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Hydrometric determinations — Geophysical logging of boreholes for hydrogeological purposes — Considerations and guidelines for making measurements

Déterminations hydrométriques — Répertoriage géophysique des trous de sonde pour des besoins hydrogéologiques — Considérations et lignes directrices relatives aux mesurages

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ISO copyright office
Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.ch
Web www.iso.ch

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Foreword

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The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

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Attention is drawn to the possibility that some of the elements of this Technical Report may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO/TR 14685 was prepared by Technical Committee ISO/TC 113, *Hydrometric determinations*, Subcommittee SC 8, *Ground water*.

Introduction

Geophysical logging of boreholes, wells and/or shafts (hereafter referred to as boreholes) for hydrogeologic purposes provides a measurement of various physical and chemical properties of formations penetrated by a borehole and of their contained fluids. Sondes measuring different parameters are lowered into the borehole and the continuous depthwise change in a measured parameter is presented graphically as a geophysical log.

Geophysical logging of boreholes is carried out to obtain information on:

a) the lithology of the formations through which the borehole is drilled;

b) the occurrence, quantity, location and quality of formation fluid (usually water);

c) the dimensions, construction and physical condition of the borehole.

The logging equipment consists essentially of three parts: the downhole sensor and oblique tool (hereafter referred to as a sonde); cable and winch; power and a surface system of power, signal processing and recording units (see Figure 1).

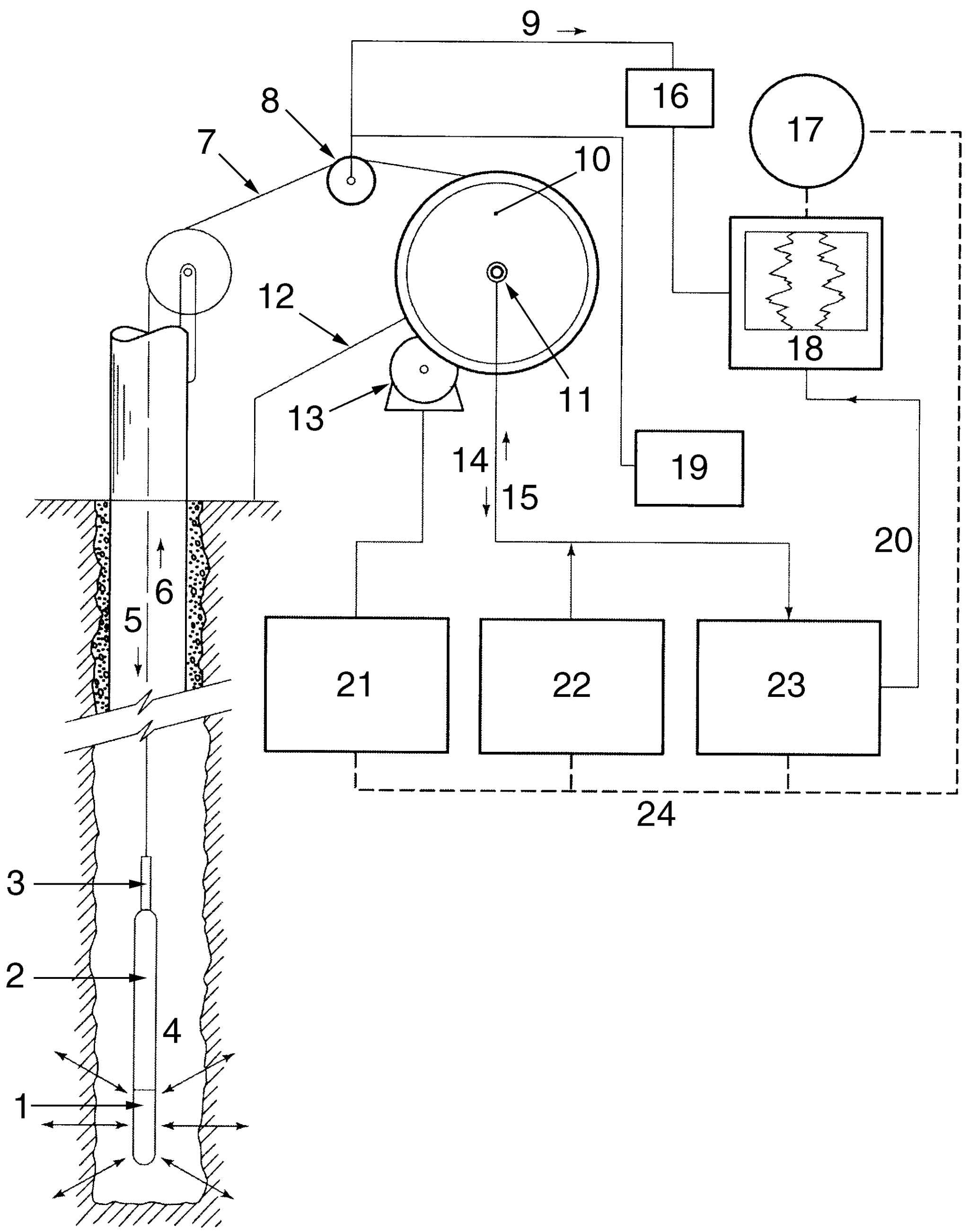
The various sondes contain sensors to enable specific properties to be measured. Output from the sondes is in the form of electronic signals, either analogue or digital. These signals are transmitted to the surface instruments via the cable and winch.

The cable serves the dual purpose of supporting the sonde and conveying electrical power and signals to and from the sonde. To this end it has a double outer layer of high tensile steel or polyurethane/kevlar.

The winch serves to raise or lower the sonde and to measure its precise depth. This is achieved by passing the cable round a measuring sheave of known diameter linked to an accurate depth measuring system.

The surface instrumentation typically consists of two sections to provide power and process the electronic signals from each of the sondes for recording purposes.

Data recorder units are either analogue or digital, comprising pen and ink recorders, film, a dedicated computer, encoding the signal data from the sonde or surface modules, formatting them and storing them on magnetic tape or disk, and driving the plotter to produce filed logs.



Key

1 Sensor
2 Electronic section
3 Cable head
4 Sonde
5 Power (down)
6 Signal (up)
7 Logging cable
8 Cable-measuring sheave
9 Recorder drive
10 Winch
11 Slip ring
12 Ground (electric logging)
13 Motor
14 Signal
15 Power
16 Vertical scale control
17 ac power source (regulated)
18 Recorder
19 Depth indicator
20 Varying dc voltage (mV) for driving recorder pens
21 Logging speed and direction
22 Downhole power (not universal)
23 Signal conditioning; zero positioning; sensitivity; time constant etc.
24 Logging controls

NOTE Taken from reference [14].

Figure 1 — Schematic of a basic geophysical logging system

Hydrometric determinations — Geophysical logging of boreholes for hydrogeological purposes — Considerations and guidelines for making measurements

1 Scope

This Technical Report is a summary of best practice for those involved in geophysical borehole logging for hydrogeological purposes. It describes the factors that need to be considered and the measurements that are required to be made when logging boreholes. There can, however, be no definite “standard” logging procedure because of great diversity of objectives, groundwater conditions and available technology. Geophysical logging of boreholes is an evolving science, continually adopting new and different techniques. Every application poses a range of problems and is likely to require a particular set of logs to gain maximum information. This Technical Report therefore provides information on field practice with the objective of how variations in measured parameters may be useful to take account of particular local conditions. It deals with the usual types of logging carried out for delineation of aquifer boundaries; mapping aquifer geometry; assessing the chemical quality and quantity of ground water; water-supply purposes; landfill investigations and contamination studies; borehole construction and conditions; and subsurface lithological information.

Applications not specifically considered in this Technical Report include mineral and hydrocarbon evaluation and geotechnical and structural engineering investigations. However, this Technical Report may be a source of general information for any borehole geophysical logging effort.

NOTE Interpretation of the data collected during logging is referred to in this Technical Report only in a general way. For full details of the analysis and interpretation of geophysical logs, reference should be made to specialized texts. Examples of such texts are included in the Bibliography.

2 Terms and definitions

For the purposes of this Technical Report, the following terms and definitions apply.

2.1
abstraction
removal of water from a borehole or well

2.2
access tube
dip tube
pipe inserted into a well to permit safe installation of instruments, thus safeguarding them from touching or becoming entangled with the pump or other equipment in the well

2.3
air lifting
method of producing a discharge of water from a borehole by the injection of compressed air

2.4
aquifer
lithological unit, group of lithological units, or part of a lithological unit containing sufficient saturated permeable material to yield significant quantities of water to wells, boreholes, or springs

2.5
aquifer properties
properties of an aquifer that determine its hydraulic behaviour and its response to abstraction

2.6
argillaceous
containing clay minerals

2.7
bed resolution
minimum bed thickness that can be resolved

2.8
bonding
seal between a borehole lining and the geological formation

2.9
cable boom
rigid support from which the geophysical sonde and cable are suspended

2.10
calibration tail
section of field log carrying information on sonde calibration

2.11
casing
tubular retaining structure, which is installed in a drilled borehole or excavated well, to maintain the borehole opening

NOTE Plain casing prevents the entry of water.

