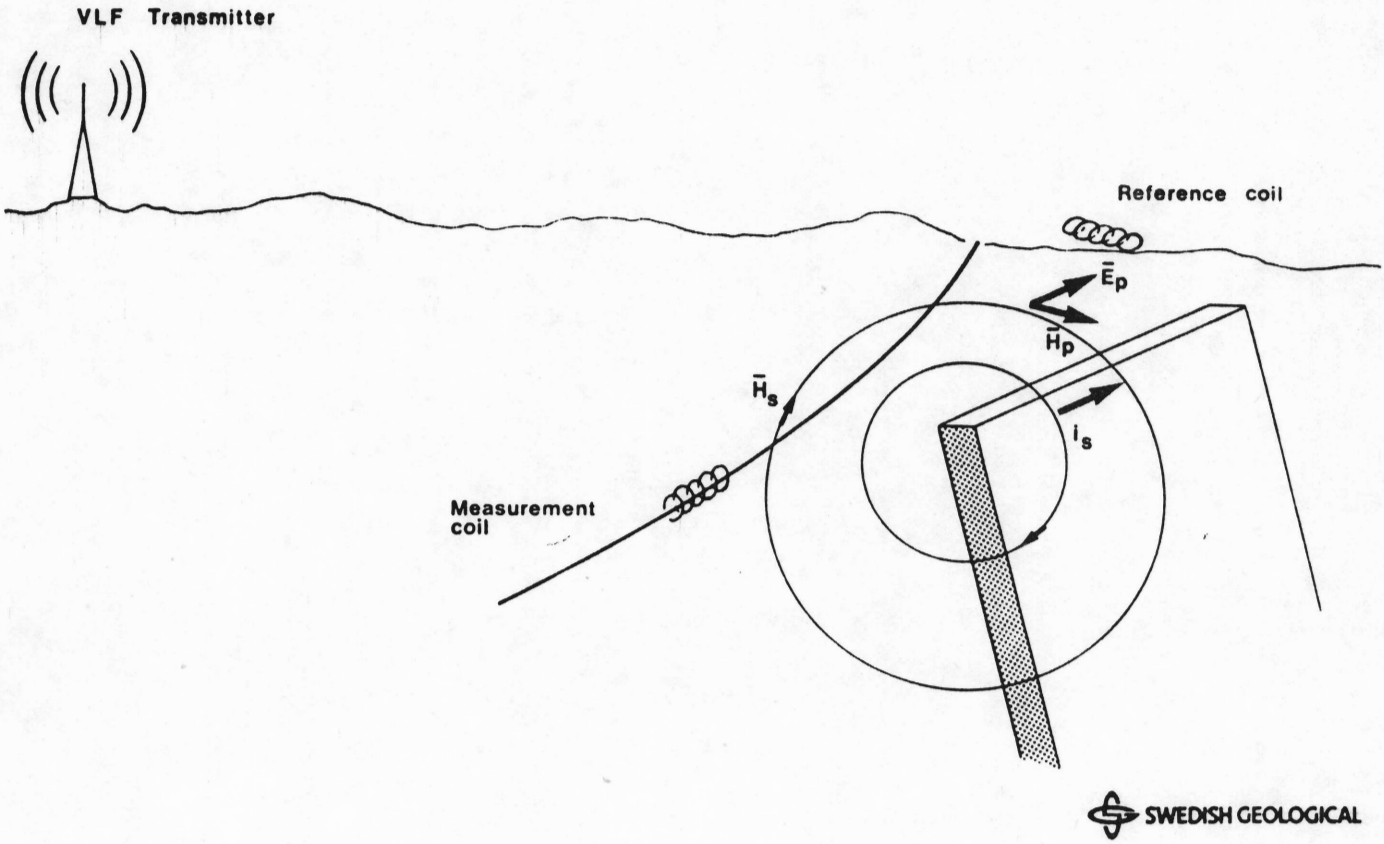


Figure 7. Principle of the borehole VLF- method.

1.13 Borehole magnetometer

The borehole magnetometer is mainly used in prospecting for iron ore. The borehole magnetometer measures the component of the magnetic field in three different directions.

