TECHNICAL REPORT

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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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Case postale 56 • CH-1211 Geneva 20
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Fax + 41 22 749 09 47
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# Contents

Page





 

# Foreword

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## 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.



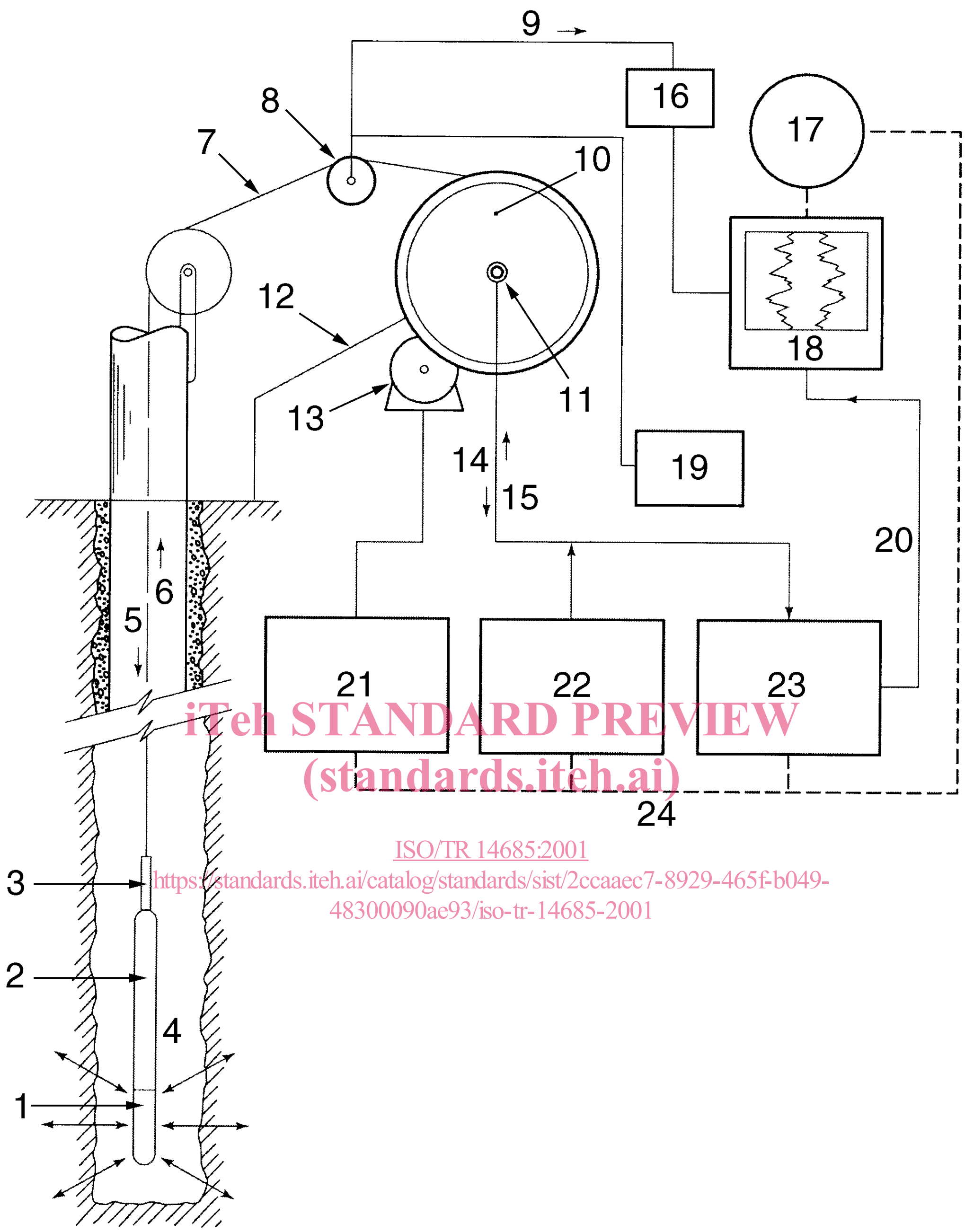
The cable serves the dual purpose of supporting the sonde and conveying electrical power and signals to and from the sonde. To this end it has a double outer layer of high tensile steel or polyurethane/kevlar.



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.