2.12
casing string
set of lengths of casing assembled for lowering into a borehole

2.13
composite log
several well logs of the same or similar types suitable for correlation, spliced together to form a single continuous record

2.14
core
section of geological formation obtained from a borehole by drilling

2.15
curve matching
comparison of individual borehole data in graphical form with standard or control data

2.16
drawdown
reduction in static head within the aquifer resulting from abstraction

2.17
drilling circulation
movement of drilling fluid (air foam or liquid) used to clear the borehole during drilling

2.18
filter pack
granular material introduced into a borehole between the aquifer and a screen or perforated lining to prevent or control the movement of particles from the aquifer into the borehole

2.19
fishing tool
grappling equipment used to locate and recover items from within a borehole

2.20
flushed zone
zone at a relatively short radial distance from the borehole immediately behind the mudcake where all of the pore spaces are filled with borehole fluid

2.21
fluid column
that part of a borehole filled with fluid

2.22
formation
geological unit or series of units

2.23
geophysical log
continuous record of a physical or chemical property plotted against depth or time

2.24
grain size
principal dimension of the basic particle making up an aquifer or lithological unit

2.25
grout
cement and water mixture

2.26
header information
description of type of data required for inclusion in a table or as input to a computer program

2.27
invaded zone
portion of formation surrounding a borehole into which drilling fluid has partially penetrated

2.28
jig
calibrating device for logging sondes

2.29
leachate
liquid that has percolated through solid wastes

2.30
lining
tube or wall used to support the sides of a well and sometimes to prevent the entry of water

2.31
lithology
physical character and mineralogical composition that gives rise to the appearance and properties of a rock or sediment

2.32
logging
recording of data

2.33
mud cake
residue deposited on the borehole wall during drilling

2.34
open borehole
unlined borehole

2.35
packer
device placed in a borehole to seal or plug it at a specific point

2.36
permeability
characteristic of a material that determines the rate at which fluids pass through it under the influence of differential pressure

2.37
photomultiplier
electronic device for amplifying and converting light pulses into measurable electrical signals

2.38
plummet
plumb bob used for determining the apparent depth of a borehole

2.39
porosity
ratio of the volume of pore space in a sample to the bulk volume of that sample

2.40
rising main
pipe carrying water from within a well to a point of discharge

2.41
rugosity
degree of roughness (of the borehole wall)

2.42
saline interface
boundary between waters of differing salt content

2.43
saturated zone
that part of earthen material normally beneath the water table in which all voids are filled with water that is under a greater-than-atmospheric pressure

2.44
screen
type of lining tube, with apertures designed to permit the flow of water into a well while preventing the entry of aquifer or filter pack material

2.45
sidewalling
running a log up or down a borehole with the sonde in contact with the borehole wall

2.46
sonde
cable-suspended probe or tool containing a sensor

2.47
unconfined aquifer
water bearing formation with a free water surface

2.48
unconsolidated rock
rock that lacks natural cementation

2.49
unsaturated zone
that part of earthen material between the land surface and the water table

2.50
washout
cavity formed by the action of drilling

2.51
water table
surface of the saturated zone at which the water pressure is atmospheric

2.52
API unit
American Petroleum Institute unit
unit or counting rate used for scaling gamma-ray logs and neutron logs

3 Units of measurement

Table 1 gives a list of parameters and units of measurement in common use. Historically there has been a mix of units, many from the oil industry and the United States.

Table 1 — Parameters and units of measurement

Parameter	Units of measurement	Logging method
Electrical resistivity	Ωm	Resistivity
Electrical conductivity	mS/m	Induction
Electrical potential	mV	Spontaneous potential (SP)
Natural gamma radiation	API units (see 2.52)	Gamma-ray
Porosity	Percent “matrix” porosity where matrix has to be stated as sandstone, limestone or dolomite porosity	Neutron; gamma-gamma; sonic
Bulk density	g/cm^3	Gamma-gamma (Compton effect)
Acoustic velocity	m/s	Sonic
Fluid temperature	°C	Fluid temperature
Temperature gradient	°C/m	Differential temperature
Fluid conductivity	µS/cm	Fluid conductivity
Conductivity gradient	S/m^2	Differential conductivity
Fluid velocity	mm/s	Flowmeter; heat pulse flowmeter; tracer pulse flowmeter; packer-flowmeter (PFM); repeated fluid conductivity/temperature logging
Borehole diameter	mm	Calliper
Cement bonding	%	Sonic bond
Casing condition	mV	Casing collar location (CCL)

4 Purpose of geophysical logging

4.1 General

Ideally, every borehole drilled for hydrogeological purposes should be geophysically logged. For a small percentage (typically 2 % to 10 %) of the cost of drilling a borehole, the return of information derived from geophysical logs can far exceed that derived from drilling samples. Logging costs are an even smaller percentage of total costs for developing a groundwater source or remediation of contamination. Even when a borehole is totally cored and 100 % recovery is achieved, many geophysical logs will continuously sample many times (10 or more) the volume of the cores.

Not only are coring and subsequent laboratory analysis very expensive, they are also time-consuming. Long-term storage of cores presents problems but digital data of geophysical logs can be stored and recalled easily. Whilst there can be no substitute for high quality lithological samples for determining strata classification, lithology, mineral content and grain size, the geophysical log provides *in situ* data on the hydrogeological regime around the borehole. Also, it provides correction for depth uncertainty of lag in sample collection.

Boreholes drilled for hydrogeological investigation are not often cored and good sample collection techniques are often difficult to achieve. Sample quality is unpredictable in these circumstances and sampling will not be possible where drilling circulation is lost. It is in such situations that geophysical logging provides a continuous quantitative set of data when compared with the drilling samples, which are always subjective. Furthermore geophysical logging can be used in old boreholes where geological records are undocumented.

In addition to lithological interpretation, a number of physical and chemical properties of the surrounding rock and fluids contained therein can be investigated.

Geophysical logs can be run in all boreholes including those cased with metal or plastic casing and filled with water, brine, mud, drilling foam or air. The greatest return of information is derived from open (uncased) boreholes filled with formation water or mud. In plain-cased boreholes, investigation of the geological formation is limited to the nuclear logs and, with plastics casing, induction logs may also be used. Conventional resistivity logs (especially focused ones) are possible to use in plastic screens.

The wealth of information from geophysical logs means that they can be used in many spheres of hydrogeological investigation; for example, in water resources projects to investigate aquifer hydraulics and distribution of yield within an aquifer of group of aquifers. In the rapidly expanding field of groundwater quality control, geophysical logging is now extensively used to monitor groundwater pollution, to trace leachate movement and to monitor the boundaries between saline interfaces.

Borehole logging is also important in investigating the deep hydraulic and hydrogeological properties of rocks in geothermal and radioactive waste disposal projects. There are a number of engineering applications of geophysical logging for investigating borehole conditions and, where television logging is available, for the inspection of casing and pumps.

Figure 2 shows an example of a composite log where the disposition of aquifers can be seen.

Geophysical logging can be repeated many times in a borehole or series of boreholes at intervals ranging from minutes to years, adding a new dimension to the information obtainable. This is particularly applicable to aquifer hydraulics and recharge and pollution studies.

Geophysical logs also provide information that can be directly used in surface geophysical studies for standardization and calibration of parameters. For example, sonic logs can be calibrated with seismic sections and resistivity logs can be compared with surface electrical resistivity surveys for resistivity standardization.

4.2 Formation logging

4.2.1 General

No geophysical log has a unique response to a particular rock type or named stratigraphic unit and at some point in any hydrogeological investigation the formation logs have to be referred to a borehole with a well-described set of samples.

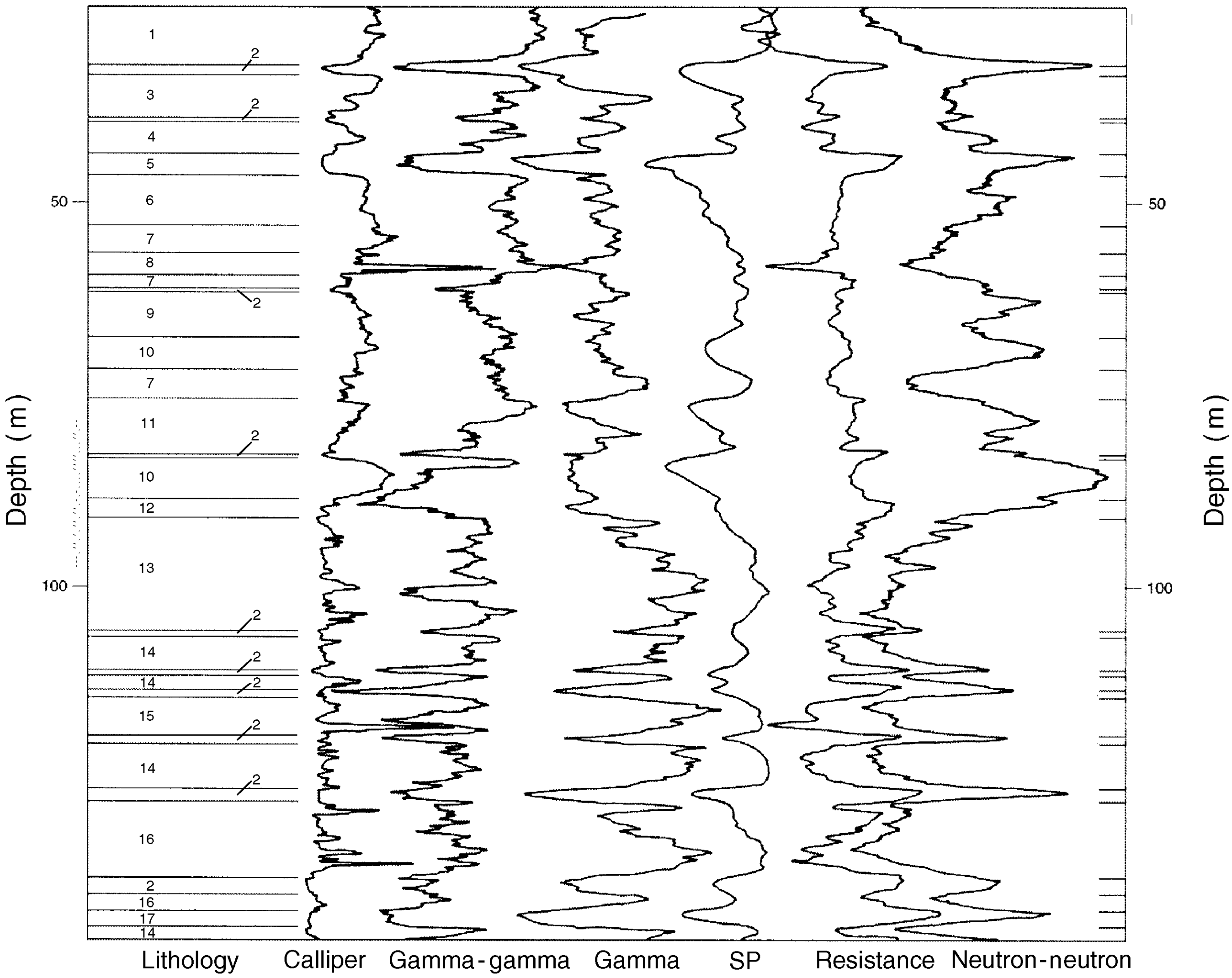
It is important therefore that formation logs should be run not just in boreholes where incomplete or no samples are available but in all boreholes, particularly any which have been cored. The three main purposes of formation logging are described in 4.2.2 to 4.2.4.