1.14 Susceptibility/ inductive resistivity

The magnetic susceptibility of the rocks is measured with this sonde. The magnetic susceptibility log gives information of about the magnetite content of the rocks. Each rock type has a characteristic magnetite content and within the same rock type variation in susceptibility occur due to alteration and weathering. Thus, magnetic susceptibility measurements is very useful in order to classify rocks, espessially in crystalline rock formations.

The true resistivity of conductive rocks with a resistivity less than 1 ohmm can also be obtained with this sonde. The method is working in either air, water or oil filled boreholes. The inductive resistivity method is useful in the classification of conductive orebodies.

1.15 Natural gamma

The natural gamma sonde (Figure 8) will measure the natural gamma radiation of the bedrock. This log will give information of the total activity of the rock i.e. the summation of the potassium, uranium, and thorium contents. Variations in the concentration of these elements will normaly correspond to mineralogical changes in the rock.

The natural gamma ray sonde contain a detector of scintillation type. The active part of this detector is a crystal of NaI(Tl). The size of the crystal is 4" (0.1 m). The crystal is optically connected to a photomultiplier, which transforms the lightpulses created in the crystal to electrical signals proportional to the incoming gamma ray.

The natural gamma sonde is calibrated at a calibration

station. The probe is calibrated both in three constructed calibration models with well determined activities and both against a radioactive source with well known activity. Results can be presented in microroentgen per hour or in American Petrolium Industri units (API).

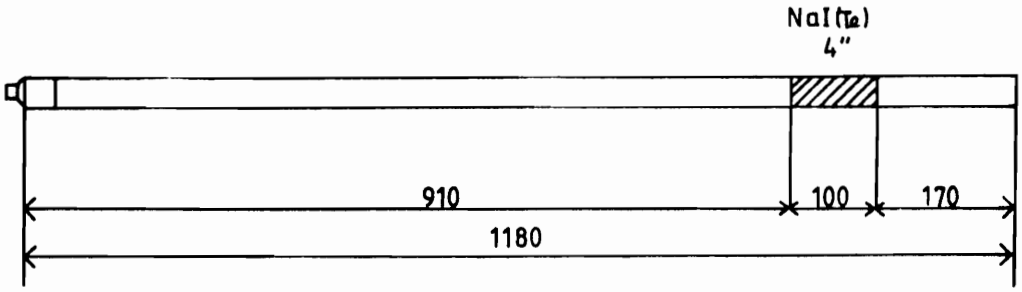


Figure 8. Natural gamma sonde

Diameter	42 mm
Lenght	1 180 mm
Weight in air	4.5 kg

1.16 Pulsegamma

Accurate determination of the natural gamma radiation in the borehole. The measured values are used to determine the contents of uranium.

1.17 Gamma spectrometer (K, U, Th)

The energy distribution of naturally emitted gamma photos is measured with this sonde. Gamma spectrometry is used for quantitative analysis of the content of potassium, uranium and thorium in the rocks near the borehole. The method is very useful for lihological classification of rocks and for uranium prospecting.

1.18 Gamma-gamma (density)/ one-arm caliper

The gamma-gamma sonde is used to determine rock density and can be used to make lithology determinations and determine variations in rock porosity and fractures.

The gamma-gamma (density) sonde (Figure 9) are made using a 300mCi Cs-137 source which emits gamma radiation and with a gamma-ray detector positioned at a distance of 0.25 m from the source.

The gamma-ray emitted will loose energy by Compton scattering collisions and other effects on their way through the formation. All these effects has a tendency to give a proportionally lower gamma ray reading in higher density formations. The reading is proportional to the electrone density of the formation. As there is a close relation between the electrone density and the bulk density of the formation, a log of the density variation along the borehole is obtained. This log also provides an porosity measurement as the bulk density depends on the fluid content in the rock and the porosity.

The one-arm caliper measurement is an integrated part of the gamma-gamma density sonde (Figure 9). The caliper has a function to press the sonde against the borehole wall. The caliper is designed to measure the distance of a caliper armtip to the sonde body, and thus the log measures the diameter of the borehole. The precence of larger open fractures will also be detected.

The gamma-gamma (density) sonde is calibrated in environments with known density. The system is calibrated in a water tank, in a laboratory-borehole with well determined densities and on an aluminium block. In field the system response is checked with an aluminium block and in water.

The response of the caliper is calibrated both in laboratory and in the field with a constructed box where the deflection of the caliper arm can be controlled and calibrated.

In the field the caliper response can be checked when lowering the sonde down through the casing.

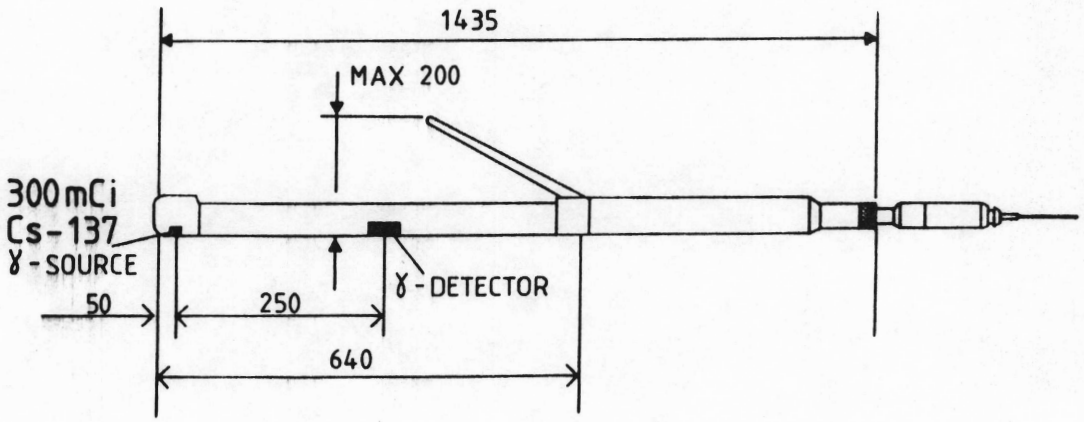


Figure 9. Gamma-gamma/caliper sonde

Diameter	52 mm
Lenght	1 435 mm
Weight in air	13.6 kg

1.19 Neutron-neutron (porosity)

The neutron-neutron sonde responds primarily to the hydrogen present in the formation. In clean formations the pore spaces are filled with water. Thus, the tool response will reflect the porosity. The method is also sensitive to variations in fluid inclusions in various bedrocks which in some cases enables lithology determinations. The method is also sensitive to mafic minerals such as iron and manganese.

The neutron-neutron sonde (Figure 10) contains a radioactive source of 5 Ci AmBe-241, which emits high energy neutrons into the formation. Two neutron detectors (He-3) are positioned at a distance of 0.26 m and 0.52 m from the source respectively.

The high energy neutrons will be slowed down by collisions with matter. The more the mass of the target equals the mass of the neutrons, the greater the loss of energy. Thus, the slowing down process of the neutron is primarly a function of hydrogen in the formation. After a few micro seconds the neutrons will slow down to what is called the thermal energy level. At this energy level these thermal neutrons can be captured by an atom, such as chlorine, hydrogen and silicon.

The instrument measures the amount of thermal neutrons present at the two detectors. The more the hydrogen present in the formation, the faster the neutrons will be slowed down and captured, and therefore less thermal neutrons are present at the detector to be counted.

Often the result is presented as the ratio of the counts at the front detector to the rear detector. If the ratio is high then more thermal neutrons have been captured in the formation between the front and the rear detector. In crystalline rock however, the porosity is low. Thus, depending on the distance from the neutron source, more neutrons still have a high energy at the front detector. Therefore less thermal neutrons will be counted at the front detector than the rear detector. Thus, the ratio between the counts at the front to the rear detector will be less than one in crystalline rock formations.

The neutron-neutron sonde is calibrated in well determined calibration models with known porosity values and controlled water contents in the pore spaces. The system is calibrated in three models at the university of Lund with porosity values of 27.2 %, 32.4 % and 39.8 %. These calibrations are used when measuring in sedimentary bedrock with high porosity.

When measuring in crystalline bedrock with small porosity values, the system is used to perform relative measurements because of the fact that no calibration models with such low porosity values exists today. At every field measurement the system response is checked with two plastic boxes.