4.2.2 Identification of lithology

Geophysical logging can provide a very detailed description of subsurface formation lithologies. Some logs such as the natural gamma log commonly provide an unambiguous delineation of shale and shale-free zones, with the SP and electrical resistivity logs supplying supporting evidence. Other logs are generally not diagnostic on their own but in combination can provide accurate information. The combination of calibrated neutron porosity and density logs, for example, will differentiate sandstone, limestone and dolomite of different porosities. The additional information provided by the sonic log enables the identification of halite, gypsum and other minerals.

Where calibrated logs are unavailable, differentiation of lithology will require some geological knowledge, this often being obtained from examination of core samples or cuttings. Where core recovery is incomplete, geophysical logs will normally provide a complete lithological description together with accurate depths to lithological boundaries.

The use of geophysical log interpretation is a major factor in the design of casing strings particularly in large thicknesses of variable unconsolidated alluvial sediments. The positioning of plain and screen casing is commonly based entirely on a natural gamma log run in a temporarily cased borehole.



Key

1 Poorly cemented very fine sandstone and siltstone
2 Anhydrite
3 Very fine sandstone
4 Very fine sandstone and siltstone with anhydrite
5 Anhydrite and shale
6 Very fine sandstone with shale and anhydrite nodules
7 Very fine sandstone and siltstone
8 Halite veins in siltstone
9 Halite veins and nodules in very fine sandstone and siltstone
10 Halite cemented very fine sandstone and siltstone
11 Hard halite cemented siltstone
12 Anhydrite and dolomite
13 Siltstone grading down into mudstone with anhydrite and halite veins and nodules
14 Mudstone
15 Mudstone with halite veins
16 Mudstone with anhydrite nodules
17 Dolomite

NOTE Taken from reference [14].

Figure 2 — An example of a composite suite of geophysical logs

4.2.3 Lithological correlation

Correlation is a particularly important use of geophysical logs. Individual sections of geophysical logs may have distinct shapes or characteristic signatures that can be manually matched with the same features on logs from adjacent boreholes, thus signifying that the lithological units extend from borehole to borehole.

Such identifications reveal the geometry of the units from which the continuity and boundaries of aquifers can be established.

Correlation of logs is carried out by curve matching logs of similar types using the same depth scale (Figure 3). With a number of recent techniques, which include the computer digitization of logs and the direct recording of logs in the field for replay on different scales in the office, it is possible to correlate or display the logs from a wide range of sites in a uniform manner for ease of correlation. In particular the logging of disused boreholes in an area of investigation can also prove productive.

Correlation may also be accomplished using computers. This is particularly useful where the log responses are less clearly defined and more than two logs per borehole are being assimilated simultaneously.

4.2.4 Evaluation of physical properties

The third purpose of formation logging is for physical property measurements and this permits quantitative interpretation of geophysical logs.

In certain cases other parameters such as permeability can be estimated where they can be related to, for example, porosity or clay content by an independent means.

Geophysical logs can be interpreted to determine the following properties: formation resistivity; formation fluid resistivity (often measured as fluid electrical conductivity); formation resistivity factor; clay content; bulk density; primary porosity; secondary or fissure porosity; zones of water movement; zones of contamination; aquifer boundaries; borehole geometry; casing position and type; casing condition, bonding and borehole condition.

4.3 Fluid logging

4.3.1 General

The most important geophysical logs run, for investigating the borehole fluid column, are borehole flowmeter logs (both mechanical and thermal), fluid conductivity logs and fluid temperature logs. Fluid logs are run for three main reasons:

a) to determine flow in the borehole;

b) to identify regional groundwater movement;

c) to assess groundwater quality.

4.3.2 Flow in the borehole

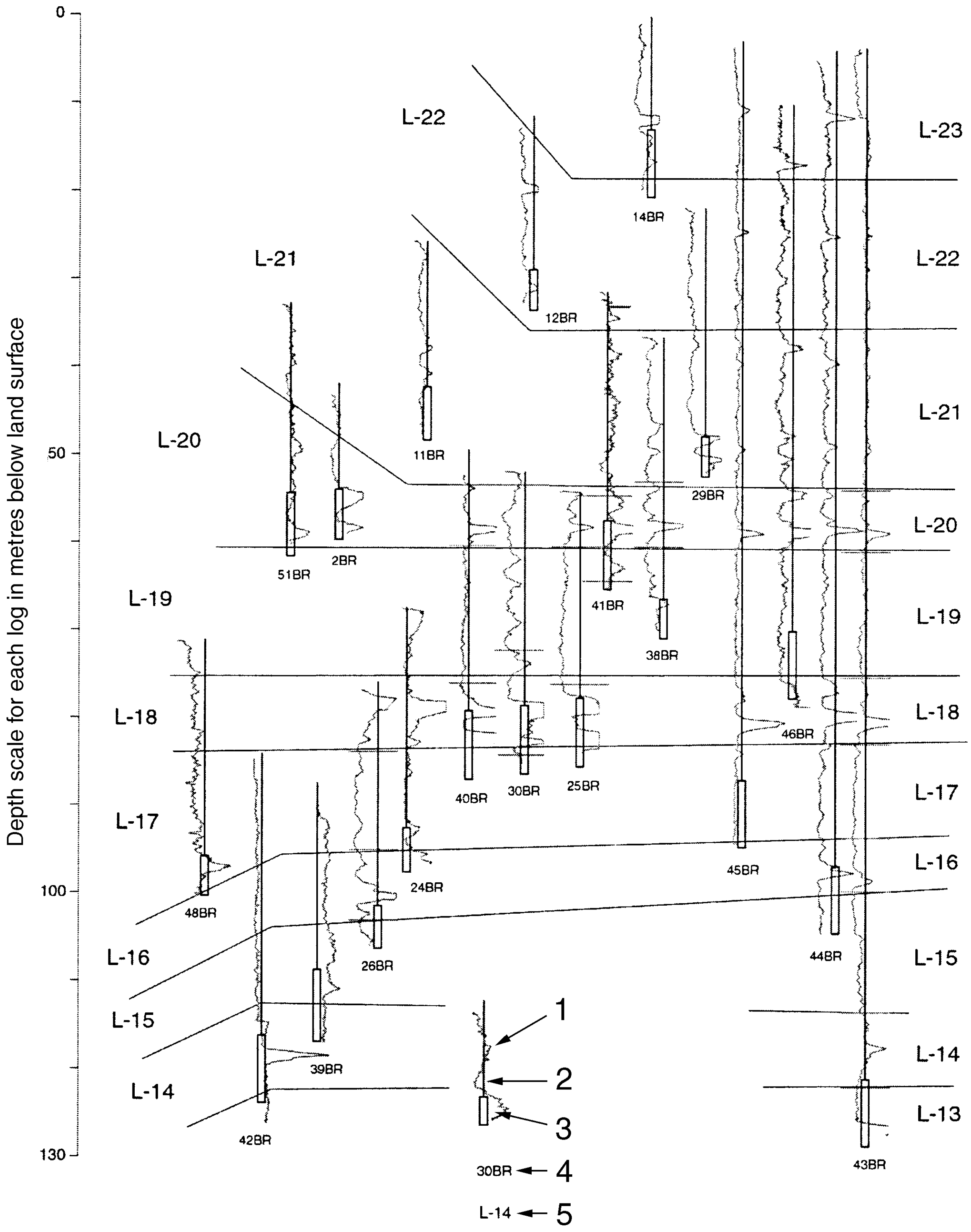
The existence of an open borehole may connect zones of differing *in situ* hydraulic head and water quality. Recognizing and understanding the effects of natural flow mixing by use of fluid logs is often important to the general hydrogeological interpretation of the site. During the drilling and subsequently with time, flow mixing will occur within the water column (see Figure 4).

When pumping or artesian movement induces flow conditions, fluid logging can accurately determine the depths from which the yield of the borehole is being derived. In fissured aquifers, fluid logs will indicate those fissures that are contributing yield. Accuracy will increase if supported by temperature logs.

Where a borehole penetrates more than one aquifer the contribution from each can be identified. Using flowmeters, quantitative measurements of the flow being derived form each zone or horizon of interest are often carried out.

In appropriate situations, fluid logs can be taken in recharge boreholes or through a packer assembly to identify active fissures, flow rate and direction, and water quality changes with time. This requires careful consideration of borehole access arrangements.

Evidence of cascading and seepage can be obtained from closed-circuit television (CCTV) logs.



Key

1 Natural gamma-ray log, radiation, in counts per second increase to the right

2 Well casing

3 Well screen interval

4 Local well number

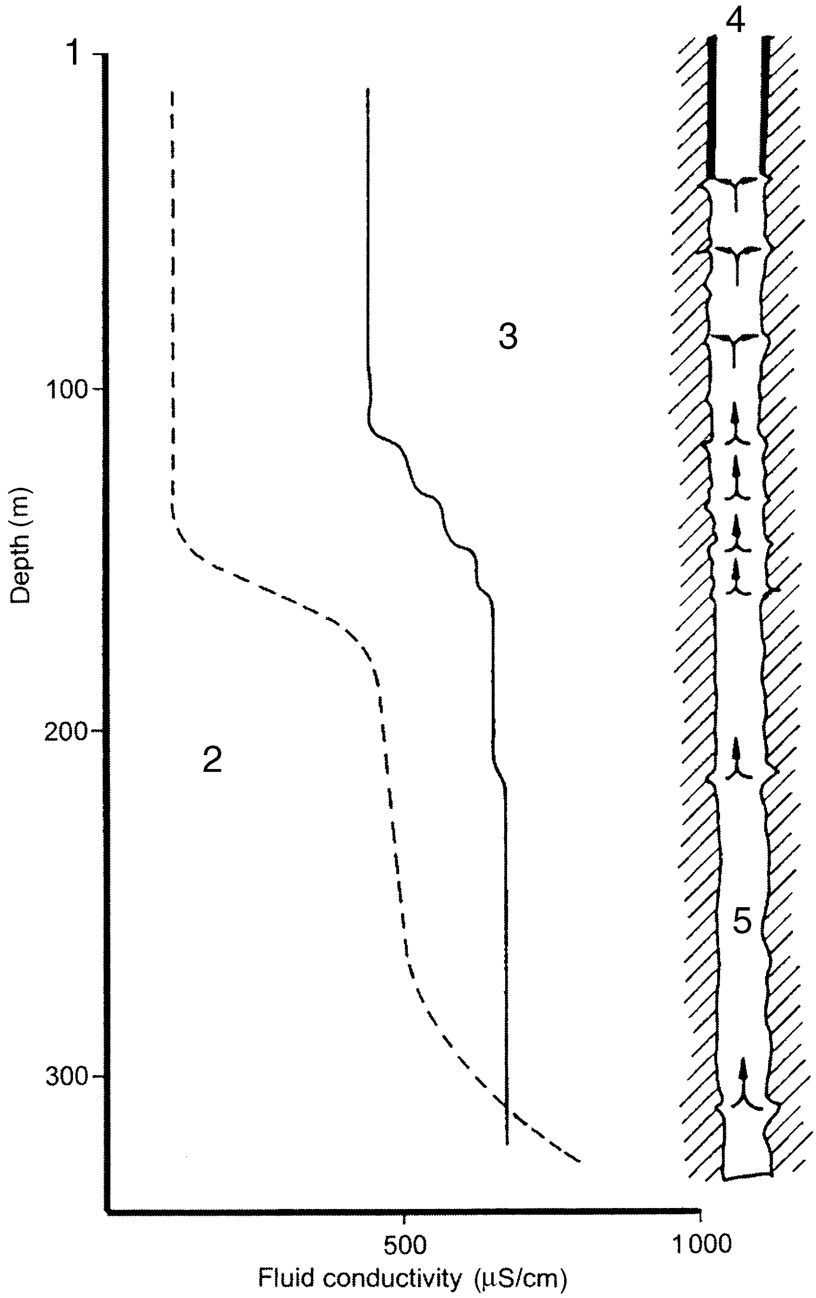
5 Bedding units

NOTE Taken from reference [16].

Figure 3 — Correlation between boreholes using natural gamma-ray logs

4.3.3 Identifying regional groundwater movement

This type of logging involves repeating logs over a period of time in a network of boreholes to monitor a particular parameter that is indicative of lateral groundwater movement. An example would be a borehole near a river. The logging of fluid temperature and fluid conductivity profiles in a series of observation boreholes between the abstraction borehole and the river, may indicate a tongue of river water being drawn towards the pumped borehole. These techniques have a particular application to the monitoring of landfill sites, where the movement of fluid leachate from a site can in some cases be traced using logs run in sampling boreholes drilled around the landfill area. Determining the direction and extent of leachate flow is a major use of fluid logging and is usually combined with a chemical sampling program and electrical logging.



Key

1 Ground level
2 Undisturbed formation porewater profile
3 Fluid log resulting from flow mixing
4 Borehole
5 Fissure flow

Figure 4 — Example of the effect of flow mixing in a borehole

4.3.4 Groundwater quality

Fluid conductivity measurements in the borehole give a first indication of the chemical quality of groundwater present. The conductivity of the water in the borehole may not necessarily be the same as in the formation alongside; particularly where there are several producing horizons or aquifers present having different hydraulic heads. Different fluids controlled by the natural hydraulic gradient may invade some horizons. Careful interpretation of the fluid logging data therefore needs to be made.

Fluid conductivity logging is usually performed under different hydraulic conditions usually without pumping and during pumping. Overlay plotting of the curves is used to identify locations where log changes, and hence water movement, takes place.

Inflows of different fluid conductivity, fresher, or more saline waters (often also of different temperature) can then be easily identified.

Water quality monitoring instruments which simultaneously measure a range of parameters including fluid conductivity, fluid temperature, dissolved oxygen, pH, redox potential and ion selective possibilities are increasingly used downhole. They are generally, though not exclusively, run on independent equipment and may make measurements in depth-profiling or data-logging mode. Currently, equipment typically allows a submergence of 150 m to 200 m, though specialist equipment is available for use at greater depths.

4.4 Construction logging

The purpose of this type of logging is to investigate the condition and construction of a borehole, its casing and any equipment installed in it. The most commonly used logging method is the three arm borehole calliper. The resulting log will indicate location of any sidewall features such as collapses, caving, obstructions, washouts and formation features such as fissures. In the cased section differentiation between plain and slotted screen is commonly possible and in some cases, casing joints and casing damage can be detected.

Another use of calliper logging is borehole volumetric calculation. Some logging systems carry out this computation in real time and display the data during logging, but generally, where the calliper log is digitally stored, volumetric calculations are carried out by software on the replayed data.

Two other logging sondes can be used to examine the borehole casing. One is the casing collar locator that is an electromagnetic device that detects the joints between casing lengths. The other is the cement bond log that uses an ultrasonic signal to determine the bonding between cement grout and the casing.

Where water clarity is good, borehole television logging using both axial and radial viewing attachments provides a very detailed visual log of all the features detectable on a calliper log, in addition to the ability to inspect borehole equipment such as pumps, transducers, and pipework and detect vertical and oblique fractures not detected by a calliper log.

4.5 Selection of logs

The nature of the investigation will dictate the geophysical logs required, i.e. whether it is formation evaluation, determination of the fluid characteristics and flow regime or a check on the borehole construction. The aim of the logging should be clearly defined and the limitations imposed by borehole construction should be considered so that the correct suite of logs is selected.

Selection of logs will be constrained by the borehole diameters presence and type of casing and borehole fluid, as well as the physical limitations of the particular geophysical method. The time available for logging may be restricted, therefore consideration has to be given to logging speeds and availability of sonde log combinations. Table 2 summarizes the applications and limitations of geophysical logs and may be used as a guide to their selection.

It is also necessary to consider the sequence of logging. For example, temperature fluid conductivity and chemical logs may be carried out during or immediately after drilling. Fluid and formation logging can be used to evaluate the lithology and groundwater chemistry so that the final depth of the borehole may be determined or a decision made for optimum location of casing or borehole screen.

5 Planning

5.1 General considerations

Under field conditions, especially where remote or rugged terrain and harsh weather conditions may influence efficiency and data quality, there is much to be gained from careful and realistic planning. General planning as far as possible in terms of the provision of equipment and operational procedures will assist in providing better overall reliability, a consistent approach by different operators and improvements in safety. This should underlie the detailed preparations required for any specific logging exercise. Planning in a general sense should include consideration of the following:

a) durability, effectiveness and accuracy of equipment under worst anticipated conditions of vibration, dust, humidity and weather;

b) reliability of power supplies;

c) layout of equipment and ease of access to instruments for operation and maintenance;

d) versatility of supporting equipment such as cable booms, tripods and pulley arrangements;

e) suitability of vehicles including capacity and manoeuvrability;

f) operator comfort including adequate temperature control, light and seating;

g) routine logging and calibration procedures, pre-log check lists, predetermined conventions for setting up logs, etc.;

h) safety aspects including internal and external electrical connections and earthing, cable and winch safety, avoidance of awkward angles, steps and heavy lifting, fire extinguishers and safety kits (including a gas monitor) and the number of persons on site;

i) the need for fishing tools to recover lost sondes;

j) liability for loss of equipment down the borehole;

k) establishment of a written safety code.

Table 2 — Application and limitation of geophysical logs

Logging method	Formation evaluation							Fluid properties				Construction features								Borehole limitations							Sonde features			
	Lithology	Bed thickness	Bed boundaries	Correlation	Permeable zones	Porosity	Density	Borehole fluid quality	Fluid movement	Formation fluid quality	Water level	Casing features	Casing location	Cement bonding	Cement location	Collapses	Caving behind lining	Diameter	Fissures	Air filled	Mud filled	Water filled	Lined (steel)	Lined (plastics)	Open hole	Quality reduces with increasing borehole diameter	Centralized	Free	Sidewalled	Typical logging speeds (m/min)
Resistivity (normal, lateral, focused)	■	■	■	■		■				■	■		■						■		■	■			■	■		■		5 to 15
Single point resistance	■	■	■	■							■		■						■		■	■			■	■		■		5 to 15
Self potential	■	■	■	■	■					■	■										■	■			■	■		■		5 to 15
Induction	■	■	■	■		■				■	■		■						■	■	■	■		■	■	■		■		3 to 10
Natural gamma	■	■	■	■															■	■	■	■	■	■	■	■	■	■		2 to 5
Neutron-neutron	■	■	■	■		■					■								■		■	■	■		■	■			■	3 to 6
Gamma-gamma	■	■	■	■		■	■				■		■		■		■		■	■	■	■	■	■	■	■			■	1 to 5
Sonic	■	■	■	■		■					■								■		■	■			■	■	■			5 to 10
Temperature								■	■		■			■					■			■	■	■	■			■		3 to 10
Fluid conductivity								■	■		■								■			■	■	■	■			■		3 to 10
Flowmeter									■		■								■			■	■	■	■	■	■			0 to 10
Casing collar locator													■							■	■	■	■			■		■		3 to 10
Calliper												■	■			■	■	■	■	■	■	■			■			■		5 to 10
Cement bond														■	■			■	■		■	■	■			■	■			5 to 10
Closed circuit TV	■								■		■	■	■			■	■		■	■		■	■	■	■	■	■	■	■	1 to 3

NOTE The log response significantly reduces with increasing borehole diameter. The reduction will be greater in cases of resistivity, single-point resistance, induction, spontaneous potential, temperature, fluid conductivity, flowmeter, casing-collar locator and closed-circuit television logs.

5.2 Safety around wells, boreholes and shafts

Over and above potential hazards arising from the use of the logging system itself, it is important to be prepared in advance for hazards that might be encountered on reaching the site. Common potential hazards include the following:

a) drilling site problems related to circulation mud pits, compressed air, slippery conditions or equipment, and work under drilling masts;

b) conditions inside old buildings including unstable roofs or floors, loose junk, gas accumulation and exhaust build-up;

c) work around large diameter wells/shafts and chambers including gas accumulation below the surface, unsatisfactory cover plates and risks of falling into the well;

d) conditions around deep boreholes including gas generation;

e) work at remote sites lacking help or communication in an emergency;

f) problems with overhead cables and current leakages;

g) presence of gas and leachate at waste disposal sites.

A safety code should be made available to all personnel to establish safe working practices in the vicinity of wells, boreholes and shafts. Particular regard should be given to the need for the following equipment or precautions:

— adequate safety clothing including helmets, gloves, boots, etc.;

— approved gas monitoring equipment to detect methane or, if appropriate, other toxic suffocating or explosive gases;

— safety harnesses;

— a minimum of two persons on site unless under certain defined circumstances;

— designated no smoking areas;

— prearranged radio communications and reporting procedures;

— a first aid kit.