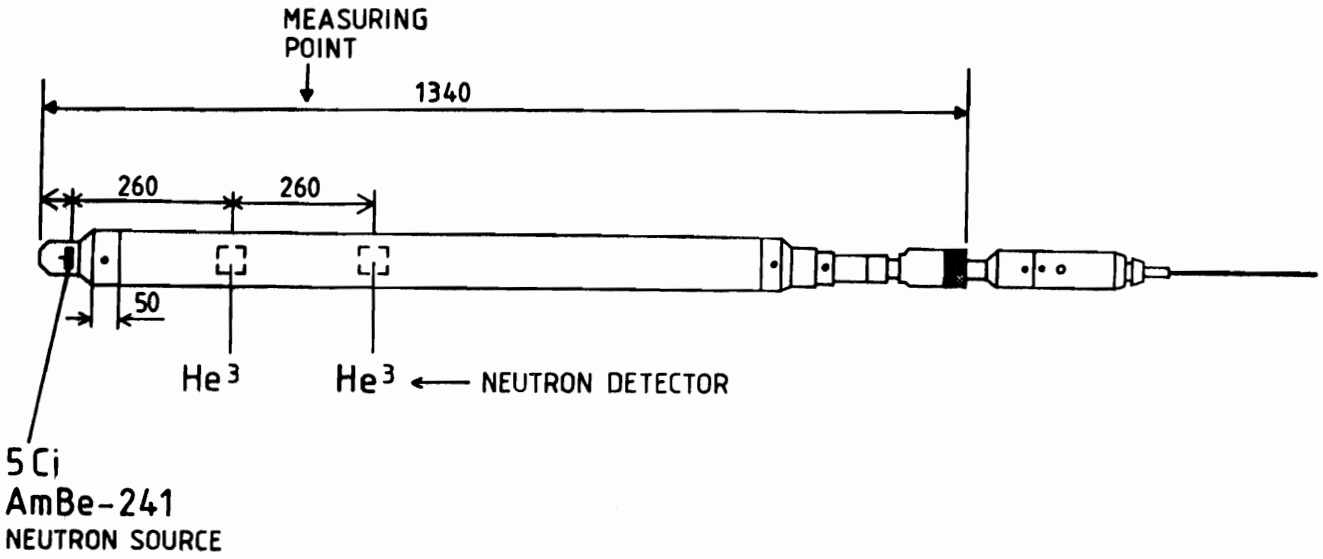


Figure 10. Neutron-neutron sonde

Diameter	54 mm
Lenght	1 340 mm
Weight in air	11.0 kg

1.20 Sonic velocity (acoustic)

The sonic velocity (acoustic) sonde records the time a compressional sound wave takes to travel a defined length between the two receivers through the investigated formation. Wave propagation is affected by the characteristics of the rocks (lithology, porosity, fractures and elastic parameters). The recording of the sonic sonde therefore contains useful information of these characteristics.

When the lithology in the borehole is known it is possible to determine the porosity of the bedrock. The individual components of a rock formation have characteristic travel times/ velocities for compressional waves. Thus, the travel

time through the entire formation is the sum of all the individual component travel times/velocities; namely the rock matrix and the fluid-filled pore/fracture space.

When run together with other borehole methods, sensitive to porosity, it can give useful crossplot information to establish better porosity determination and to conduct secondary porosity determination.

The sonic velocity sonde uses an acoustic transmitter of magnetostrictive type to generate a compressional sound wave (Figure 11). The elastic wave frequency of the transmitter are in the range of 20 000 Hz and is sent in short pulses with a firing rate of 15 Hz. The distance from the transmitter to the near reciever is 3 feet. The separation between the recievers are 1 or 2 feet. The time difference for the sound wave to travel between the two receivers are computed and the results are presented as microseconds per meter. Data can also be presented in s/ft, m/s or km/s.

The sonic velocity log is designed so that the direct sound wave through the sonde will propagate slower to the receivers than the sound wave propagating through the rock formation.

The measurements with the sonic velocity tool is dependent on the sonde geometry and a very accurate timing and no field calibration is therefore needed for the measurements.

The specification are as follows (Figure 11).