5.3 Site access

Planning of the logging exercise should have regard to the following:

a) legal rights of vehicular or non-vehicular access;

b) verbal permission from the owner or tenant;

c) physical constraints such as soft or firm surfaces, width of openings and gates, headroom, gradients, etc.;

d) damage to crops, fields and fences;

e) line of sight access from top of borehole cable boom or tripod;

f) availability of power supply;

g) need for stock-proof fencing;

h) noise and nuisance.

5.4 Access within a borehole

If logging is to be carried out where there is a risk of entanglement or wrapping of cables, pressure lines, rising mains or pumps, an access tube should be provided. This should have a smooth internal profile and a minimum internal diameter of 100 mm and should extend not less than 2 m below a working pump. The diameter and length of the sondes to be used may dictate that larger access tubes are required. In the case of a small diameter borehole, dummy runs should be made with a heavy plummet to ensure free access.

Possible hazards to be considered in designing an access tube include:

a) debris falling on top of the sonde or floating slivers of plastic which can cause jamming;

b) snagging that may arise where a small diameter tube opens downwards into a larger borehole, particularly where verticality is suspect.

A smooth profile to the cable head and provision of a funnel at the base of the access tube will assist in trouble-free access.

5.5 Equipment

All equipment should be regularly serviced in accordance with the manufacturer's recommendations. It is good practice to maintain logging sondes and rocks and the general working environment in a clean, dust-free condition and to carry out routine pre-logging checks on each function. Attention should at all times be paid to the condition of the equipment as slow deterioration can often go unnoticed; in particular the safety of all electrical connections and the correct condition and operation of the cable head. Appropriate measures should be taken to ensure that any equipment used in a water supply borehole is washed and sterilized immediately before use.

5.6 Borehole details

To prepare equipment adequately, basic details of the borehole will be required before arriving at the site. Certain systems with data recording facilities may also require the input of header information or supplementary comment. It is useful in any case to have as much data on the borehole as possible in order to aid on-site interpretation. A list of relevant data to be considered is as follows:

a) location and national grid reference;

b) national water well number or other identifier;

c) total depth of the borehole;

d) standing water level and/or pumping water level;

e) date constructed;

f) drilling fluid, whether water, mud, air or foam;

g) lining or casing details including diameter, depth, plain or slotted, material (plastics, steel, fibreglass, etc.), grouting details, construction of borehole top and datum levels;

h) uncased hole diameters and reductions;

i) borehole fluid;

j) zones of collapse or possible constriction;

k) presence of pump (dip tubes, flanged rising main, electrical cables, etc.);

l) likelihood of junk in borehole;

m) methane content of water;

n) presence of saline interfaces;

o) position of underground services or above ground cables;

p) pumping rates and possible influence of nearby abstraction of recharge boreholes;

q) presence of contamination, whether from direct pollution into borehole, surface layers of oil or diesel, or leachate plumes.

Much of this information will be appropriate for presentation along with the final log. This is discussed in clause 10.

The precise logging sequence depends on local conditions and requirements. It is, however, advisable to conduct the logging in a pre-planned sequence, to aid in interpretation and to minimize mutual log disturbance.

5.7 Logging sequence

In the case of fluid logging, consideration should be given in advance to the effects of drilling or other disturbing mechanisms in the water column such as pumping. Where appropriate, arrangements may be required for those to cease, ideally at least 24 h prior to logging.

Alternatively, the object of logging a borehole might be to determine conditions during pumping. Certain formation logs may be required during or immediately after drilling to evaluate lithology or pore water quality perhaps to assist in deciding the final depth or the optimum location of casing or borehole screen.

In the case of an open borehole where special requirements do not apply, a suggested logging sequence might be as follows:

a) determination of total depth and clear access to borehole (e.g. with plummet);

b) fluid temperature and conductivity logging;

c) flow logging;

d) calliper log;

e) formation logging.

Although it is important to measure fluid temperature and conductivity profiles in their undisturbed state as a downhole log, this does require a compromise. It would be unwise to place any expensive logging sonde into a borehole without prior knowledge of the depth to which there is unhindered access. The jamming of a sonde, the coiling of lightweight cables or, at the very least, the clogging of conductivity rings by mud in the base of hole can largely be avoided by a little care. In newly drilled boreholes in alluvial aquifers it is wise to wait an hour before logging in case the borehole collapses. A hand-wound plummet is an effective means of detecting potential problems arising from obstructions, bridging, collapse or situation. However, the introduction of such a device may affect the delicate thermal balance of the water column and interpretation of the fluid logs should take account of this.

Following fluid logging in this sequence, the calliper log not only provides a useful aid to on-site interpretation of subsequent formation logs but also highlights in detail any potential hazards for larger or more complex sondes such as sonic sondes or sondes containing radioactive sources.

5.8 Quality assurance

Before, during and after logging a number of checks should be made on the data and sonde as follows.

a) Calibration checks of the sondes:

   1) each log parameter should be calibrated at the recommended interval;

   2) jig checks should be made in the field before and after logging;

   3) calibration certificates should be fully completed.

b) During the logging operation, a short repeat section (typically 5 m to 20 m) of the log should be recorded in addition to the main run in order to provide a check on equipment stability and repeatability and in the case of radiometric tools an indication of statistical variations.

c) Other checks include:

   1) making sure that the sonde depth reference returns to the log datum within acceptable limits after each logging run and that any discrepancy be recorded on the field sheet;

   2) verifying that the calliper log measurement (where run) agrees with the expected dimensions of well casings;

   3) verifying that the water level detected by appropriate logs agrees with the water level measured by a conventional independent method.

d) Data collected by magnetic recordings should be backed up or the tape given a unique identification.

6 Formation logging

6.1 General

Formation logs respond to the physical properties of the geological formations around the well and the fluids they contain.

The formation logs are described in 6.2 to 6.6.

6.2 Electric logs

6.2.1 Resistivity

6.2.1.1 Property measured

The electrical resistivity of the formation around the borehole is measured.

6.2.1.2 Applications

Applications for measuring the resistivity include:

a) determination of formation water quality and the borehole fluid level;

b) determination of bed thickness and type;

c) correlations between boreholes;

d) determination of porosity;

e) detection of casing and/or open hole boundary.

6.2.1.3 Principles of measurement

6.2.1.3.1 Resistance

The simplest electrical measurement is a single point resistance (SPR) log, the electrical resistance of the ground being measured between one surface electrode and one downhole electrode. The measurements cannot be calibrated as resistivity and for this reason the log is suitable for qualitative interpretations only. It is very much affected by hole size and fluid conductivity. However, it provides considerable detail and is useful for correlation.

6.2.1.3.2 Resistivity

The use of multi-electrode sondes enables resistance measurements to be made of known or assumed volumes of earth and hence the measurements are calibrated in terms of resistivity. Common electrode arrangements are the 0,4 m (16 in) (short) and 1,6 m (64 in) (long) normal and the 7,5 m (224 in) lateral arrays. The short normal array is designed to measure the resistivity of the invaded zone of the formation close to the borehole wall. The long normal and lateral arrays are used to obtain the resistivity of the undisturbed formation beyond the invaded zone. The radius of investigation of normal (potential) electrical sondes is approximately equal to twice the electrode spacing, while the radius of investigation of the lateral sonde is about equal to the electrode spacing.

6.2.1.3.3 Other resistivity logs

Other resistivity logs have been devised to investigate deeper into the formation to obtain a more accurate value of the formation resistivity. These are the focused current tools such as the guard and laterolog, which are specifically designed to measure true readings and relatively high formation resistivities through conductive borehole fluids. With focused sondes, a much better vertical resolution (i.e. bed thickness evaluation) is achieved than with the short normal array.

6.2.1.4 Calibration

This is achieved by connection of resistances of accurately known values to the sonde, prior to logging.

6.2.1.5 Interpretation

Resistivity logs along with porosity information may be used to determine porewater quality using empirical relationships. Resistivity logs are quite useful in deciphering water-bearing zones and in determining porosity based on Archie's empirical relationship as follows:

$$F = \frac{R_\mathrm{t}}{R_\mathrm{w}} = \frac{1}{Q_\mathrm{m}}$$

where

F is the formation factor;

R_t is the formation resistivity;

R_w is the formation fluid resistivity;

Q is the porosity;

m is the cementation factor.

6.2.2 Spontaneous potential (SP)

6.2.2.1 Property measured

Electrical potentials caused by electrochemical and oxidation-reduction differences occur at the contact of the geological strata with borehole fluid and at the contact between the geological strata. A single electrode, usually made of lead, is run down the borehole and the potential difference is measured between this electrode and one placed at the surface.

6.2.2.2 Applications

Applications for determining the spontaneous potential include:

a) lithological identification;

b) determination of formation water resistivity.

6.2.2.3 Principles of measurement

The SP is a function of the chemical activities of fluids in the borehole and adjacent formation. It is the combination of membrane, liquid junction and streaming potentials. The SP is measured in millivolts.

6.2.2.4 Calibration

The system is calibrated using known potentials over the range of the instrumentation.

6.2.2.5 Interpretation

The primary function of this log in groundwater applications is as a sand/clay indicator or limestone indicator. However, porewater conductivity, and hence quality, can be estimated from certain empirical formulae using SP logs provided there is sufficient electrochemical contrast between the fluid in the borehole column and formation porewater fluids. The borehole fluid resistivity is determined through a mud resistivity meter. However, these conditions are seldom met in fresh water aquifers and errors in these estimates can be large.

6.2.3 Induction

6.2.3.1 Property measured

Electrical conductivity of the formation around the borehole is measured.

6.2.3.2 Application

Applications for determining induction include:

a) determination of true formation resistivity;

b) measurement of bed thickness and type;

c) correlations between boreholes;

d) fracture location in low porosity fresh water formations;

e) usage in open or plastic-cased boreholes, that are air, water or mud filled.

6.2.3.3 Principles of measurement

The induction sonde comprises between two and six coaxial coils (focused tools) one of which is the transmitter and another is the receiver (main coils) coil spaced between 0,7 m and 1 m apart. The remaining coils (focusing coils) are used to improve vertical and radial resolution of the device.

The transmitter coil is energized by high frequency alternating current. The resulting magnetic field induces secondary currents in electrically conductive formations; these in turn create magnetic fields inducing signals in the receiver coil.

These signals are proportional to the conductivity (reciprocal of resistivity) of the formation. Any signals produced by direct coupling between the transmitter and receiver in the measuring circuits are balanced out.

6.2.3.4 Calibration

A calibration loop is accurately positioned around the tool that induces a signal in the receiver coils that corresponds to a fixed conductivity value.

6.2.3.5 Interpretation

Provided the formation has not been deeply invaded by the drilling fluid, then the induction log values are close to the true formation resistivity. Induction logs may be run in air-filled and plastic-lined holes (see Table 2).

6.2.4 Limitations of electric logs

Electric logs cannot be run in cased (metal or plastic) or air-filled boreholes. Induction logs cannot be run in metal-cased holes. Also, active electrolytic corrosion of the casing may give rise to spurious potentials on the self-potential log (see Table 2).

6.3 Natural gamma-ray logs

6.3.1 Property measured

The natural gamma-ray log is a measure of the natural radiation emitted as a result of the disintegration of the radioactive elements uranium, thorium and potassium. These are concentrated in minerals such as feldspar, mica, glauconite and clay minerals. Within sedimentary rocks, the potassium-40 isotope contained in clay minerals is mainly used in the evaluation of clay (shale) content.

6.3.2 Applications

Applications for natural gamma-ray logs include:

a) lithological identification;

b) correlation purposes;

c) clay content evaluation.

6.3.3 Principles of measurement

The sonde normally consists of a scintillation counter, commonly a sodium iodide crystal and photomultiplier and its associated electronics.

Gamma-ray emission is statistical in nature; the resultant electronic signals are a series of random pulses. The statistical variations can be reduced by averaging a number of pulses recorded during a given time or depth interval.

A statistical check can also be carried out by holding the sonde stationary in the borehole opposite well-defined strata and recording the log response over a given period of time.

6.3.4 Interpretation

The log is mainly used for lithological identification to distinguish clays, shale and marls (high gamma activity) from sandstones and carbonates (low gamma activity). Correlation of logs from multiple boreholes can be accomplished using gamma-ray logs as shown in Figure 3. Normal gamma-ray logs can be run in cased holes.

6.3.5 Calibration

The log may be calibrated by using a small source of gamma radiation set in a jig that is related to a standard response following the instructions provided by the manufacturer.

6.3.6 Limitations

An increase in hole diameter decreases the gamma log response. The presence of water, casing and grout also affect the sensitivity of the log, as do crystal size, logging speed and filter characteristics.

6.4 Neutron-neutron (porosity) logs

6.4.1 Property measured

The neutron log is a direct measurement of the hydrogen content of the formation.

6.4.2 Applications

Applications for neutron-neutron (porosity) logs include:

a) delineations of saturated porous formations;

b) determination of moisture content (porosity);

c) correlation purposes.

6.4.3 Principles of measurement

The neutron tool contains a source of high-energy neutrons (commonly americium-beryllium) with thermal neutron detectors at fixed distances away from the source (i.e. 200 mm or 480 mm). The emitted neutrons collide elastically with the atoms in the rock. The neutron mass is essentially the same as that of hydrogen, hence collisions with hydrogen atoms cause the maximum energy loss. Thus, with hydrogen present, the number of neutrons counted at the detector will be inversely proportional to the number of collisions taking place and hence the hydrogen content. Since water is the main source of hydrogen in rocks, the neutron log can be calibrated to measure the total water content (porosity) of the formation. Similar statistical checks to the natural gamma-ray log are made.

6.4.4 Calibration

Calibrating sleeves related to standard responses are placed over the sonde following the instructions provided by the manufacturer. Alternatively, the logs may be calibrated against laboratory porosity determinations on core samples for a given aquifer.

6.4.5 Interpretation

The log is interpreted along with other logs so that corrections may be made for the hole diameter and lithology. When calibrated, porosity values can be read directly from the log. As the log measures the total hydrogen content of the formation, high responses can be expected for clays (high water content) and coal (high hydrocarbon content).

6.4.6 Limitations

Increases in the borehole diameter give rise to false porosity values unless corrected. Ideally, neutron logs should be run in small diameter boreholes (less than 300 mm diameter). Casing reduces the log response by holding the tool away from the formation. The presence of grout or plastic casing reduces the neutron log response due to, respectively, high hydrogen or high chlorine contents. Mud cake also keeps the tool away from the wall of the borehole by introducing low-density, high-porosity material between the formation and tool. Neutron logs cannot be used to distinguish between bonded water in clays and free water in sands.

6.5 Gamma-gamma (density) logs

6.5.1 Property measured

Attenuation of back-scattered gamma radiation as a function of electron density of the rock surrounding the borehole is measured.

6.5.2 Applications

Applications for gamma-gamma (density) logs include:

a) measurement of bulk density;

b) derivation of porosity;

c) identification of lithology;

d) location of cavities and cement outside the borehole lining;

e) correlation purposes.

6.5.3 Principles of measurement

The sonde contains a source of gamma radiation (such as cobalt-60 or cesium-137) that is placed at a set distance from the detector. Shielding prevents radiation from the source directly reaching the detector; consequently, most of the radiation arriving at the detector is via the formation. The gamma radiation is scattered by the atoms in the formation such that the number of gamma rays arriving at the detector is inversely related to the density of the rock.

Some sondes use two or more detectors at different spacing from the source so as to provide either correction for borehole effects, such as mud cake and small irregularities in borehole diameter, or a higher bed resolution capability.

All sondes are run down the side of the borehole while being pressed against the borehole wall by either bowsprings or calliper arms.

6.5.4 Calibration

Primary standards are fresh water-filled limestone blocks of accurately known densities. Secondary standards are large blocks of magnesium, aluminium and a tank of water into which the sonde is inserted.

6.5.5 Interpretation

Lithological identification is possible where a sufficient density contrast occurs between formations such as that between a “clean” (clay free) formation and a shale formation.

6.5.6 Limitations

Variations in borehole size due to fissures and caving can result in a loss of contact with the borehole wall. The wall rugosity introduces a source of error from the low-density medium (fluid, mud, mudcake) between the sonde and formation. Casing or grout decreases the sensitivity of the log due to increased attenuation of gamma radiation. The method is not suitable for highly uncompacted formations.

6.6 Sonic logs

6.6.1 Property measured

The acoustic (or sonic) log provides a measure of the velocity and attenuation characteristics of acoustic waves over a given interval of formation adjacent to the borehole.

6.6.2 Applications

Applications for sonic logs include:

a) lithological identification;

b) porosity;

c) seismic velocities;

d) mechanical properties;

e) fracturing/permeability.

6.6.3 Principles of measurement

The sonde consists of one or two transmitters, one or more receivers spaced at fixed distances apart and associated electronics. The acoustic transmitters are pulsed at regular intervals and either the time for each pulse to reach each receiver is measured or the full acoustic wave form arriving at each receiver is displayed and recorded. Usually “interval transit time” of slowness in microseconds per metre is recorded instantaneously. This is the reciprocal value of the sonic velocity of the longitudinal (P) waves.

6.6.4 Calibration

The times measured are related to an accurate electronic clock within the sonde.

6.6.5 Interpretation

Variations in the P wave (compressional) velocity may be used to determine changes in lithology and derive porosity of the formations.

Analysis of the full wave recording (dependent upon sonde type and conditions) may permit identification of compressional shear and Stonely waves from which elastic moduli (along with density) and fracture properties of the rock can be determined.

The attenuation and distortion characteristics of the waveform may also provide information on fracturing and permeability characteristics of the rock.

6.6.6 Limitations

The sonde should normally be run in the middle of boreholes of up to 500 mm in diameter (dependent upon transmitter and/or receiver spacing and sonde diameter) and in unlined fluid-filled sections. In large diameter boreholes, certain sonde designs may be run sidewalled.

6.7 Other logs

6.7.1 General

Other logging methods are in use in the petroleum industry and have application in hydrogeophysical logging, but are used only occasionally. They include, for example, dipmeter measurements, electromagnetic propagation measurements, lithodensity logging, spectral gamma-ray measurements and imaging such as acoustic televiewer and formation micro-scanner logging. For details on these measurements, the reader is referred to texts listed in the Bibliography.

6.7.2 Dipmeter

The dipmeter tool provides an apparent dip of beds by comparing detailed micro-resistivity curves from opposing sides of the borehole. The verticality of the borehole is also usually measured. An azimuth orientation of the measurements is given by a magnetometer or gyrocompass. The dip is computed from the offset of resistivity changes recorded by multiple electrode arms that contact the borehole wall. Early tools recorded three resistivity curves; modern tools record six or eight curves from three or four independent arms.

The dipmeter resistivity and orientation data is processed to determine the dip and strike of formations encountered in the borehole. It can be used to locate faults, unconformities, fractures and joints. It is increasingly used for sedimentology studies.

Because the processing is complex, it is one of the more expensive tools to run. A borehole diameter of at least 150 mm (6 in) is needed for good accuracy.

6.7.3 Spectral gamma ray

Spectral gamma-ray logging is a variation of natural gamma-ray logging in which the individual proportions of potassium, uranium and thorium which make up the total spectrum are determined by measurements in several energy windows. The ratio of these elements is used to identify the types of clay mineral present.

The tool is of larger diameter than natural gamma-ray tools because of the need to use a larger volume detector.

6.7.4 Lithodensity log (photoelectric absorption)

The lithodensity log is a variation of the formation density log that, in addition to bulk density, measures the photoelectric absorption index of the formation. The photoelectric absorption curve is used to identify the lithology more accurately than the density log because porosity and the pore fluid have less influence on it. Used together with spectral gamma measurements, it can also identify clay minerals that may be present in the formation.

6.7.5 Acoustic televiewer or borehole televiewer

The acoustic televiewer is a sonic logging method that uses a rotating transducer to provide an image of the acoustic reflectivity of the borehole wall. The image shows the borehole wall as it would appear if split vertically and laid flat. The image is orientated using a magnetometer inside the tool and is useful for identifying fractures. Vertical fractures appear as straight lines; inclined fractures as sinusoidal traces. The direction and dip of the fractures and other structural features (bedding) relative to magnetic north can be read from the image.

It can be used in boreholes where conventional video images are not available due to poor visibility but cannot be used where there is no mud or water required for the sonic coupling (i.e. above the water table or in dry holes).