Diameter	52 mm
Length	3 860 mm
Distance transmitter-near receiver	915 mm
Distance between receivers	305 - 610 mm
Weight in air	22 kg

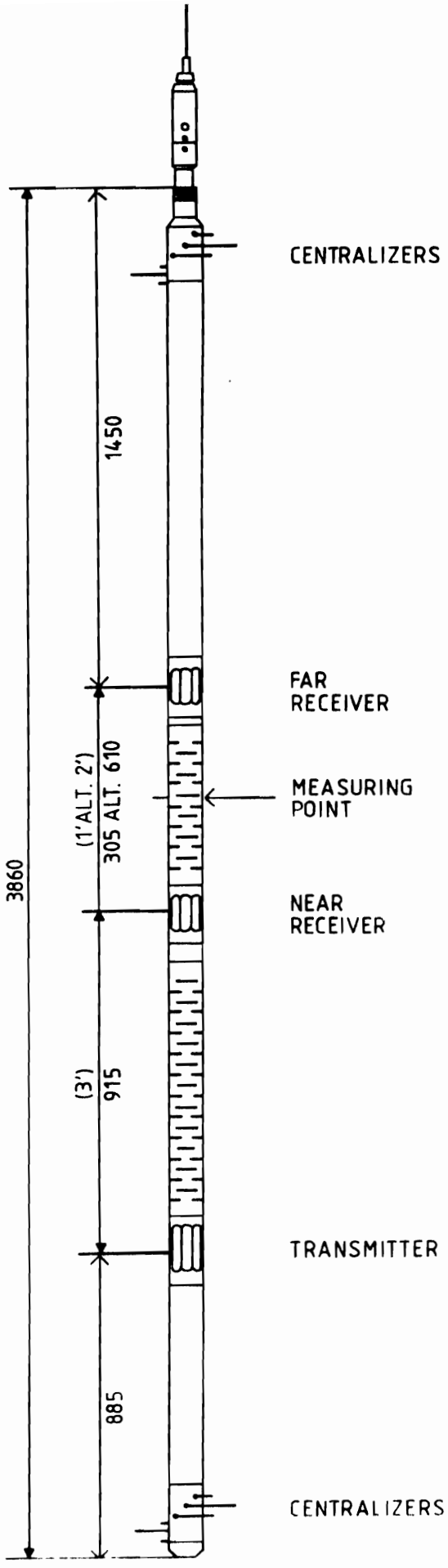


Figure 11. Sonic velocity sonde.

1.21 VSP (downhole seismics)

1.22 Tube wave

In an unbounded, homogeneous medium, elastic waves propagate in the form of longitudinal P- waves and transverse S- waves. A fluid can only support P-waves. However, a borehole can support guided surface waves propagating along the surface of the borehole with very little attenuation. Such waves are called "tube waves" or Stoneley waves. They have been the subject of investigations in borehole seismic surveys for many years, mainly because of their interfering effects in the identification of reflections in VSP-surveys (Vertical Seismic Profiling.

The velocity of propagation of tube waves is slightly lower than the P- wave velocity of the borehole fluid. The tube wave velocity depends on the fluid P- wave velocity, fluid density and the shear modulus of the formation surrounding the borehole. The tube wave is "bound" to the wall of the borehole in the sense that its amplitude decreases exponentially with distance from the borehole wall. Tube waves may be generated by mode conversion of P- or S- waves impinging on elastic discontinuities in the borehole, e.g. fracture zones.

A multichannel hydrophone array lowered stepwise into the borehole is used to identify permeable fractures and fracture zones intersecting the borehole (Figure 12). For each array position a small dynamite charge is detonated in a shallow shothole at an offset distance of 20 - 40 m from the well head. The seismic wave train is recorded with a hydrophone array, using 12 pressure sensitive hydrophones. The data is recorded digitally on a 24- channel signal enhancement seismograph and then transferred to a casette tape on an HP-85 desk top computer. The data can then be transferred to a main frame computer for permanent storage and subsequent analysis.

Elastic properties of the rock around a borehole can also be estimated from tube wave measurements. Thus, tube wave measurements may be used to obtain a measure of the average

elastic properties of a large volume of rock.

In general, there is a good correlation between tube wave sources and sections of high or increased hydraulic conductivity in the borehole. In general terms, it appears that tube waves may be detected from zones with a hydraulic conductivity exceeding 10^{-10} m/s. The tube wave method is a good tool for the detection of permeable fracture zones in a borehole. The method can only give qualitative results but it is considerably quicker than hydraulic injection tests. For example, the tube wave data can be used for the selection of sections for detailed hydraulic tests, or for the selection of sampling points for hydrogeochemical studies. It should be noted that tube waves may also be generated by clay filled impermeable fracture zones.