6.7.6 Formation micro-scanner

The formation micro-scanner provides an electrical image of the borehole wall by measuring electrical conductivity from any array of buttons on pads that contact the borehole wall. The electrical measurements are processed into orientated images of strips of the borehole wall. The images are two-dimensional and highly resolved and can be used to identify bedding, fractures and sedimentary features. It is an expensive tool to run and is not normally used in water wells.

7 Fluid logging

7.1 General

These logs record the properties and movement of water within the borehole. The parameters measured are temperature, electrical conductivity and flow.

7.2 Temperature

7.2.1 Property measured

Temperature of the borehole fluid surrounding the sonde is measured.

7.2.2 Applications

Applications for logging the temperature of the borehole fluid include:

a) detection of fluid movement within the borehole;

b) identification of zones of inflow/outflow (including casing leaks) within the borehole;

c) determination of geothermal gradient;

d) data provided for the correction of other logs such as fluid conductivity and formation resistivity.

7.2.3 Principles of measurement

The sonde contains a thermal detector, thermistor or solid state device and its electronics.

As well as recording the absolute fluid temperature, differential temperature is often obtained by measuring the difference between two depths (typically 0,25 m to 2,5 m apart) using two sensors or more commonly by digital techniques. Differential logs are particularly useful as small changes in the temperature gradient are sharply accentuated.

7.2.4 Interpretation

There is a natural geothermal gradient of increasing temperature with depth. This gradient varies with the thermal conductivity of the geological formation and is modified by water flowing in and out of the borehole. Interpretation of the log can determine the flow pattern within the borehole.

7.2.5 Limitations

The log may be run in all sizes of borehole, although in very large diameter wells thermal variations across the well may affect the results.

The borehole fluid is disturbed during logging. Consequently, this log should be run first in a downward direction (and normally combined with fluid conductivity).

Drilling, cementing and pumping disturbs the thermal environment of the borehole fluid and time should be allowed for the borehole fluid to approach equilibrium prior to logging.

7.3 Fluid conductivity

7.3.1 Property measured

The electrical conductivity of the borehole fluid is measured.

7.3.2 Applications

Applications for logging the fluid conductivity include:

a) determination of borehole fluid quality;

b) identification of zones of fluid movement into, out of and within the borehole.

7.3.3 Principles of measurement

The fluid conductivity sonde usually contains a series of encased electrodes of inert metal or carbon. An alternating current is passed between one pair of electrodes and the resultant voltage across another pair is measured. Conductivity may also be measured by electromagnetic methods whereby coils are used in place of electrodes.

Differential logs are particularly useful as small changes in conductivity are sharply accentuated.

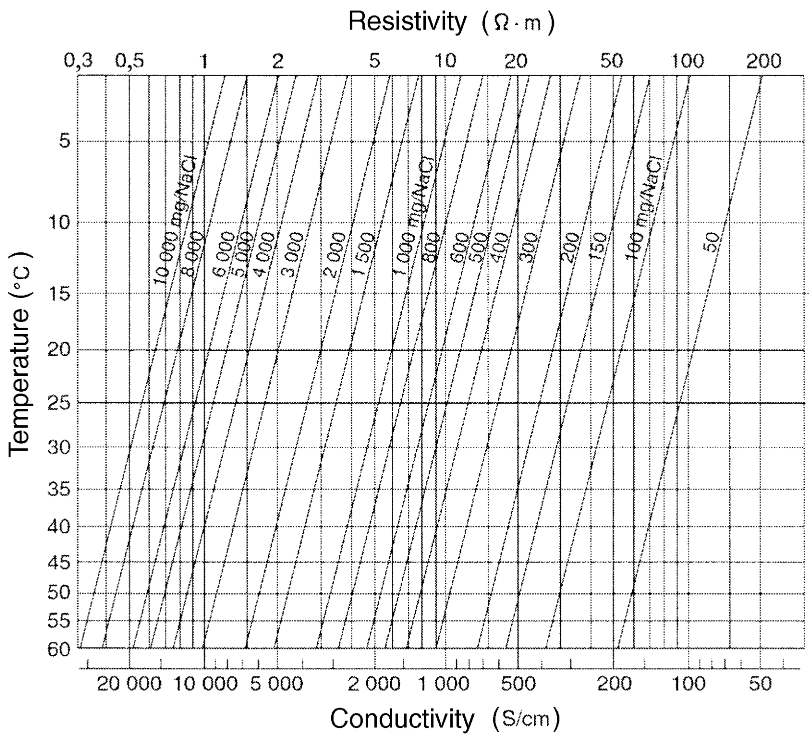
7.3.4 Calibration

The sonde is placed in fluids of known electrical conductivity and temperature. Corrections are then made to a standard temperature (normally 25 °C).

7.3.5 Interpretation

The electrical conductivity of water is related to the total dissolved solids and is therefore a measure of the quality of the groundwater.

Charts such as those given in Figure 5 may be used to determine the electrically equivalent sodium chloride concentration. The conductivity log should always be corrected for temperature, as conductivity is a function of temperature. The shape of the log trace can indicate zones of inflow/outflow.



NOTE Taken from reference [1].

Figure 5 — Electrically equivalent concentrations of a sodium chloride solution as a function of conductivity or resistivity and temperature

Specialized techniques of repeated fluid conductivity/temperature logs in connection with pumping test data can allow for the calculation of the transmissivity of inflow zones. This technique is particularly suitable for lower transmissivities (fractured rocks) and has been applied in many planned repositories for nuclear waste.

7.3.6 Limitations

This log should be run together with the temperature log in an undisturbed fluid column. Drilling, cementing and pumping disturbs the column and sufficient time should be allowed for this to settle down prior to logging. If the sonde is allowed to stand in mud at the base of the hole, or mud on a ledge, subsequent readings may be erroneous.

7.4 Flow

7.4.1 Property measured

Fluid velocity in the borehole is measured.

7.4.2 Applications

Applications for logging the flow include:

a) determination of flow rates and direction within the borehole;

b) identification of permeable zones;

c) location of casing leaks;

d) determination of vertical profile of permeability or transmissivity (in connection with pumping test).

7.4.3 Principles of measurement

There are several means of measuring vertical flow in boreholes, dependent on the magnitude of the anticipated velocities. The most common is an impeller type that consists of a turbine whose revolutions against time are counted. The range of flows measurable by this method is 30 mm/s to 5 000 mm/s. Velocities lower than 30 mm/s may be detected using an impeller by applying the difference method, i.e. running the impeller both up and down the borehole at constant speeds and noting the differences between the two logs. For high velocities, the impeller may be held stationary at points of interest.

Low-flow measurements may also be made using specialized techniques such as head-pulse, packer-flowmeter, tracer methods or repeated fluid conductivity and/or temperature logging. Other methods such as electromagnetic measurement of flow are currently being introduced.

7.4.4 Calibration

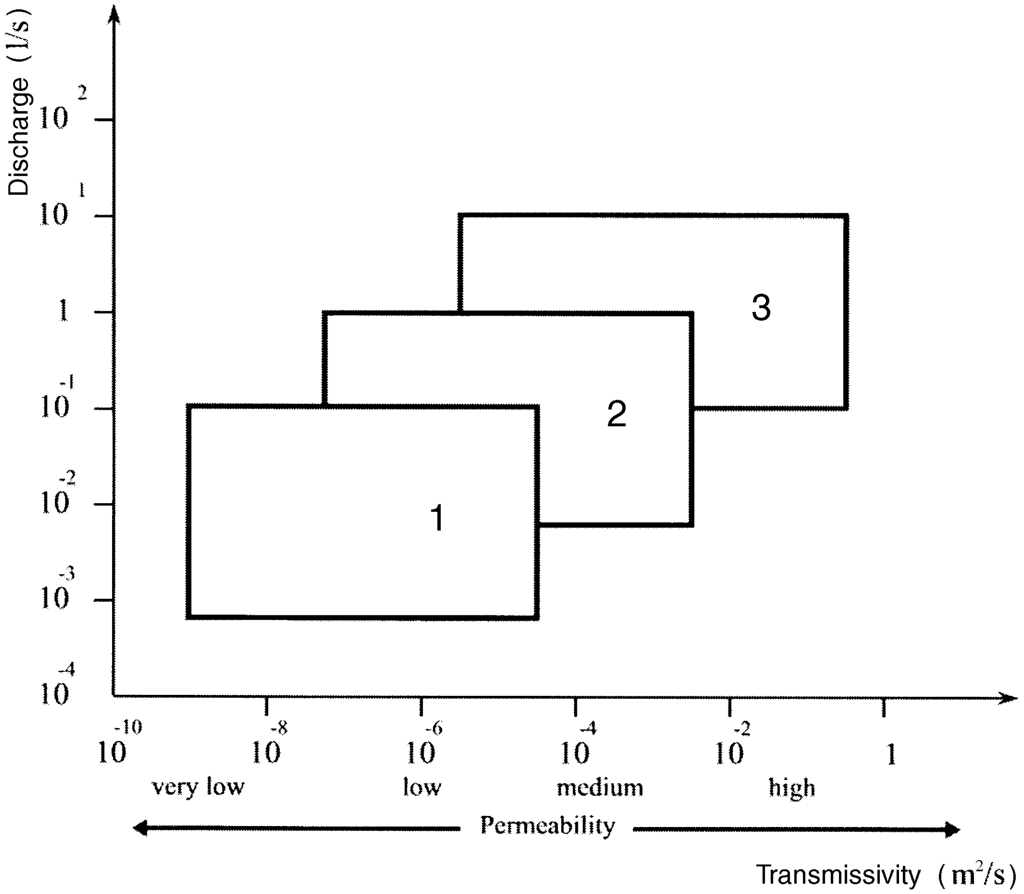
Flow measuring sondes may be calibrated in special flow rigs or in the lined sections of a borehole under controlled pumping or recharge.

7.4.5 Interpretation

Flow rate can be calculated from a combination of fluid velocity and calliper logs.

7.4.6 Limitations

Corrections for borehole diameter changes have to be made. The sonde should, if possible, be centralized in the borehole. Some flowmeters can only be run in one direction either up or down the borehole. Other flowmeters can be used only in clean water conditions (after flushing or pumping) because of optical detection systems. Figure 6 shows the recommended fluid flow logging method for ranges of discharge and permeability.



Key

1 Temperature/fluid electrical conductivity heat pulse flowmeter
2 Packer flowmeter
3 Flowmeter

Figure 6 — Recommended fluid flow logging methods for ranges of discharge and permeability

8 Construction logging

8.1 General

There are several sondes available to measure the physical characteristics of the borehole construction such as diameter, depth to casing, location of casing joints and the integrity of the cement grout.

Additionally, some of the logs in the previous sections have applications in constructional determinations, such as the density log for detection of cavities behind the casing and temperature for grout location.

8.2 Calliper

8.2.1 Property measured

The sonde measures the diameter of the borehole.

8.2.2 Applications

Applications for logging the diameter of the borehole using a calliper include:

a) location of casing, type and breaks;

b) location of diameter changes in the borehole and packer settings;

c) location of fractures/fissures and other openings;

d) identification of soft and hard formations;

e) provision of data for correcting other geophysical logs;

f) calculation of borehole volume.

8.2.3 Principles of measurement

Callipers are mechanical devices consisting of one to four spring-loaded arms held against the borehole wall. Any movement of these arms may be arranged to give a mean diameter or two orthogonal diameters (x-y calliper). Callipers are often run as part of a combination sonde and measurements always taken while moving the sonde up the borehole.

8.2.4 Calibration

Calibration is carried out using jigs or cylinders that enable an arm to be set at different radii.

8.2.5 Interpretation

The log shows borehole diameter changes, which can be attributed to drill bit changes, washouts, fissuring, caving and mudcake formation.

8.2.6 Limitations

The presence of rising mains, pumps and other hardware in the borehole will give erroneous results. Silts, sands and mud may prevent the calliper arms from operating correctly.

8.3 Casing collar locator

8.3.1 Property measured

This log measures the changes in the magnetic flux due to the magnetic property of the material present.

8.3.2 Applications

Applications for logging the magnetic flux using a casing collar locator include:

a) location of other magnetic hardware such as rising mains, pumps and debris;

b) control log for other geophysical logs that are affected by the presence of casing.

8.3.3 Principles of measurement

The casing collar locator device consists of a magnet and coil arrangement. Changes in the magnetic flux caused by the variation of casing thickness results in an induced voltage. The log is run at constant speed and sharp changes in the record indicate casing collars, etc.

8.3.4 Calibration

Calibration as such is normally not necessary, other than adjustment of the electronics for the required sensitivity.

8.3.5 Interpretation

The log curve is generally a base line with periodic marks (or pulses) indicating the depths at which there is a change in the amount of metal present.

8.3.6 Limitations

The position of the sonde in the borehole affects the magnitude of the signals. For this reason, in large diameter boreholes, the sonde should be run close to the side. Changes in logging speed give erroneous readings. The log can be susceptible to electrical noise, such as that from nearby electrical pumps.

8.4 Cement bond

8.4.1 Property measured

The cement bond log is obtained using a sonic sonde where the amplitude and/or waveform of the received acoustic signal is measured.

8.4.2 Applications

Applications for logging cement bonds include:

a) the determination of the amount of bonding between the steel casing, cement grout and formation, or degree of channelling within the grout;

b) the location of the cement seal.

8.4.3 Principles of measurement

Steel casing suspended freely (unbonded) in a fluid-filled borehole transmits elastic energy at a velocity of 5 340 m/s with little attenuation over the transmitter receiver spacing. When cement is present and properly bonded around the casing, the elastic energy is dissipated before reaching the receiver. The received amplitude is therefore a function of bonding.

8.4.4 Calibration

At a level of 100 % bonding the signal amplitude should ideally be zero; this point can be obtained electronically. The 0 % bond position of the sonde can be obtained by setting the sonde in freely suspended lengths of casing.

8.4.5 Interpretations

Variations in the amplitude curve are interpreted in terms of the casing cement bonding. Corrections have to be made for casing joints. More commonly, the full wave form is recorded and displayed in variable density format which allows easier identification of bonding of the casing.

8.4.6 Limitations

The sonde should normally be run centralized (typically in boreholes up to 500 mm diameter, dependent upon transmitter, receiver spacing and sonde diameter) and in steel-lined fluid-filled sections. In large diameter boreholes, certain sonde designs may be run sidewalled.

8.5 Closed circuit television log

8.5.1 Property measured

Physical features of borehole are measured and recorded.

8.5.2 Applications

This log not only measures the depth of visual features but also is useful for checking the condition of well casing or screen, examining geological features along the borehole walls, identifying collapses and obstructions, and for examining installed pipework.

8.5.3 Principles of measurement

A video signal from the borehole closed circuit television camera is sent to the surface control unit via the logging cable. Many closed circuit television systems are operated with a special cable, especially in the case of deep boreholes (more than 300 m). This surface equipment includes a monitor and video recorder. Logging and borehole information, including depth, is also recorded using a television writer.

The camera should be fitted with lenses and light sources to facilitate forward views (looking down the borehole) and a rotating side view to examine the borehole well or construction.

Some cameras may have devices that can be fitted to record directional orientation.

8.5.4 Interpretation

The pictures obtained may be difficult to interpret without other geophysical logs and require experience on the part of the operator to make a full analysis.

It is possible to evaluate flows within the borehole, either by observing the movement of suspended particles or by attaching lightweight streamers within the field of view of the camera and noting their movement.

Evidence of cascading and seepage can also be obtained by this method.

8.5.5 Limitations

None of the visual information is quantitative. The clarity of the picture is affected by particulate matter in the borehole fluid which reflects light, causing flaring on the screen. Picture quality is also reduced in large diameter boreholes.

9 Log presentation

9.1 General

Geophysical logs are an invaluable record and should be clearly presented for proper interpretation. Logs filed away with no header information and only cryptic annotation can be virtually useless when the details of logging have been forgotten.

The standards of presentation suggested here are in keeping with generally accepted practices and with the outputs from a wide range of instrumentation.

On-site log output is usually from a multi-channel chart recorder in the form of plotted or printed-paper output.

Digital logging systems often provide the facility to replay logs off-site, allowing for clean and suitably-scaled versions to be produced.

Whether conducted for “in-house” purposes or by a service company, the resulting logs have to be capable of interpretation by others. The site and logging information sheets (see Figures 7 and 8) provide information to identify the borehole and have to describe all logging activities and details of equipment used.

The example header contains all information necessary for common water well logs. It is designed to describe all the background information relating to the log without any other documentation. The data requested are self-explanatory and can be used for analogue or digital logging systems. The header allows for several logging runs to be merged; for example, a resistivity log run in an uncased borehole can be joined to a subsequent log and the header will provide details of both runs so that quantitative evaluation can be made for the complete borehole section.

The equipment used has to be described, especially detector spacing and whether the tool is centralized or sidewalled. Calibration data should be included in the space provided to enter jig readings or calibration coefficients.

LOGO	**Log type**

Client	
Well name/number	
Location	

Permanent datum		Elevation		Other logs
Log measured from				
Drilling measured from				

Run No.	**Borehole record**			**Casing record**			
	Bit	From	To	Size	Type	From	To

Date		Fluid type	
Run No.		Fluid level	
Depth drilled		Fluid resistivity at temperature	
Depth logged		Fluid density	
Bottom logged interval		Time in	
Top logged interval		Time out	
Operator		Witness	

Equipment, logging and recording data

Log type							
Run No.				Calibration type			
Tool No.	Diameter				Data		
	Spacing				Data		
	Position				Data		
Source	Type		Panel time constant		Sensitivity		
	Strength			Offset			
Digital filter	Width		Log recorded				
	Data interval		Tape/disk reference				
Logging speed			Direction		Direct/replay		

Depths	From						
	To						
	Interval						

REMARKS	

Vertical scale	General	1:	Detail:	

Log scales

(Attach log top section here)

Figure 7 — Example of site and logging information sheets: header section

(Attach log tail section here)				
Log scales				
Vertical scale	General	1:	Detail	
Client				
Location				
Well number/Name				
Log type				

Figure 8 — Example of site and logging information sheets: tail section

The header can describe up to a six-function tool string that is sufficient for water well purposes. Full use should be made of the remarks space to note any other relevant data such as circulation loss details.

9.2 Track layout

Standard layouts are either a plain metric scale grid or preferably the conventional three-track system. The left track, track 1, is normally used for gamma, calliper and spontaneous potential logs. The right-hand tracks 2 and 3 are used for other logs. An acceptable variation is to use tracks 2 and 3 for detailed gamma logs.

A variety of track chart paper width is available depending on the type of logger used. Analog loggers use 25 cm width paper and digital loggers use 6,4 cm (2,5 in) width paper. Where a large range of log values is expected in resistivity or conductivity logs, a three-track version with logarithmic scales on tracks 2 and 3 is available providing the hardware output options are suitable. Track widths divided into 5 or 10 divisions and depths in metres are now superseding these.

9.3 Log parameter scales

Parameter scales may be chosen which suit the range of data and the output of the equipment. It is essential that the scale title should state if processed logs have been corrected or compensated. All logs are conventionally displayed from left to right.

9.4 Depth scales

The convention for general logging is a depth scale of 1 to 200. Borehole sections where more detail is required should be logged at 1 to 50. Logs for regional correlation purposes should be run at 1 to 500. Digital recording systems allow logs to be replayed at any depth scale with only one logging run.

The basis for selection of depth scales is:

a) depth of borehole to be logged;

b) thickness resolution required;

c) ease of correlation and consistency with other logs.

9.5 Composite logs

Digital log recording and appropriate software can be used to provide very useful composite logs where all logs from one borehole can be output on one sheet. This is an obvious aid to multi-parameter evaluation and to produce report-ready logging summaries. Depth scales of 1 to 500 provide 100 m of borehole information on a convenient A3 size plot.

9.6 Differential logs

As well as reading absolute values of parameters, such as temperature and conductivity, measurements may be obtained of the difference between two sensors a short distance (0,25 m to 2,5 m) apart. However, with digital recording now common, it is normal to compute the differential from measurements using a single sensor.

Differential logs are commonly computed from temperature, conductivity and flow logs for the following reasons:

a) an abrupt change on a temperature, conductivity or flow log, which represents a water inflow or outflow, is converted to a peak on a differential log. This is thought by many to be more easily interpreted;

b) strong vertical temperature or flow gradients can mask smaller changes due to inflows and outflows at fissures. The differential log effectively measures the gradient and enables the use of more sensitive scales.

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