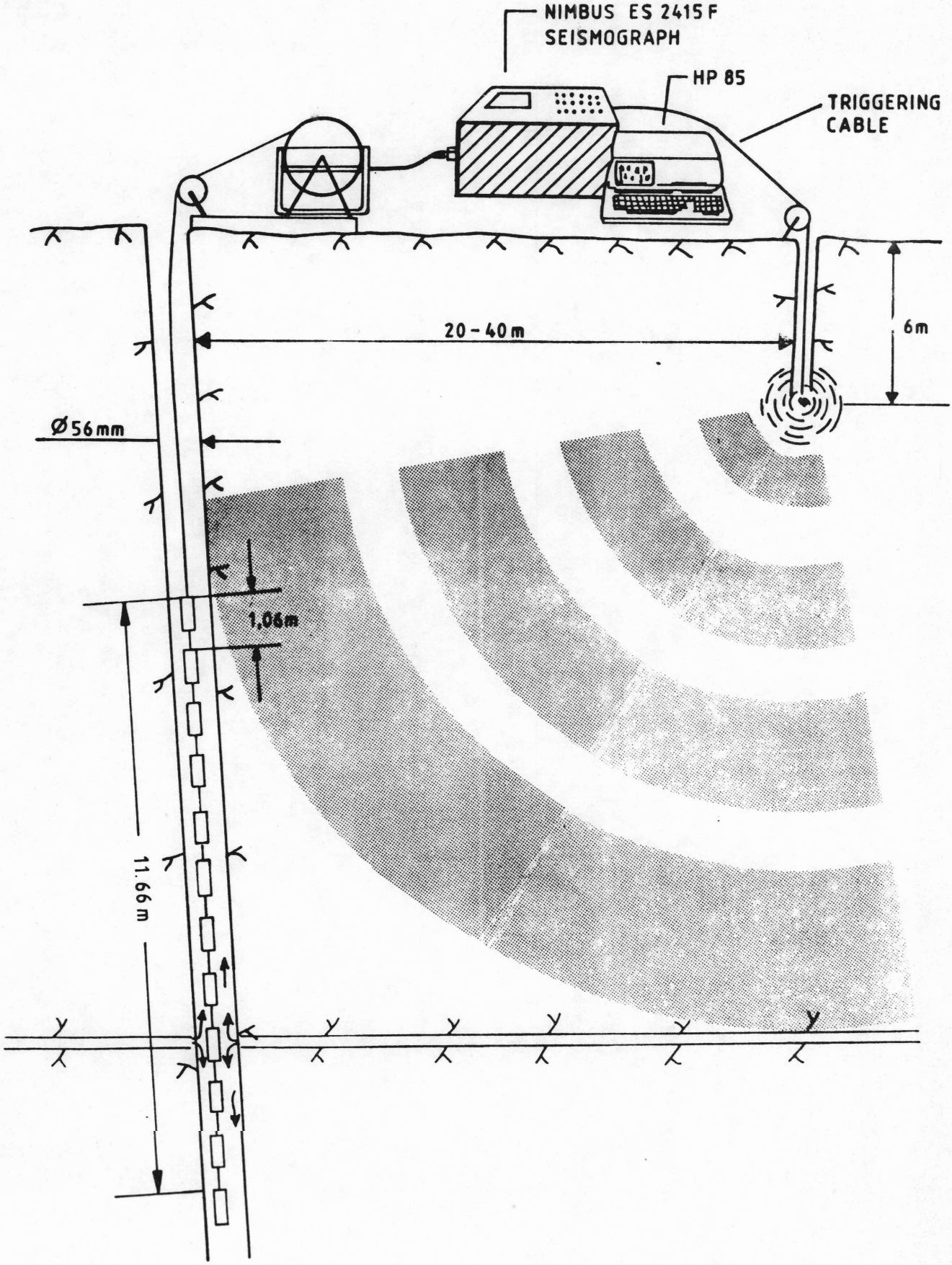


Figure 12. Principle of the tube wave method using a multiple hydrophone array lowered into the borehole.